Water Quality Report: 2020
Quabbin Reservoir Watershed
Ware River Watershed

Boat Launch Area 2 Quabbin Reservoir, New Salem, MA (Katharine Langley, 2021)

July 2021

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

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Abstract

This report is a summary of water quality monitoring methods and results from 25 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 2020. 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, Amherst
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)

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 2020.

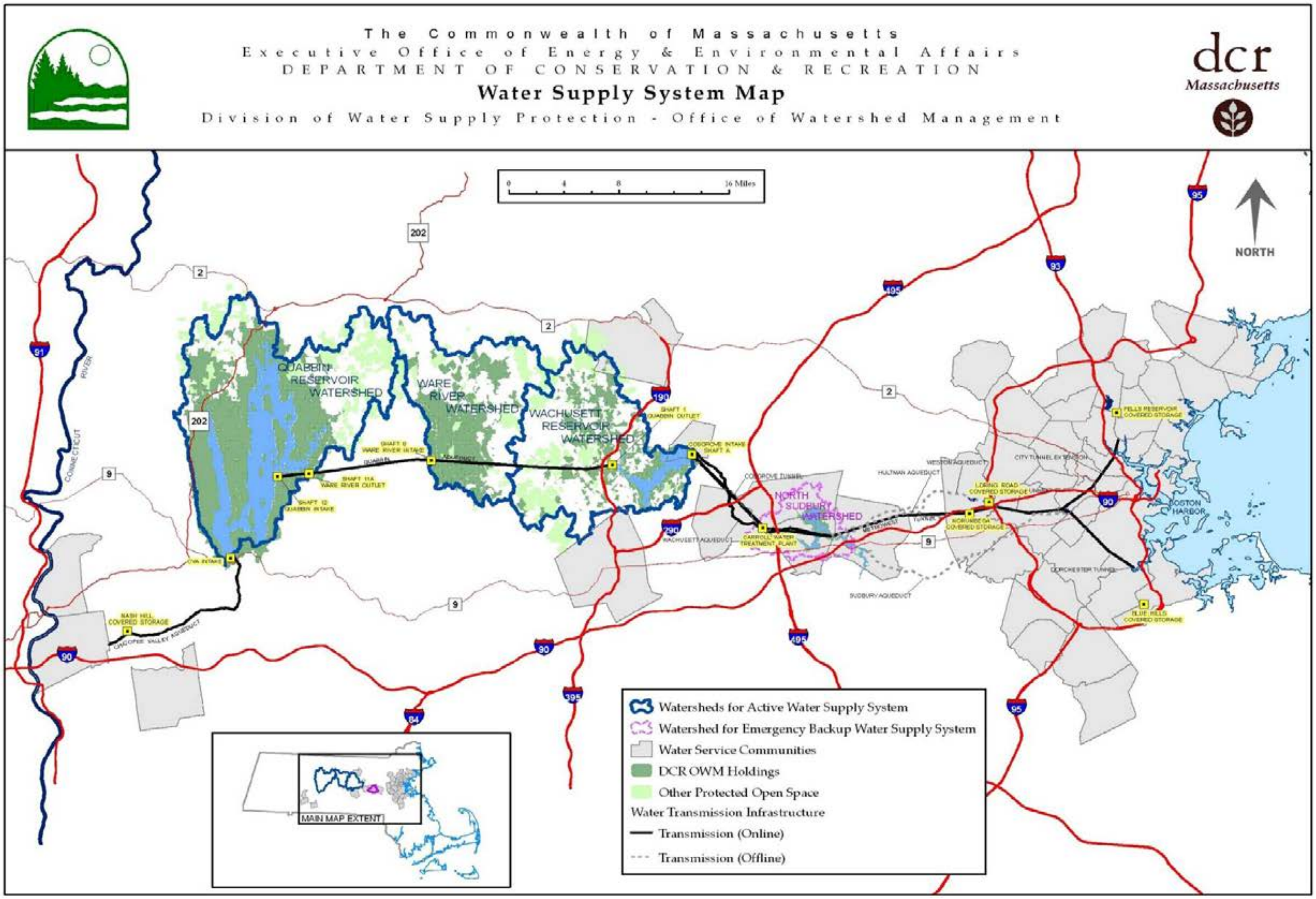

Figure 1: Quabbin Reservoir, Ware River, and Wachusett Reservoir Watershed System. Interstate highways are represented by red lines. Inset map in lower left depicts location of the watershed system relative to MA.

1.1 Public Water Supply System Regulations

The U.S. EPA introduced the SWTR in 1989 to ensure that public water supply systems using surface waters were providing safeguards against the contamination of water by viruses and bacteria. The regulations require filtration by every surface water supplier unless strict source water quality criteria and watershed protection goals can be met. The DWSP and MWRA have maintained a waiver from the filtration requirement since 1989.

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

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

1.2 DWSP Monitoring Program Objectives

MWRA, as an unfiltered water supplier, is required to have a watershed protection program intended to promote and preserve high quality source water by utilizing a range of methods and strategies that ultimately control the release, transport and fate of pollutants in the watersheds. A primary function of DWSP is to design and implement this watershed protection program for the DCR/MWRA water supply system. Watershed protection measures enacted by DWSP have been detailed in DWSP Watershed Protection Plans (WPPs) and WPP updates, since 1991 (DWSP, 2018a). The 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. Data generated by long-term monitoring programs conducted by DWSP are used to assess current and historical water quality conditions, establish expected ranges of various water quality parameters, allow for routine screening of potential threats to water quality, provide early detection of trends, and assess current watershed trends. Shorter-term investigations may also be conducted to evaluate specific issues. Monitoring efforts are reviewed and updated annually by DWSP to ensure that DWSP programs remain current, appropriate, and informative for the WPP goals. Changes to annual water quality monitoring programs performed by DWSP staff are discussed in the annual water quality report for the affected watersheds (DWSP, 2019a; DWSP, 2019b).

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

1. Maintain long-term water quality statistics relative to the protection of public health.
2. Document 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). Other protected lands include property identified by MassGIS as Open Space protected in perpetuity less DWSP, fee lands, and WPRs (WPR = Watershed Preservation Restriction, similar to a Conservation Restriction). Acreage may vary from that of from previous years due to increased accuracy of MassGIS data.

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

b) Quabbin Reservoir Watershed General Information		
Description	**Units**	**Quantity**
Watershed Area (includes Quabbin Reservoir)	Acres	119,935
Land Area	Acres	95,466
	(% Total watershed area)	80
DWSP Controlled Area (includes Quabbin Reservoir)	Acres	77,747
	(% Total watershed area)	64.8
Total Protected Area (DWSP Fee, DWSP WPR, Other protected)	Acres (excludes reservoir)	80,995
	(% Total watershed area)	84.8

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
Total Protected Area (DWSP Fee, DWSP WPR, Other protected)	Acres	35,781
	(% Total watershed area)	58.0

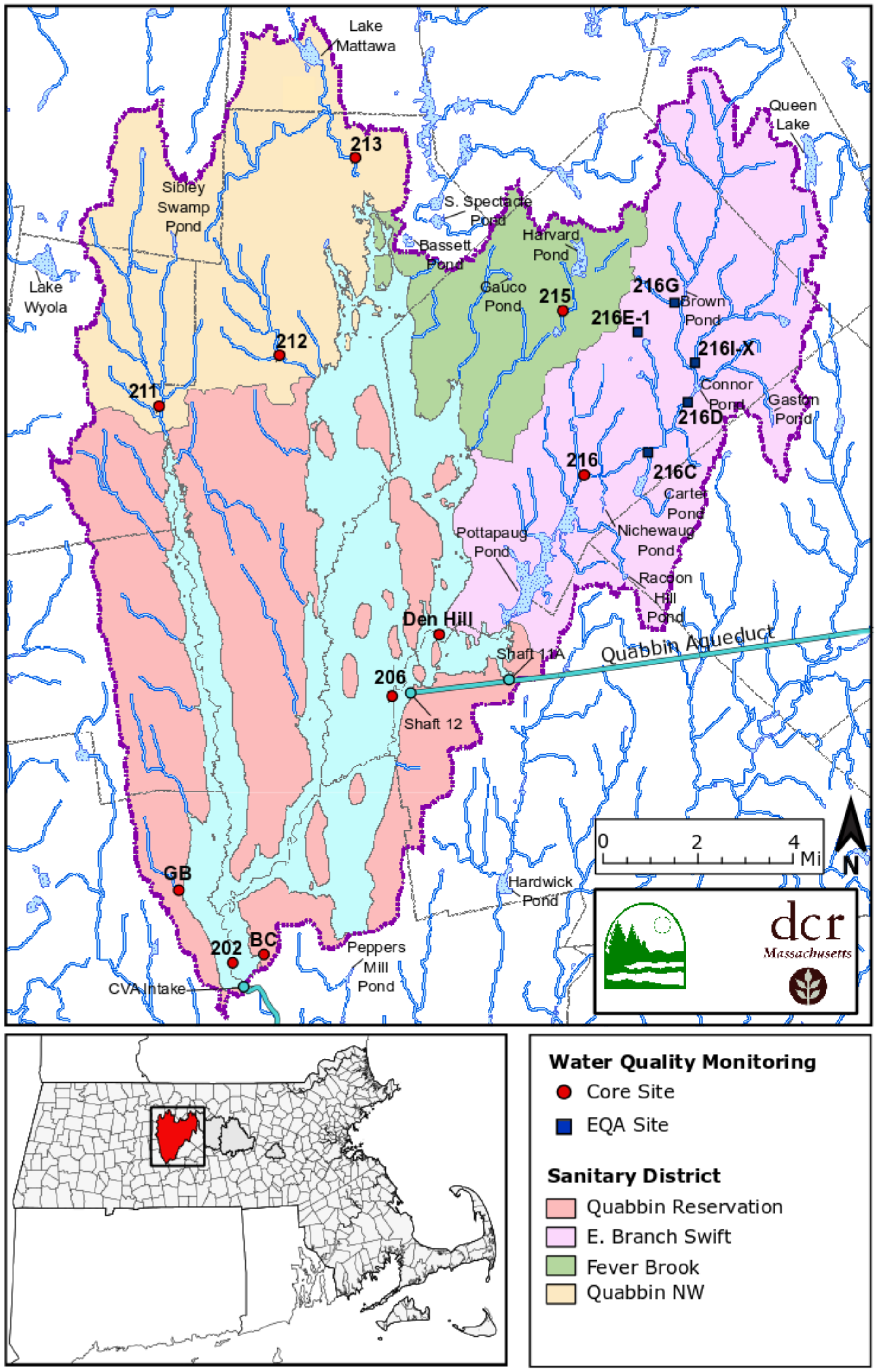

Figure 2: Map of Quabbin Reservoir watershed showing locations of Core and EQA monitoring sites sampled in 2020. Inset map in lower left depicts location of the watershed relative to MA and MWRA system.

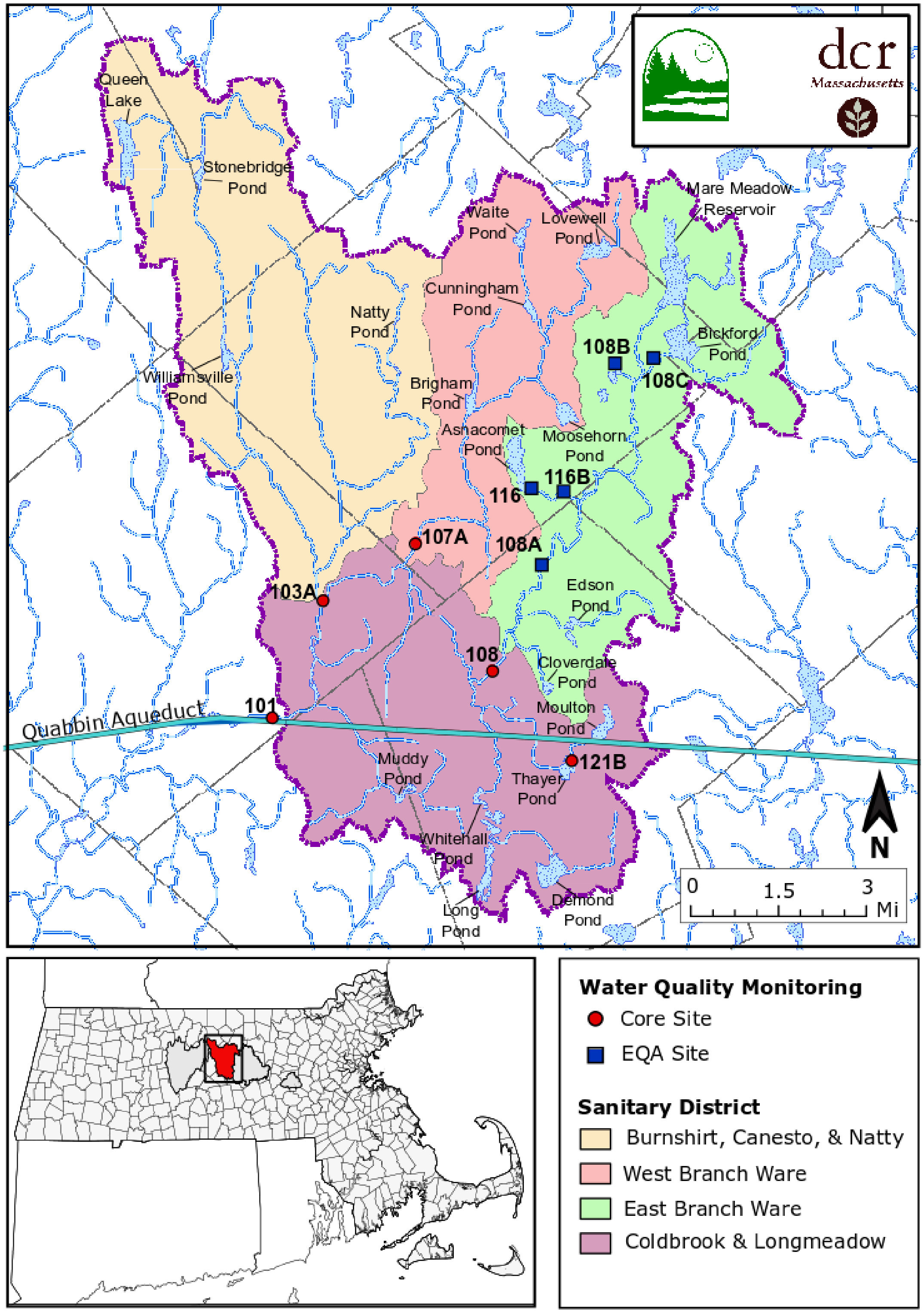

Figure 3: Map of Ware River watershed showing locations of Core and EQA monitoring sites sampled in 2020. Inset map in lower left depicts location of the watershed relative to MA and MWRA system.

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 boat decontamination programs, and monitoring and associated management of aquatic invasive species within the reservoir and in water bodies within the Quabbin Reservoir and Ware River watersheds. Standard operating procedures outlining specific details (e.g., make/model of equipment used) were developed by DWSP staff, and generally follow methods outlined in USGS and EPA protocols.

2.1 Description of Quabbin Reservoir and Ware River Watersheds

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

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

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 a total area comprised of less than 2% each of developed (further classified as rural-residential) or agricultural cover (Table 2). DWSP owns and controls 77,747 acres (64.8% of the total watershed area) for water supply protection purposes, and approximately 84.7% of the total land area in the watershed is protected by other means (Table 1). The relatively high proportion of forested, protected lands in the Quabbin Reservoir watershed helps maintain a level of exceptional water quality in the Quabbin Reservoir.

2.1.2 Land Cover Characteristics of the Ware River Watershed

Land cover in the Ware River watershed is predominantly forest (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 flood control associated with the Barre Falls Dam, on the Ware

River in Barre, MA. Agriculture comprises less than 3% of total watershed area for the Ware River watershed (Table 2).

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

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

2.2 Monitoring Programs

DWSP staff monitored water quality at 22 surface water sites in the Quabbin Reservoir and Ware River watersheds and three sites within the Quabbin Reservoir (Table 3, Figure 2, Figure 3). in 2020. The tributary monitoring locations within each watershed include Core sites and Environmental Quality Assessment (EQA) sites. Core sites represent long-term monitoring sites throughout the watershed that are included in the monitoring plan each year. Core sites are critical for DWSP assessments, as they provide a long-term record of water quality data from primary tributaries within each watershed. Each watershed is divided into sub-watersheds, referred to as sanitary districts (Figure 2, Figure 3). EQA sites within a single sanitary district are sampled approximately once every four 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 East Branch Swift River sanitary district and the East Branch Ware River sanitary district were monitored in 2020.

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

2.2.1 Meteorological and Hydrological Monitoring

2.2.1.1 Precipitation and Air Temperature

Daily measurements of precipitation and air temperatures were recorded at three locations within Quabbin Reservoir and Ware River watersheds in 2020 (Table 3). DWSP maintains one weather station in the Quabbin Reservoir watershed at the DCR Administrative Building in Belchertown, MA. The National Oceanic and Atmospheric Administration (NOAA) maintains a Climate Data Online portal through the National Center for Environmental Information, allowing access to records from weather stations within the DWSP watersheds at the Orange Municipal Airport in Orange, MA, and at the US Army Corps of Engineers Barre Falls Dam in Barre, MA. Meteorological summaries presented in this report correspond to these DWSP (USC00190562) and NOAA weather stations (USW00054756, USC00190408). Historical records are also available from the Ware, MA NOAA weather station (USC00198793). As of 2017, this station is no longer active, and records from this station are not summarized in this report.

DWSP staff measured snow depth and snow water equivalent (SWE) weekly (during periods of snow cover) at six locations in the Quabbin Reservoir watershed in 2020 (Table 3). Reported snowpack measurements (depth and SWE) represent the average depth and weight, respectively, of six snow cores for each sample site, for each site visit. Weekly results were reported to NOAA and the National Operational Hydrologic Remote Sensing Center (NOHRSC).

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

Measurement	Site Name	Site ID	Managed by	Period of Record
Air Temperature, Precipitation	Belchertown, MA	USC00190562	DWSP	1947-2020
	Orange Municipal Airport, Orange, MA	USW00054756	NOAA	1996-2020
	Barre Falls Dam, MA	USC00190408		1959-2020
	Ware, MA	USC00198793		1947-2017
Snowpack	4NW Hardwick - Q1 (Gate43A)	Q1	DWSP	2018-2020
	3SW Petersham - Q2 (Gate40)	Q2		2018-2020
	2NW New Salem - Q3 (West of 202)	Q3		2018-2020
	1N Pelham - Q4 (Pelham Lookout)	Q4		2018-2020
	4E Belchertown - Q5 (Blue Meadow)	Q5		2018-2020
	3NW Petersham - Q6 (Balls Crn)	Q6		2018-2020
Mean Daily Streamflow (cfs)	Ware River, Barre	1172500	USGS	1987-2020
	Ware River, Intake Works, Barre	1173000		1987-2020
	Ware River, Gibbs Crossing	1173500		1987-2020
	Swift River, West Ware	1175500		1995-2020
	East Branch Swift River, Hardwick	1174500		1987-2020
	West Branch Swift River, Shutesbury	1174565		1987-2020
	Lower Hop Brook	HOPB	NEON	2017-2020
	Parker's Brook	PARB	DFW-DER	2012-2020

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 2020 (Table 3). Mean daily streamflow at USGS stations in the Quabbin Reservoir and Ware River watersheds has been recorded continuously since October 1987, aside from the USGS monitoring station located along the West Branch Swift River (DWSP site ID 211; USGS 01174565), where monitoring began in 1995. Massachusetts Department of Fish and Wildlife, Division of Ecological Restoration (DER) maintains a stream gauge at Parkers Brook in the Ware River watershed, generating daily streamflow data beginning in late 2012 (DWSP site ID 102). The National Ecological Observatory Network (NEON) began the development of a streamflow monitoring station along Lower Hop Brook (DWSP site 212) in 2017. Daily streamflow data generated by NEON are available beginning in late 2020 (NEON, 2020). DWSP maintained staff gauges at several monitoring locations (sites

GB, 213, 215, and 216) in 2020. Development of rating curves from these stream gauges will continue in 2021.

2.2.2.2 Reservoir Elevation

Daily surface elevation of the Quabbin Reservoir is routinely measured. The DWSP Civil Engineering Section has established various spillway watch triggersFigure 9, to aid in management decisions such as drought management and flood control.

2.2.3 Tributary Monitoring

DWSP staff monitored water quality at 22 surface water sites in the Quabbin Reservoir and Ware River watersheds (Table 4) in 2020. The tributary monitoring locations within each watershed include Core sites and Environmental Quality Assessment (EQA) sites. Core sites represent long-term monitoring sites throughout the watershed that are included in the monitoring plan each year. Core sites are critical for DWSP assessments, as they provide a long-term record of water quality data from primary tributaries within each watershed. Each watershed is divided into sub-watersheds, referred to as sanitary districts (Figure 2, Figure 3). EQA sites within a single sanitary district are sampled approximately once every five years. Data from EQA sites are used to support assessments of potential threats to water quality within each sanitary district. Monitoring of EQA sites provides a year-long assessment of water quality within a specific area of each watershed, allowing for greater spatial coverage, higher-resolution understanding of transport processes operating across the watershed, and elucidation of potential upstream impacts to Core sites. The East Branch Swift River sanitary district and the East Branch Ware River sanitary district were monitored in 2020.

Samples were collected at tributary monitoring sites approximately biweekly in 2020, with sampling conducted in Quabbin Reservoir watershed and Ware River watershed alternating weekly. Frequency of analyses for nutrients (NO_3-N, NH_3-N, TKN, and TP) increased from quarterly to biweekly in 2020. Routine monitoring of tributaries was suspended following collection on March 11, 2020 in response to the COVID-19 State of Emergency declaration issued for the Commonwealth of Massachusetts on March 10, 2020 (Baker and Polito, 2020). Biweekly sampling of tributaries for nutrients, UV_{254}, major ions, and in situ measurements resumed on April 14, 2020. Analyses for the remaining constituents (total coliform, E. coli, turbidity, and alkalinity) resumed at reduced frequency beginning on May 18, 2020. Monitoring frequency for the latter returned to biweekly in August 2020. The low flow conditions present throughout much of the summer and fall months further inhibited biweekly collection of samples from Core tributaries during 2020. No samples were collected from site 215 in the Quabbin Reservoir watershed from August 4 to December 9, 2020 due to a lack of flowing water. The impacts of changes to sampling frequency on seasonal statistics and variability across sites are discussed in Section 3.2.

Table 4: DWSP tributary monitoring program components for Quabbin Reservoir watershed and Ware River watershed, 2020 (DWSP, 2019b; DWSP, 2007; MassDEP, 2009; DWSP, 2015).

Watershed	Site Type	Site Description	DWSP Site ID	Sub-catchment Characteristics		
				Drainage Area (mi^2)	Wetland (%)	DWSP Owned Land (%)
Quabbin Reservoir Watershed	Core	West Branch Swift River, at Route 202	211	12.42	3.40	45.0
		Hop Brook, inside Gate 22	212	4.62	2.50	32.2
		Middle Branch Swift River, at Gate 30	213	9.00	8.20	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	9.50	2.10
		Gates Brook, at mouth	GB	0.93	3.00	100
		Boat Cove Brook, at mouth	BC	0.15	<1.00	100
	EQA	Carter Pond, below outlet (at Glen Valley Rd)	216C	2.44	6.63	0
		Connor Pond outlet, at dam (near Pat Connor Rd)	216D	21.6	10.5	0.83
		Roaring Brook, Petersham Center	216G	1.00	6.77	0
		Northern Tributary of 216E, at South St	216E-1	0.07	9.65	0
		Moccasin Brook, above Quaker Road	216I-X	7.00	16.5	1.30
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	2.00	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 (Bickford Pond) at Lombard Rd	108C	3.39	0.14	0
		Comet Pond Outlet	116	0.84	0.30	0.21
		Comet Pond Outlet Trib. Near Clark Rd	116B	1.50	0.22	0.26

2.2.4 Reservoir Monitoring

The Quabbin Reservoir was sampled regularly in 2020 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 in conjunction with plankton sampling. Phycocyanin was not collected July 6 to September 3, 2020 due to sensor malfunction and extended delay in repairs as a result of COVID-19. At site 202, phytoplankton was sampled biweekly from May to September, and monthly from October to April. At site 206, phytoplankton was sampled monthly. Sampling frequency was increased (to weekly at 202 and biweekly at 206) in response to elevated concentrations of taxa of concern. Phytoplankton sampling was suspended following sampling on March 24th in response to the COVID-19 State of Emergency declaration issued for the Commonwealth of Massachusetts on March 10, 2020 (Baker and Polito, 2020). Deviations from the typical sampling plan for phytoplankton are explained in Section 3.3.9.

Samples were collected monthly from May to December at three depths from three stations within the Reservoir for analyses of nutrients, UV_{254}, total organic carbon, and bacteria (in addition to collection of depth-profiles of physiochemical parameters). Alkalinity was sampled monthly May to November. Sodium and chloride were measured in May, June, July, October, and December (quarterly). Calcium was measured quarterly at three depths, with the exception of May, when it was sampled at one depth. Typically, monthly sampling would have begun in April, but was suspended in response to COVID-19 State of Emergency delaration issued for the Commonwealth of Massachusetts on March 10, 2020 (Baker and Polito, 2020). Water-column profiles were collected in conjunction with phytoplankton sampling, and nutrient sampling. Due to COVID-19 safety protocols, this sampling occasionally occurred on different dates in 2020, resulting in the collection of more water-column profiles than a typical year. Reservoir monitoring results are discussed in Section 3.3 of this report.

Table 5: DWSP Quabbin Reservoir monitoring program components, 2020.

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

Seven water bodies in the Quabbin Reservoir (n=5) and Ware River watersheds (n=2) were surveyed for the presence of aquatic invasive species (AIS) in 2020 (Table 6). These assessments were conducted by ESS Group Inc, under a MWRA contract. MWRA and the contracted consultant assist DWSP with early detection of AIS by surveying portions of the Quabbin Reservoir and the Ware River annually.

DWSP additionally monitors for AIS in the watersheds. Several water bodies within the Quabbin Reservoir and Ware River watersheds are monitored for AIS annually, whereas additional water bodies are evaluated every five years as a component of the current Environmental Quality Assessment. The Quabbin Reservoir consists of four sanitary districts, which comprise the area investigated for the purpose of the annual Environmental Quality Assessments, completed on a five-year basis. Thus, the water bodies in a single sanitary district, for each the Quabbin Reservoir watershed and the Ware River watershed, are surveyed for AIS every five years. Select water bodies in the Quabbin Reservation sanitary district and East Branch Ware River sanitary district were surveyed for AIS in 2020.

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

Table 6: Water bodies surveyed in 2020 for aquatic invasive macrophyte species by DWSP and ESS.

Watershed	Location	Water Body Name
Quabbin Reservoir	Quabbin Reservoir	Boat Launch Area 2 - Shoreline
		Boat Launch Area 2
		West Arm
	Hardwick	Pottapaug Pond
	New Salem	O'Loughlin Pond
Ware River	Barre	Ware River
		(upstream of Shaft 8)

2.2.5 Special Investigations

2.2.5.1 Forestry Monitoring

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

2.2.5.2 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 2020 focused on the East Branch Swift River sanitary district and the East Branch Ware River sanitary district (Figure 2 and Figure 3, respectively). Concentrations of constituents measured in tributary monitoring sites in 2020 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 2020 was compared to regulatory thresholds/limits, when applicable.

2.3 2020 Watershed Monitoring Parameters and Historical Context

DWSP water quality monitoring was comprised of 24 unique water quality characteristics (e.g., physical, chemical, and biological) measured in the Quabbin Reservoir and Ware River watersheds in 2020 (Appendix A). Parameters monitored by DWSP included those that may directly affect water quality (and thus, potability) and/or may indicate the presence of potential future negative impacts to water quality. An extensive discussion including relevant regulatory and guidance thresholds for the parameters monitored by DWSP is provided in Appendix A, along with analytical methods for concentration data. Results for various water quality parameters are compared to regulatory levels (e.g., maximum contaminant levels (MCLs)), thresholds for aquatic life protection, recreational contact, and the EPA Ecoregional Nutrient Criteria for Rivers and Streams, when applicable (Appendix A).

2.4 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 annual water quality reports for Quabbin Reservoir and Ware River watersheds and for Wachusett Reservoir Watershed (DWSP, 2020a-b). 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 2020 (Helsel, 2012).

Water quality, precipitation, and streamflow data collected since 1989 are stored in a Microsoft SQL Server database, maintained by DWSP-EQ. The WAtershed system data Visualization Environment (WAVE) is a custom R/Shiny (R Core Team, 2019; Winston et al., 2019) application developed as a collaborative effort between individuals from the Department of Civil and Environmental Engineering at the University of Massachusetts Amherst and DWSP. WAVE serves as a portal to view and track data within the SQL Server database. Data generated from tributary and reservoir water quality monitoring in 2020 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 2020. 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 2020 are summarized in Section 3.2.8.3.

3 Results

3.1 Hydrology and Climate

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

3.1.1 Climatic Conditions

3.1.1.1 Air Temperature

Average daily median temperature of 50.3°F, 49.9°F, and 50°F were observed at the three Quabbin Reservoir watershed and Ware River watershed weather stations (Belchertown, Barre, and Orange, respectively). Minimum and maximum recorded temperatures ranged from 2°F-96°F (Belchertown), -2°F to 99°F (Barre), and -6°F to 97°F (Orange) at the three weather stations.

Daily median temperatures throughout the Quabbin Reservoir and Ware River watersheds during 2020 typically fell within average daily temperature ranges for the period of record (Figure 4). The winter months (January, February, and December) of 2020 included several spans of unseasonably warm days observed across all three weather stations. A max air temperature of 67 to 68°F was recorded on January 12, 2020 at all weather stations across the two watersheds. Winter months in 2020 had higher median monthly temperatures compared that of the period of record for all three weather stations. January 2020 median monthly temperature was 8.5°F higher compared with median monthly temperature from the period of record at all sites. Average daily temperatures during spring months (March, April, May) ranged from 21.5°F to 76°F across the Quabbin Reservoir and Ware River watersheds (Table 7). Daily temperatures in the summer (June through August) ranged from 49.5°F to 82.5°F, largely tracking within the historical mean daily temperature ranges for the sites with many daily median temperatures on the high end of the historical range. Temperatures in the fall trended within the average range, with some average temperatures both below (e.g. 21.5°F on November 19, 2020 at Barre Falls Dam) and above (e.g. 63°F on November 12, 2020 at Barre Falls Dam) historical daily average daily temperature ranges (Figure 4).

Table 7: Average monthly temperature range (presented as average daily min - max per month) for the period of record and 2020 for each meteorological station in the Quabbin Reservoir and Ware River watersheds. Note: gaps exist in the period of record for daily temperature data from each of the reported weather station. Records were incomplete for certain years at Barre (1959, 1970, 1990-2002, 2006, 2008, 2017, 2019), Belchertown (1948-2008), and Orange (1996, 2014, 2017, 2018) weather stations.

Month	Barre (°F)		Belchertown (°F)		Orange (°F)	
	1959 - 2019	2020	1947 - 2019	2020	1996 - 2019	2020
Jan	10.92 - 31.56	20.26 - 38.74	13.61 - 31.57	22.71 - 38.97	12.72 - 32.26	20.77 - 38.90
Feb	12.18 - 33.96	20.41 - 39.59	14.36 - 34.98	22.14 - 39.21	14.48 - 35.85	21.69 - 39.31
Mar	21.31 - 42.71	25.65 - 50.94	24.18 - 43.86	29.52 - 49.65	23.02 - 43.96	28.23 - 50.77
Apr	31.59 - 55.47	30.10 - 54.60	35.01 - 57.28	31.87 - 52.33	33.06 - 57.72	33.23 - 54.07
May	41.45 - 67.09	41.68 - 73.03	46.34 - 68.81	43.48 - 68.10	44.46 - 69.12	44.26 - 70.10
Jun	50.44 - 75.17	52.37 - 84.90	54.26 - 76.24	54.67 - 80.77	53.89 - 76.95	54.20 - 80.90
Jul	55.61 - 80.23	62.16 - 88.77	61.28 - 82.74	63.19 - 85.74	59.18 - 82.36	64.35 - 86.42
Aug	53.54 - 78.35	56.58 - 86.42	58.79 - 80.71	60.65 - 83.06	57.70 - 80.77	59.00 - 82.68
Sep	45.55 - 71.21	46.67 - 77.23	52.34 - 74.28	51.23 - 74.33	49.85 - 73.46	48.50 - 74.50
Oct	35.03 - 59.64	38.42 - 62.42	40.88 - 60.84	42.32 - 61.74	38.01 - 60.30	40.00 - 60.61
Nov	27.52 - 47.88	29.33 - 53.93	31.26 - 48.72	32.77 - 54.23	28.23 - 48.38	30.07 - 54.57
Dec	16.90 - 35.86	21.23 – 40.00	22.58 - 38.17	23.10 - 40.39	20.04 - 38.09	21.26 - 39.90

Average monthly minimum and average monthly maximum temperatures in 2020 were above the historical average minimum and average maximum for most months across all three weather stations (Table 7). The exceptions were for the months of April, May, and September, where average monthly minimums and maximums were within the historical average range. January was the month with the largest difference in average daily minimum temperatures between 2020 and the period of record across all stations, with 2020 average daily minimum temperatures 8.05 to 9.34°F higher than the historical record. February was the month with the second largest difference across all stations, ranging from 7.21 to 8.23°F higher average daily minimum temperatures in 2020 compared to previous years.

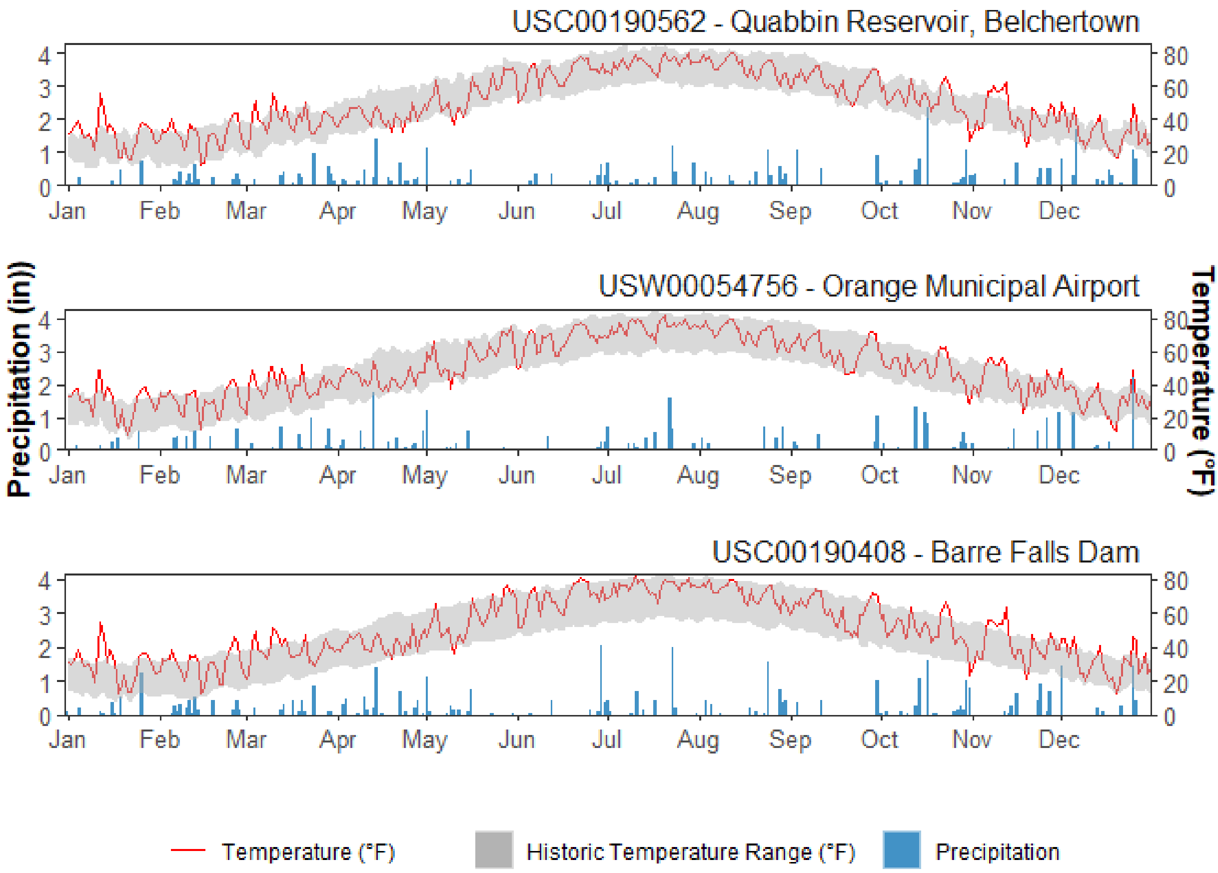

Figure 4: Climatograph of precipitation totals and daily median temperatures for weather stations in the Quabbin and Ware watersheds from January 1 through December 31, 2020. Shaded band represents historical mean daily temperature ranges for Belchertown (1947-2019), Orange (1996-2019), and Barre (1959-2019) weather stations.

3.1.1.2 Precipitation

Daily precipitation records date back to 1947 (Belchertown), 1951 (Barre), and 1998 (Orange) from the three Quabbin Reservoir and Ware River watershed weather stations. In 2020, total annual precipitation ranged from 37.57 to 42.4 inches at the weather stations, below the long-term averages by 1.74, 2.85, and 4.19 inches for Orange, Barre, and Belchertown, respectively (Figure 5). Total annual precipitation at Belchertown was in the lower 25% percentile of total annual precipitation records on record (Figure 5). Monthly precipitation totals were below average monthly precipitation total for the months of January, May, June, August, and September at all three weather stations, with the largest differences occurring in May and June (Table 8). Total annual snowfall at Belchertown was 21-in, below the historical annual average of 51.9-inand the second lowest annual cumulative snow total since 1947 (DWSP 2021a). The highest average watershed snow depth was 10.4-in on February 2, 2020 (DWSP 2021b).

The Quabbin Reservoir-Ware River Region was under drought designations for six consecutive months in 2020. According to the Massachusetts Drought Management Task Force, the Quabbin region entered drought conditions as early as May 2020, with the area being listed as Level 2-Significant Drought from May 22 through June 23, as well as during September. The U.S. Drought Monitor listed the Quabbin area at level D0 (abnormally dry) drought in early/mid-June, then D1 (moderate) drought starting in late June, and D2 (severe) drought from late September through mid-October. The MA Drought Management Task Force reported the state free of drought on December 1, 2020 (DWSP 2021a).

Table 8: Average total monthly precipitation (period of record) and total monthly precipitation (2020) for each meteorological station in the Quabbin Reservoir and Ware River watersheds. Note: gaps exist in the period of record for daily precipitation data from each of the reported weather station. Records were incomplete for certain years at Barre (1959, 2006, 2008), Belchertown (1947, 1986, 1997, 2001), and Orange (1998) weather stations.

Month	Barre (in)		Belchertown (in)		Orange (in)	
	1951 - 2019	2020	1947 - 2019	2020	1998 - 2019	2020
Jan	3.28	2.49	3.51	1.74	2.41	1.59
Feb	2.82	3.27	3.06	3.06	2.50	2.95
Mar	3.35	2.68	3.69	3.60	2.87	3.41
Apr	3.84	4.53	3.87	4.21	3.14	4.57
May	3.78	2.61	3.87	1.95	3.25	2.28
Jun	3.97	3.08	4.09	2.14	4.43	1.10
Jul	3.83	4.08	4.18	3.76	3.19	4.51
Aug	4.14	4.07	4.61	4.13	3.52	2.36
Sep	3.87	1.82	4.00	2.55	3.97	2.09
Oct	4.15	5.59	4.10	5.91	4.10	4.67
Nov	3.74	3.13	3.84	3.34	2.82	3.80
Dec	3.74	4.31	3.77	6.01	3.11	4.24

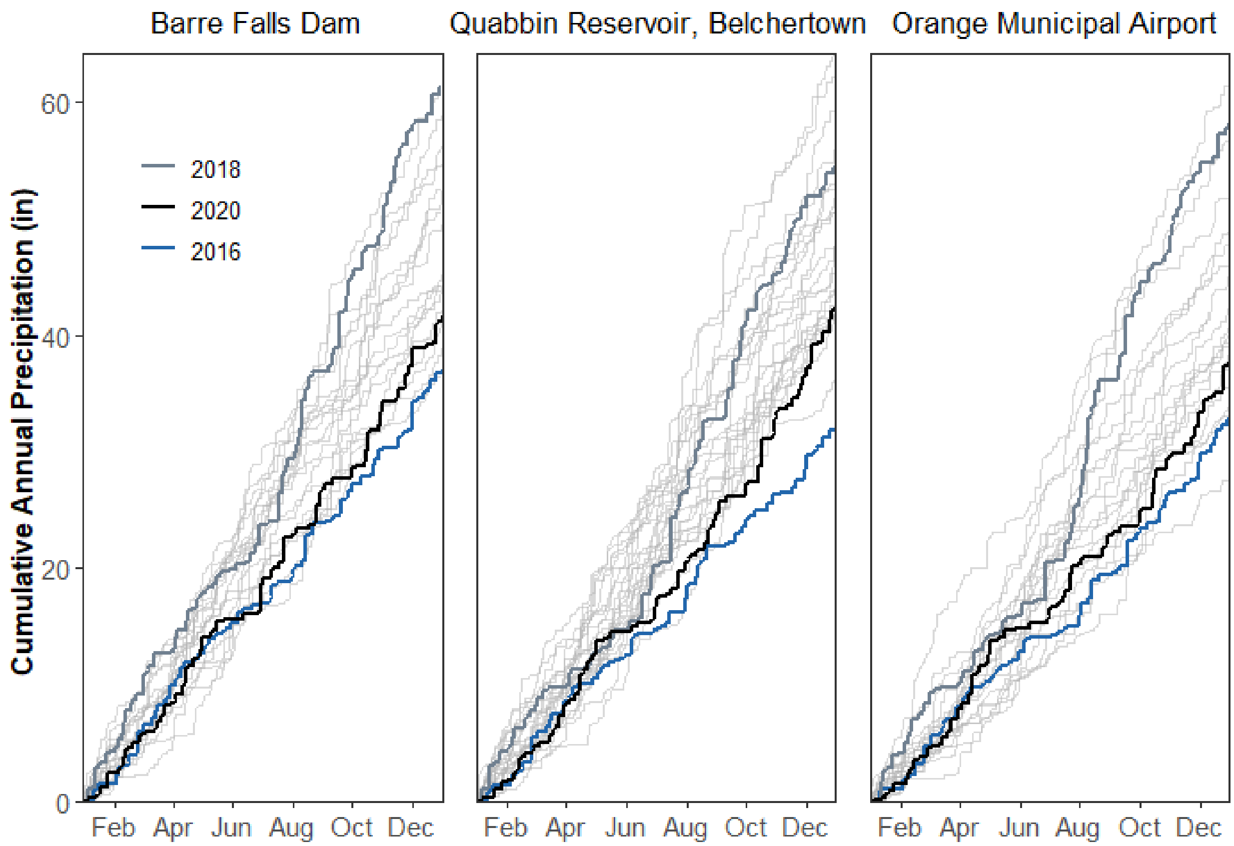

Figure 5: Annual cumulative monthly precipitation totals for Barre Falls Dam (USC00190408), Quabbin Administrative Building in Belchertown, MA (USC00190562), and Orange Municipal Airport (USW00054756) weather stations. Colored lines indicate recent years of high and low annual precipitation totals (2018, and 2016, respectively) compared to the period of record (shaded lines, see table 3 for site-specific record ranges) and 2020 (black line) at the three weather stations. Note: years with less than 350 precipitation records at each station were excluded from this figure.

3.1.1.2.1 Snow

Results from snow monitoring in Quabbin Reservoir watershed are presented in an annual memo summarizing seasonal patterns and multi-year trends prepared by the DWSP Civil Engineering Section (DWSP 2021b). The top yielding snowfall event in 2020 took place on December 5 (1.67 inches). Annual cumulative snowfall totals in 2020 were the second lowest on record since 1947. The total snowfall of 21 inches measured in 2020 was less than half the historical average of 51.89 inches.

3.1.2 Streamflow

Daily stream gauge records from the USGS at two major tributaries to the Quabbin Reservoir (the West and East Branches of the Swift River) exhibited similar seasonal patterns in discharge, while varying in magnitude (Figure 6). The gauge on the East Branch Swift, located at a horseshoe dam at the outlet of Pottapaug Pond, ranged in mean daily streamflow in 2020 from 0.01 cfs (September 21to 29) to 657 cfs (December 26) , with an average mean daily streamflow of 68.27 cfs. The gauge at the West Branch Swift, ranged in daily mean streamflow from 0.36 cfs (October 12) to 374 (December 25) cfs, with an average mean daily streamflow of 20.5 cfs. Daily average discharge records in these tributaries were generally at or slightly below normal range for the first half of 2020 and fell into an extended period of lower-than-normal flows from June through September. From October through December, daily average discharge values slowly rose from slightly below normal to normal conditions following late fall and December precipitation events. The hydrographs of these two rivers both display several above-normal peaks in the spring (March through May) and winter (January, February, December) months. Most notably, the maximum daily average streamflow in 2020 at these sites occurred on December 25 to 26 (Figure 7). This resulted in the 9th highest average daily discharge records in the West Branch Swift River gauge site and the 37th highest at the East Branch Swift River gauge site in their respective historical records.

The hydrograph from a USGS gauge located on the Ware River at the Intake Works in Barre, MA exhibits distinct discharge patterns of the Ware River watershed in 2020 (Figure 6). Winter and spring mean daily flow were normal to slightly above normal, while summer and fall mean daily flows fell below normal for extended periods in 2020. The maximum streamflow event occurred on April 14 to 15 with an average daily flow of 596 cfs, while the December 25th rain event resulted in high mean daily flows through the end of December. Low flow conditions were observed in late September, with a minimum average daily streamflow of 8.19 cfs on September 23. Average mean daily streamflow for the Ware River at Intake Works station in 2020 was 142.83 cfs.

Downstream releases from the Quabbin Reservoir into the Swift River can be observed from the daily average discharge records from the USGS gauge in West Ware (Figure 6). The minimum average daily streamflow at this site was 33.6 cfs (August 9) and the maximum average daily streamflow was 291 cfs (May 19) in 2020. Average daily streamflow was consistently on the low end of the normal range throughout 2020, with the exception of late April through June flow conditions, corresponding with additional discharge from the Quabbin spillway, as well as daily flows in late August through October. A small number of years with very high spillover volumes (e.g. 2019, 2006, 1997) result in a winter historical streamflow average above the normal range at this site.

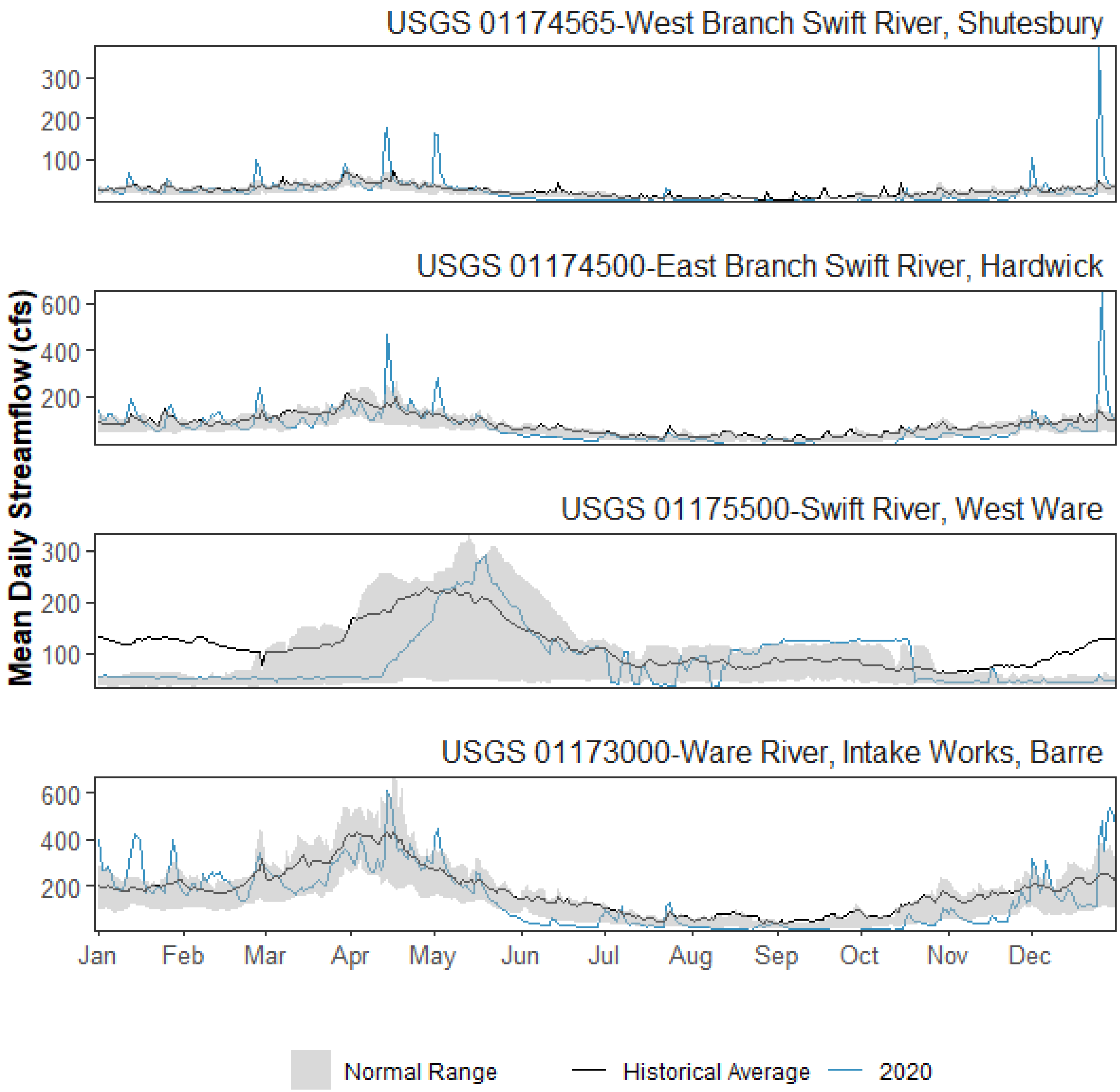

Figure 6: Hydrograph of mean daily streamflow (cfs) at four USGS stream gauges in the Quabbin and Ware watersheds. The average of mean daily flows for the period of record are represented by the solid black line. Average daily flows in 2020 are represented by the blue line. The gray band denotes the normal (25th to 75th percentile) flow range for the period of record.

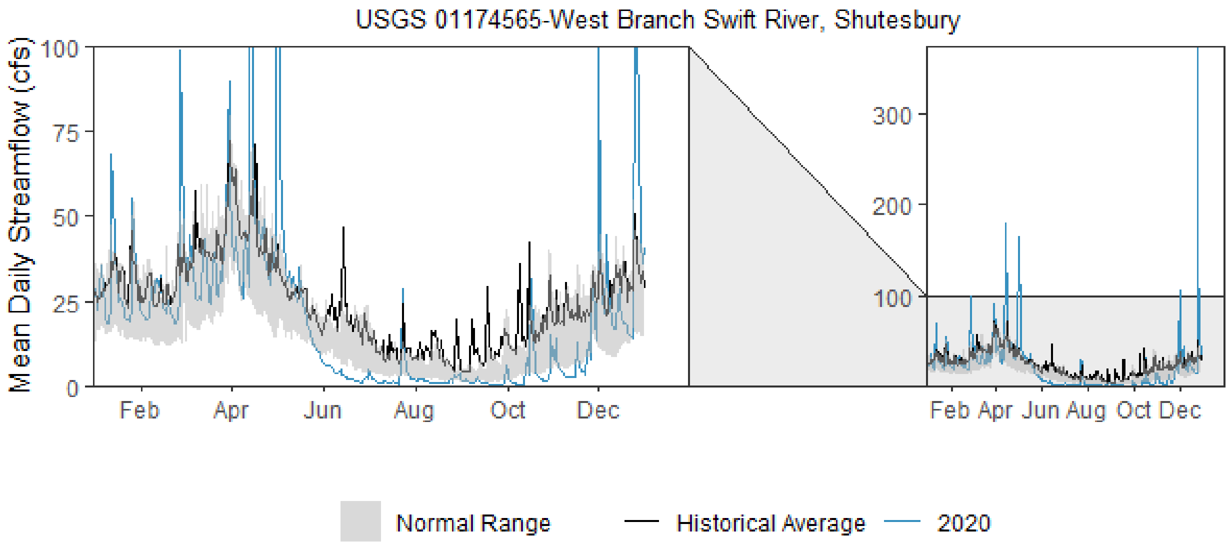

Figure 7: Hydrograph of mean daily streamflow from the West Branch Swift River USGS Gauge in Shutesbury, MA. The high discharge event from December 25-26 is placed in context with the historical range of normal flow conditions. The average of mean daily flows for the period of record (1995) are represented by the solid black line. Average daily discharge in 2020 are represented by the blue line. The gray band denotes the normal (25th to 75th percentile) flow range for the period of record.

Cumulative annual discharge calculated from average daily discharge records were lower than average across three stream gauges in the Quabbin and Ware watersheds (Figure 8). The West Branch Swift stream gauge recorded a cumulative total of 7,505 cfs in 2020, a value in the lower half of annual cumulative totals from the 25-year period of record for the gauge. 2020 cumulative discharge was lower than the historical mean (9,144 cfs) and median (8,476) values at the site (range 4,441 to 16,019 cfs). Cumulative discharge records at the East Branch Swift River gauge totaled 24,987 cfs in 2020, the 10th lowest value record from the 33-year period of record corresponding to this gauge, and lower compared to historical mean (29,964 cfs) and median (27,835 cfs) values (range of 12,593-49,297 cfs). The stream gauge on Ware River at the Intake Works in Barre, MA recorded a cumulative total of 52,277 cfs, below the historical mean (63,783 cfs) and median (64,224 cfs) based on the 33-year period of record (range 32,796 - 102,105 cfs). Cumulative discharge across all sites exhibited a similar seasonal pattern, with spring rain events leading to an increase in cumulative discharge, followed by comparatively lower streamflow contribution in the summer and fall months. An increase in cumulative streamflow can be seen in December due high stream flows following the large rainfall (including rain-on-snow) events at the end of the month (see also Figure 6, Figure 7, and Figure 8).

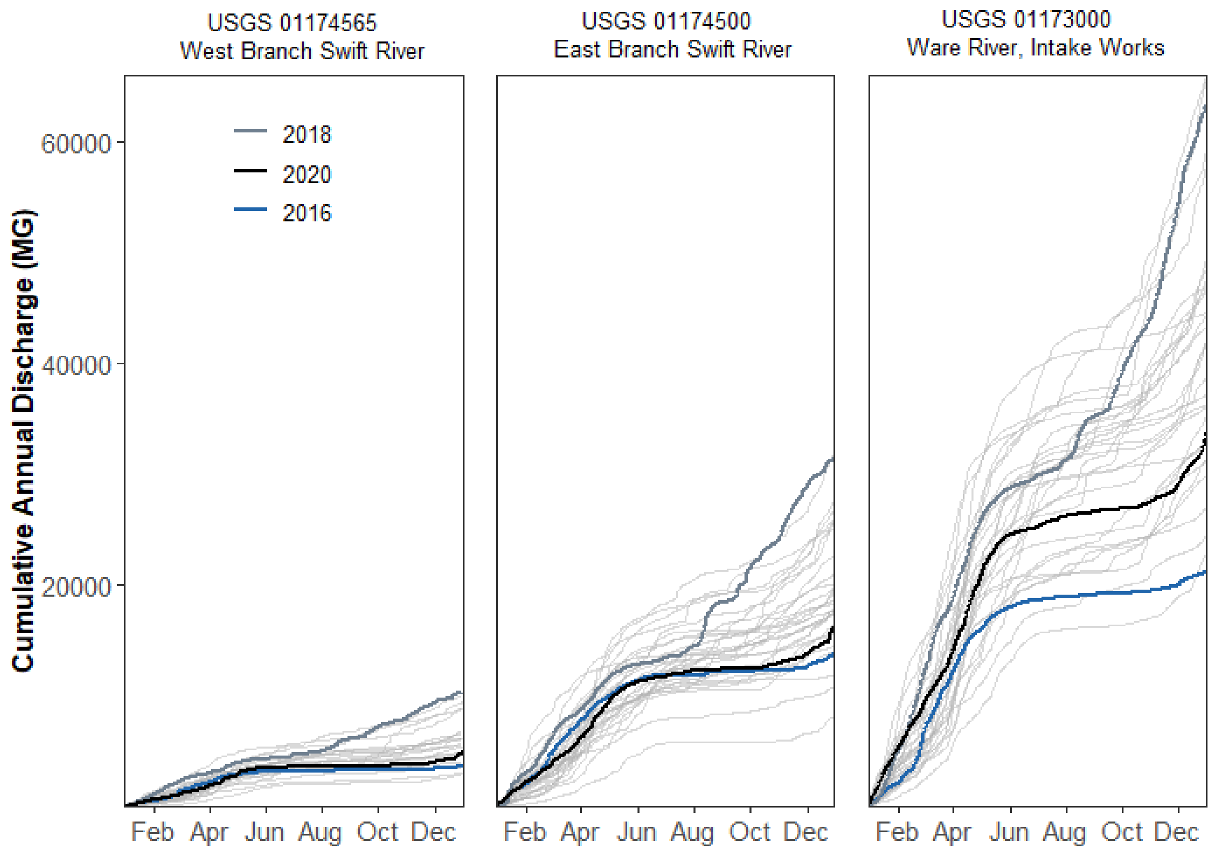

Figure 8: Cumulative annual discharge (in millions of gallons) calculated from average daily discharge records at three USGS stream gauges in the Quabbin and Ware watersheds. Colored lines indicate recent years of high and low cumulative annual discharge totals (2018, and 2016, respectively) compared to the period of record (shaded lines, see Table 3 for site-specific record ranges) and 2020 (black line) at the three USGS stream gauges. Note: years with less than 350 daily average streamflow records at each station were excluded from this figure.

3.1.2.1.1 Reservoir Elevation

Quabbin Reservoir elevation remained within normal operating range throughout the entirety of 2020. Daily reservoir elevation exceeded the spillway watch trigger of 528 ft BCB beginning on March 25 and continuing through July 11, 2020. Elevation of the water surface of Quabbin Reservoir ranged from a minimum of 523.68 to 530.07 ft BCB on November 23, 2020 and May 19, 2020, respectively (Figure 9). A single row of stop logs was installed across all five bays of the Quabbin Reservoir spillway on March 5, 2020 (bringing the lower spillway elevation to 528.69 ft BCB). The reservoir was actively discharging via the spillway from April 11 through June 22, 2020 (4,490 MG total discharge). Annual dynamics of reservoir elevation followed that of previous years, driven predominantly by seasonal changes in precipitation/snowmelt and subsequent riverine inputs (DWSP, 2021a).

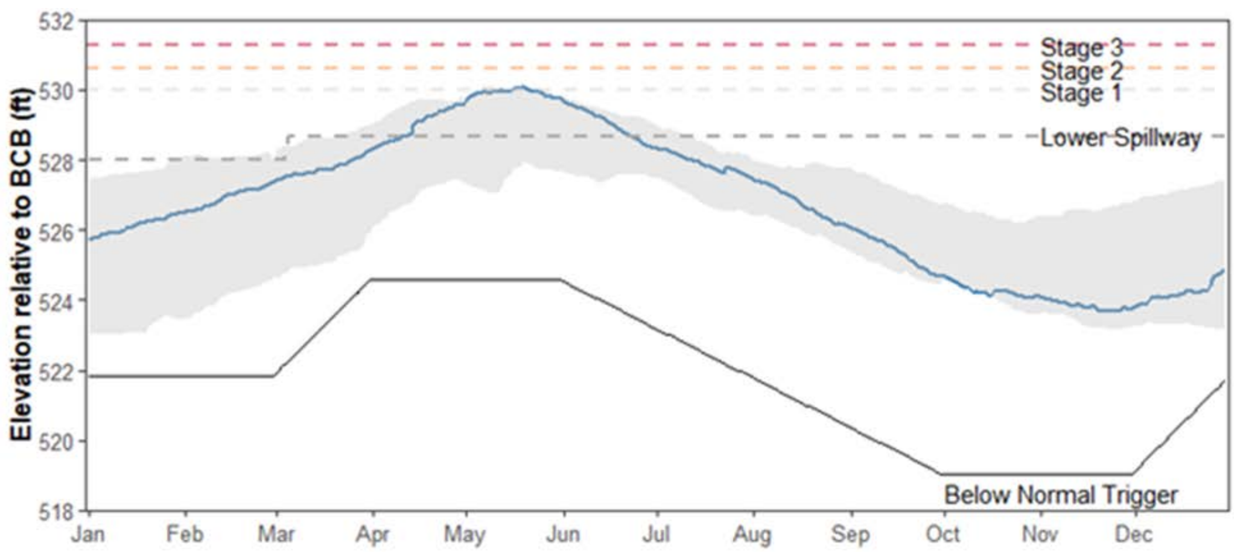

Figure 9: Daily elevation of the Quabbin Reservoir from January 1 through December 31, 2020, relative to spillway watch triggers (DWSP, 2019d) established by DWSP Civil Engineering Section. Gray band represents normal (25th to 75th percentile) operating range for the period of record (1990-2020).

3.2 Tributary Monitoring

3.2.1 Water Temperature and Dissolved Oxygen

3.2.1.1 Water Temperature

Temperature in Quabbin Reservoir watershed Core tributaries ranged from -0.07 to 23.7 ˚C in 2020. In Ware River tributaries, water temperatures spanned a comparable range of -0.08 to 28.34 ˚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. Seasonal median water temperatures observed during the spring and summer of 2020 were generally greater than that of the period of record. However, descriptive statistics corresponding to spring water temperatures were impacted by the suspension of sampling from mid-March to mid-May in 2020 (Section 2.2.1.1). The low flow conditions present through much of the summer months may have also contributed to the rise in median summer water temperatures observed in 2020. Seasonal median water temperatures during the fall and winter months of 2020 approached or fell below those of the period of record, reflective of riverine response to recent precipitation inputs and/or atmospheric cooling (Appendix C).

3.2.1.2 Dissolved Oxygen

Dissolved oxygen concentrations in Core tributary monitoring sites in the Quabbin Reservoir watershed were comparable to those observed in the Ware River watershed in 2020, with concentrations ranging from 4.69 to 14.77 mg/L and 2.89 to 14.68 mg/L, respectively. Dissolved oxygen concentrations in Core tributaries in either watershed generally followed typical seasonal patterns, similar to that of water temperature (Appendix C).

Dissolved oxygen fell below the MassDEP aquatic life criteria for cold water fisheries threshold of 6 mg/L in two tributaries in the Quabbin Reservoir watershed (site 215 on two dates in July and at site 213 on four sample dates from June through August 2020). Otherwise, dissolved oxygen remained above the MassDEP aquatic life criteria threshold of 5 mg/L for warm water fisheries during this time (aside from at site 213 on August 4, 2020). This period of relatively low dissolved oxygen (4.69 to 5.78 mg/L) observed at sites 213 and 215 in 2020 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 2020. Dissolved oxygen remained below 5 mg/L at Core monitoring site 121B in the Ware River watershed on select dates in late-June through mid-September 2020. This location represents the outlet of Moulton Pond and inlet to 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. This location has previously demonstrated seasonally depleted dissolved oxygen concentrations (DWSP, 2020a).

3.2.2 Specific Conductance, Sodium, and Chloride

3.2.2.1 Specific Conductance

Specific conductance ranged from 18.4 to 156.3 µS/cm in Quabbin Reservoir watershed Core monitoring tributaries and from 49.2 to 372.7 µS/cm in Core monitoring tributaries in the Ware River watershed during 2020. 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 2020. 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 2020 (Figure 10, Figure 11). Specific conductance was generally elevated during low flow conditions (June through mid-December 2020; Section 3.1.2) and declined with increasing streamflow. The extended period of below normal stream flow during 2020 resulted in a prolonged interval of elevated specific conductance (above seasonal medians for the period of record). Intra-annual patterns of elevated specific conductance were most pronounced in Boat Cove Brook in the Quabbin Reservoir watershed and tributaries in the Ware River watershed – a pattern potentially driven by spatial variability in specific conductance of groundwater.

3.2.2.2 Sodium and Chloride

Routine monitoring for sodium (Na) and chloride (Cl) began in DWSP Core monitoring sites in Quabbin Reservoir watershed in September 2018 and Ware River watershed in January 2019. Concentrations of Na observed in Core monitoring tributaries in the Ware River watershed ranged from 7.49 to 46.7 mg/L and from 1.46 to 19.6 mg/L in Quabbin Reservoir watershed tributaries in 2019. Concentrations of Cl observed in 2019 ranged from 1.03 to 32.1 mg/L in and from 12.8 to 148 mg/L in Quabbin Reservoir and Ware River watersheds, respectively. The secondary MCL for Cl in drinking water (250 mg/L) established by the US EPA was not exceeded in any Core tributary samples collected in 2020 from the Quabbin Reservoir or Ware River watersheds. Concentrations of Na in samples collected at 121B in the Ware River watershed exceeded the MassDEP Office of Research and Standards (ORS) guidelines for Na in drinking water for the entirety of 2020 (n = 22 samples > 20 mg/L Na). Seasonal dynamics in Na and Cl in Quabbin Reservoir and Ware River watershed tributaries mirrored specific conductance in 2020.

Spatial and temporal patterns in specific conductance and associated concentrations of Na and Cl observed in 2020 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 latter half of 2020 - coincident with abnormally dry to severe drought conditions throughout the region - likely resulted in elevated stream Cl concentrations during this time. Gradients in specific conductance between monitoring sites were associated with differences in land cover, proximity to major paved surfaces (e.g., roads and parking lots), and geogenic variability (Figure 12). Median annual concentrations of Na, Cl, and specific conductance were generally greater in tributaries within the Ware River watershed, relative to Core monitoring sites in the Quabbin Reservoir watershed in 2019 (Table 9, Table 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 select EQA monitoring sites in the Ware River watershed increased significantly from the prior monitoring period (2015), and at most EQA sites in the East Branch Ware River sanitary district since 2011. A detailed discussion of statistics for specific conductance, Cl, and Na in EQA monitoring sites during 2019 is presented in Appendix B.

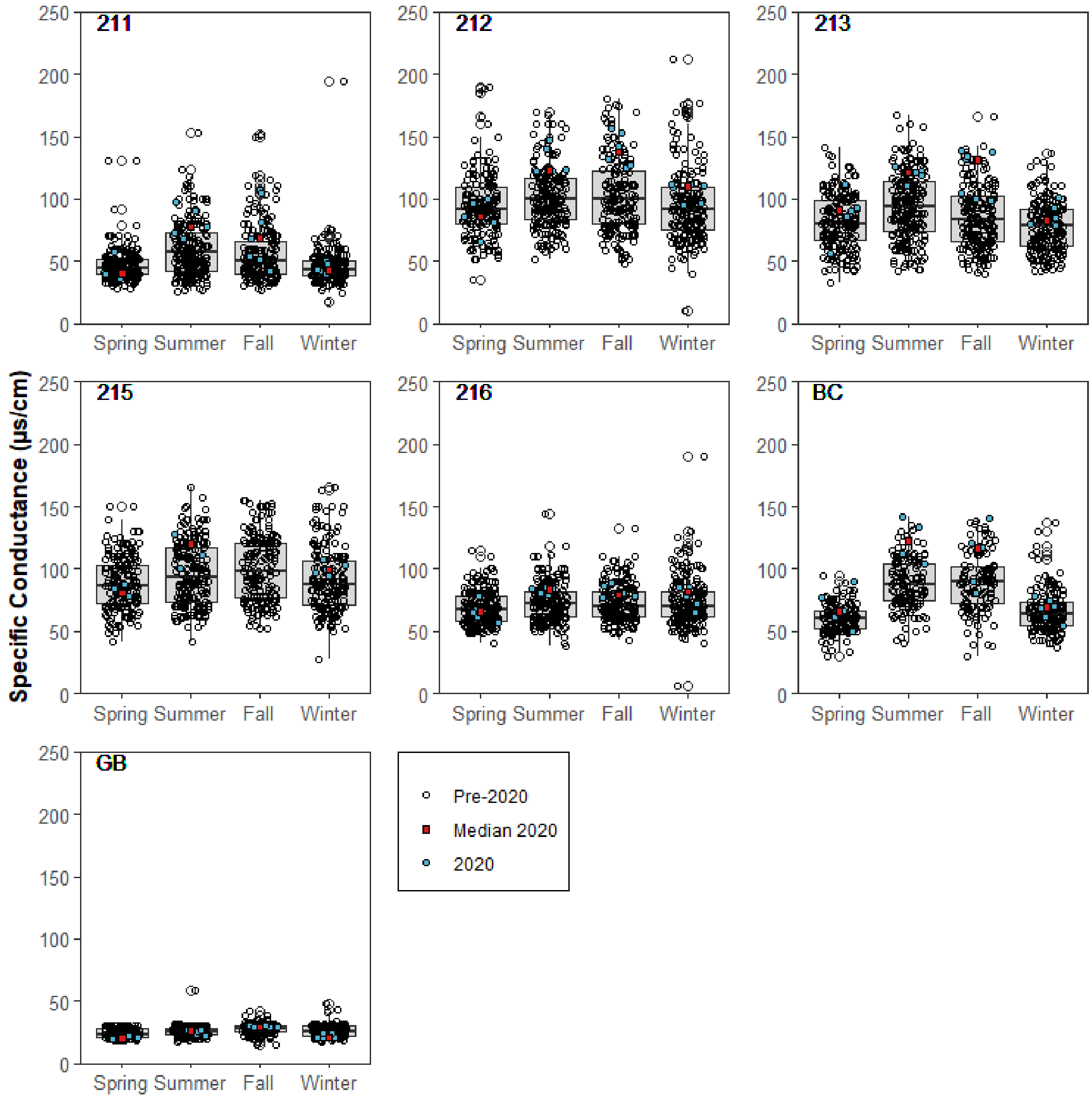

Figure 10: Boxplots depicting the seasonal distributions of specific conductance observed In Quabbin Reservoir watershed DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2020 are signified by the blue points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

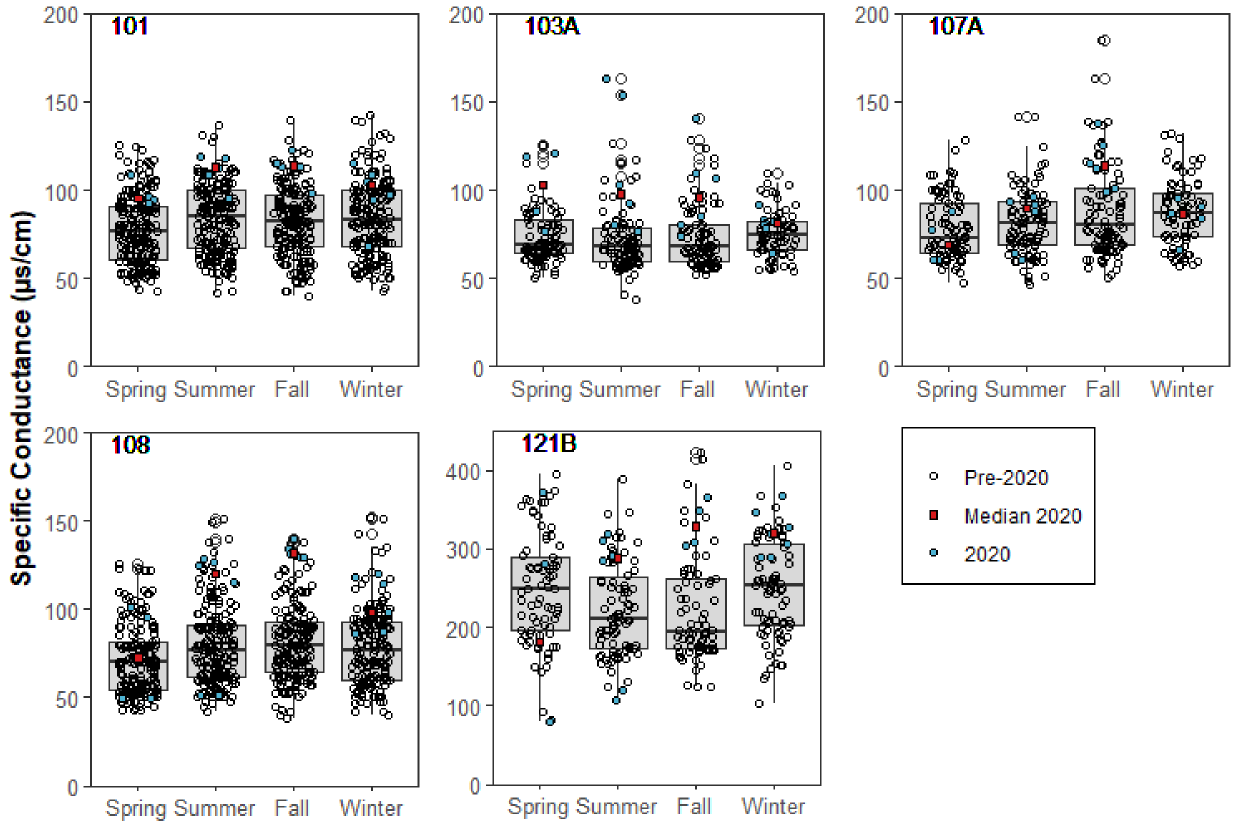

Figure 11: Boxplots depicting the seasonal distributions of specific conductance observed In Ware River watershed DWSP Core tributary monitoring sites. Results corresponding to samples collected in 2020 are signified by the blue points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. Note: y-axis extent for site 121B.

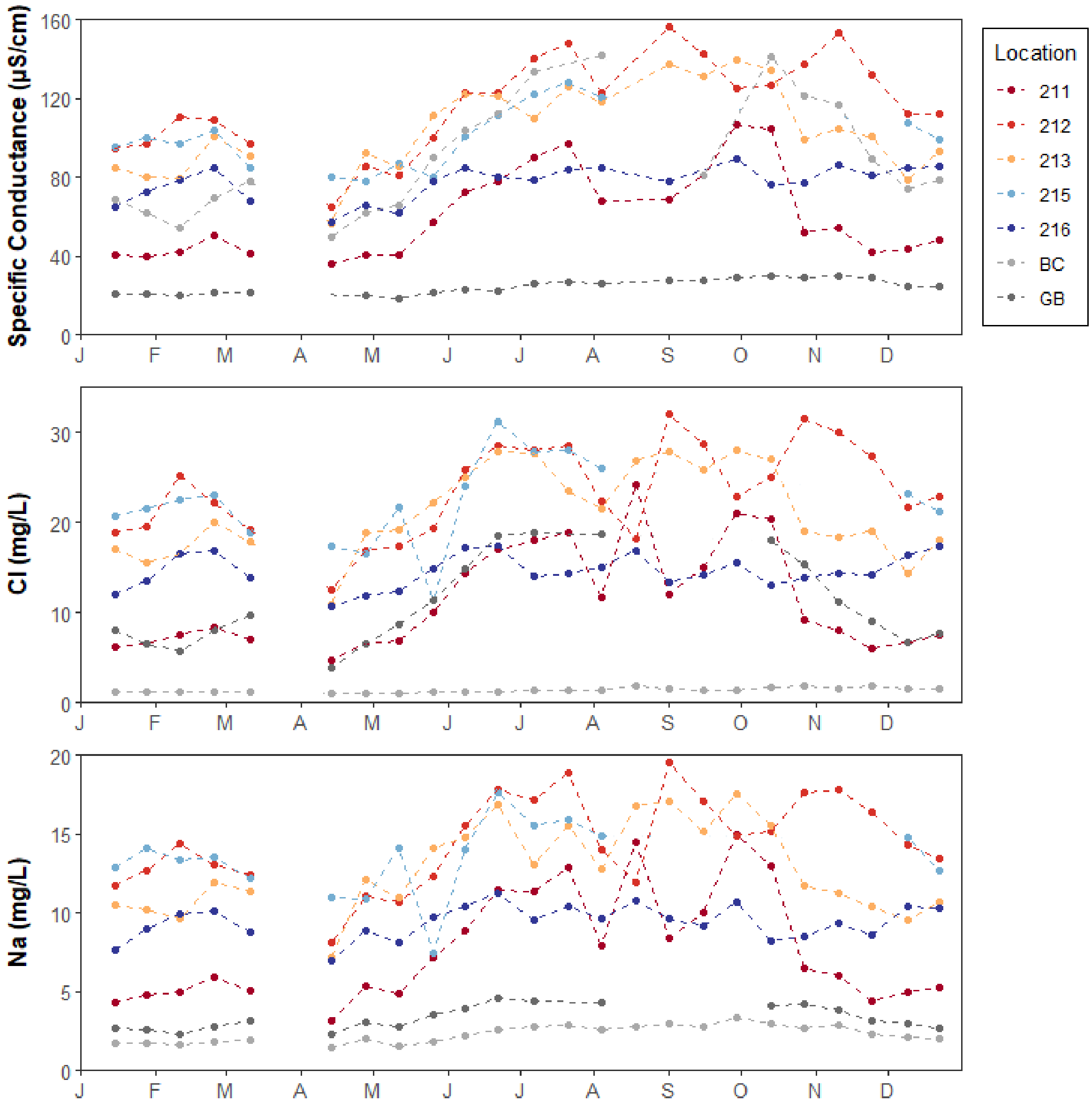

Figure 12: Time series of specific conductance, Cl, and Na measured in Quabbin Reservoir watershed core tributary sites in 2020.

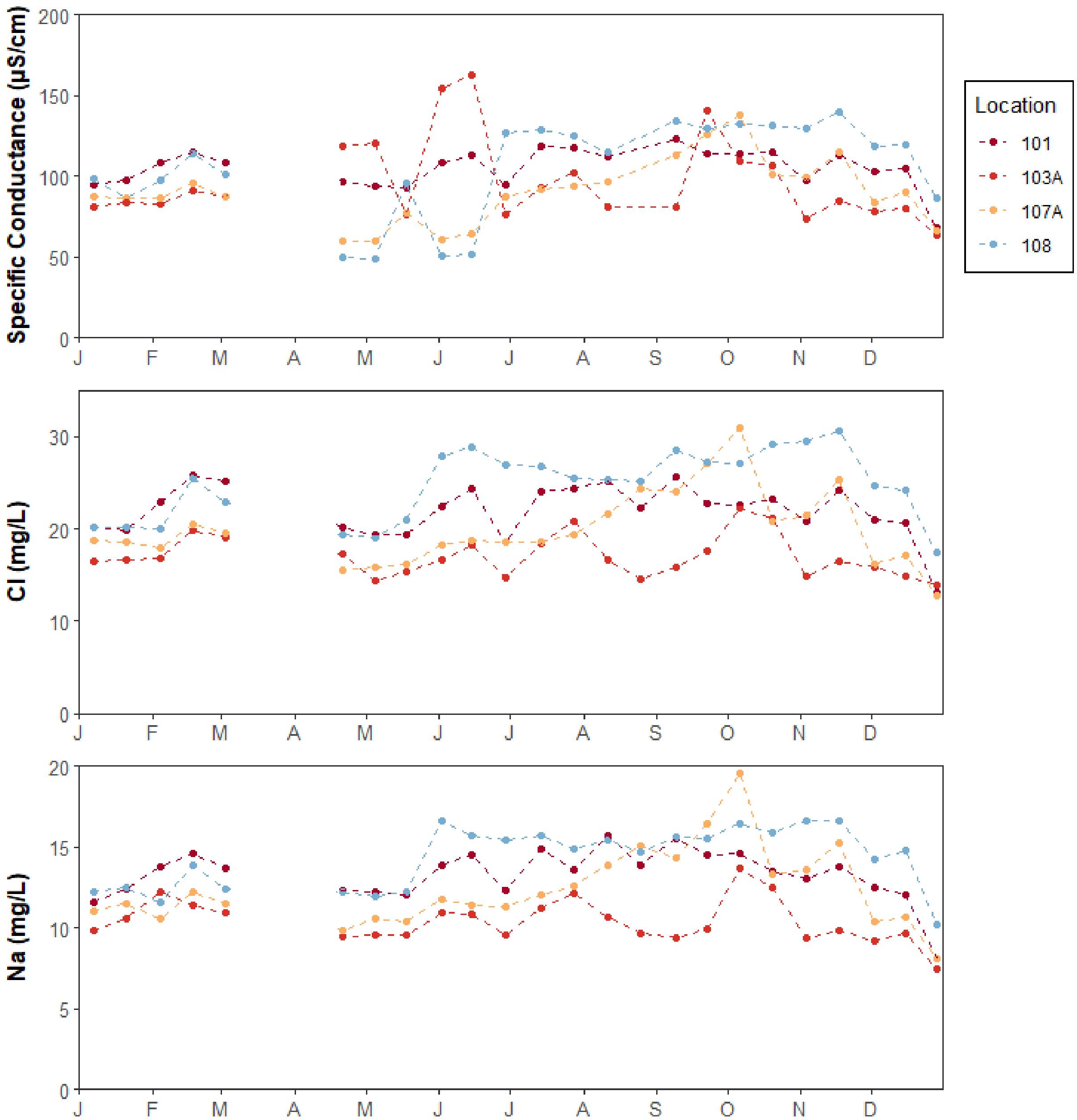

Figure 13: Time series of specific conductance, Cl, and Na measured in Ware River watershed core tributary sites in 2020. Specific conductance, Cl, and Na concentrations for Site 121B were markedly greater than all other Core tributary monitoring sites in the Ware River watershed during 2020, and thus are visualized separately (Appendix C).

Table 9: Descriptive statistics (minimum, median, average, and maximum) for a) specific conductance, and b) Na and Cl in Core tributary monitoring sites in the Quabbin Reservoir watershed during 2020. * Note: No samples were collected from site 215 in the Quabbin Reservoir watershed from August 4 to December 9, 2020 due to a lack of flowing water.

a)

Site	Season	Specific Conductance (µS/cm)				
		Count	Min	Med	Avg	Max
211	Spring	5	36.0	40.5	43.1	57.4
	Summer	5	67.7	77.4	81	97.2
	Fall	7	41.9	68.3	72.5	107
	Winter	6	39.7	42.7	43.9	50
212	Spring	5	65.1	85.7	85.6	99.9
	Summer	5	122	123	131	148
	Fall	7	125	138	139	156
	Winter	6	94.7	110	106	112
213	Spring	5	56.7	90.9	87.3	111
	Summer	5	110	121	119	126
	Fall	7	99	131	121	139
	Winter	6	78.9	82.5	86.2	101
215	Spring	5	77.5	80.3	81.9	87.2
	Summer	5	100	120	116	128
	Fall*	0	-	-	-	-
	Winter	6	95.1	99.4	100	107
216	Spring	5	57	65.5	65.9	78
	Summer	5	78.9	83.6	82.4	84.8
	Fall	6	76.3	79.4	81.2	88.9
	Winter	6	64.5	81.6	78.4	85.2
GB	Spring	5	49.4	65.8	68.8	89.6
	Summer	4	104	123	12123	142
	Fall	5	80.9	116	110	141
	Winter	6	54.3	69.1	67.7	78.2
BC	Spring	4	18.4	20.3	20.2	21.6
	Summer	5	22.2	25.9	24.8	26.7
	Fall	7	27.4	29.2	28.8	29.8
	Winter	6	19.6	20.8	21.7	24.7

b)

Site	Season	Sodium (mg/L)					Chloride (mg/L)				
		Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max
211	Spring	5	3.19	5.07	5.13	7.16	5	4.77	6.83	7.04	10.1
	Summer	6	7.9	11.5	11.2	14.5	6	11.7	17.6	17.4	24.2
	Fall	7	4.45	8.45	9.06	15.0	7	6.00	12.1	13.1	21.1
	Winter	6	4.34	4.99	5.04	5.90	6	6.26	7.10	7.16	8.42
212	Spring	5	8.14	11.1	10.93	12.4	5	12.5	17.3	17.0	19.3
	Summer	6	11.9	16.4	15.9	18.9	6	18.2	27.0	25.3	28.5
	Fall	7	14.9	17.1	17.0	19.6	7	22.9	28.7	28.3	32.1
	Winter	6	11.7	13.3	13.3	14.4	6	18.8	22	21.7	25.2
213	Spring	5	7.17	11.4	11.2	14.1	5	10.9	18.8	17.8	22.2
	Summer	6	12.8	15.2	15.0	16.9	6	21.6	26	25.4	27.8
	Fall	7	10.4	15.2	14.1	17.6	7	18.3	25.9	23.6	28
	Winter	6	9.53	10.4	10.4	11.9	6	14.3	16.9	17	20
215	Spring	5	7.48	11	11.1	14.1	5	11.4	17.3	17.2	21.7
	Summer	5	14.0	15.6	15.6	17.7	5	24	27.9	27.4	31.2
	Fall*	0	-	-	-	-	0	-	-	-	-
	Winter	6	12.7	13.5	13.6	14.8	6	20.7	22.0	22.0	23.2
216	Spring	5	6.98	8.81	8.52	9.78	5	10.7	12.4	12.7	14.9
	Summer	6	9.58	10.4	10.4	11.3	6	14.0	16.0	15.8	17.4
	Fall	7	8.21	9.17	9.17	10.7	7	13.1	14.2	14.1	15.6
	Winter	6	7.69	10.0	9.57	10.4	6	12.0	16.4	15.4	17.4
GB	Spring	5	1.46	1.85	1.76	2.00	5	1.03	1.10	1.14	1.26
	Summer	6	2.21	2.68	2.64	2.93	6	1.21	1.41	1.43	1.85
	Fall	7	2.33	2.87	2.86	3.36	7	1.41	1.52	1.59	1.83
	Winter	6	1.67	1.81	1.85	2.10	6	1.21	1.24	1.34	1.60
BC	Spring	5	2.31	3.08	2.98	3.55	5	3.82	8.74	8.01	11.3
	Summer	4	3.94	4.34	4.30	4.57	4	14.9	18.7	17.8	18.8
	Fall	4	3.15	4.02	3.86	4.26	4	9.11	13.3	13.5	18.1
	Winter	6	2.28	2.72	2.67	2.98	6	5.62	7.23	7.09	8.00

Table 10: Descriptive statistics (minimum, median, average, and maximum) for a) specific conductance, and b) Na and Cl in Core tributary monitoring sites in the Ware River watershed during 2020.

a)

Site	Season	Specific Conductance (µS/cm)				
		Count	Min	Med	Avg	Max
101	Spring	4	92.9	95.3	97.9	108
	Summer	6	95.0	113	111	119
	Fall	6	97.9	114	113	123
	Winter	7	67.9	103	98.6	115
103A	Spring	4	76.5	103	101	121
	Summer	6	76.1	97.5	111	163
	Fall	6	73.7	95.9	99.4	141
	Winter	7	63.9	81.1	80.1	91.5
107A	Spring	4	60.1	68.9	71.4	87.8
	Summer	6	60.8	89.7	82.4	96.2
	Fall	6	99.0	114	115	138
	Winter	7	66.6	86.4	85.2	95.5
108	Spring	4	49.2	72.8	74	101
	Summer	6	51.0	120	99.6	128
	Fall	6	129	132	133	139
	Winter	7	86.4	98.6	103	120
121B	Spring	4	80.1	181	204	373
	Summer	6	108	288	239	319
	Fall	4	304	329	332	366
	Winter	7	289	320	321	368

b)

Site	Season	Sodium (mg/L)					Chloride (mg/L)				
		Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max
101	Spring	4	12.0	12.3	12.6	13.7	4	19.4	19.8	21.0	25.1
	Summer	7	12.3	13.9	14.1	15.7	7	18.5	24.1	23.0	25.2
	Fall	6	13.0	14.2	14.2	15.5	6	20.8	23.0	23.2	25.7
	Winter	7	8.05	12.4	12.1	14.6	7	13.2	20.6	20.5	25.8
103A	Spring	4	9.45	9.57	9.87	10.9	4	14.4	16.4	16.6	19.1
	Summer	7	9.52	10.8	10.7	12.1	7	14.5	16.7	17.1	20.8
	Fall	6	9.36	9.85	10.8	13.7	6	14.9	17.1	18.0	22.2
	Winter	7	7.49	9.80	10.2	12.2	7	14.0	16.5	16.4	19.9
107A	Spring	4	9.85	10.5	10.6	11.5	4	15.6	16.0	16.8	19.5
	Summer	7	11.3	12.0	12.6	15.1	7	18.2	18.8	19.9	24.3
	Fall	6	13.3	14.8	15.4	19.5	6	20.8	24.7	24.9	30.9
	Winter	7	8.08	10.7	10.6	12.2	7	12.8	18.0	17.4	20.5
108	Spring	4	11.9	12.2	12.2	12.4	4	19.1	20.2	20.6	22.9
	Summer	7	14.7	15.4	15.5	16.6	7	25.1	26.7	26.6	28.8
	Fall	6	15.5	16.2	16.1	16.6	6	27.0	28.9	28.7	30.6
	Winter	7	10.2	12.5	12.8	14.8	7	17.5	20.2	21.7	25.4
121B	Spring	4	33.3	36.1	38.1	46.7	4	64.9	70.2	75.1	95.3
	Summer	7	33.5	37.1	37.3	41.3	7	63.2	69.9	82.7	148
	Fall	4	34.4	39.3	39.1	43.4	4	72.6	81.6	81.9	91.8
	Winter	7	33.4	34.3	37	43.3	7	64.9	72.1	74.5	95.9

3.2.3 Turbidity

Turbidity in Core monitoring tributaries in Quabbin Reservoir and Ware River watersheds was within historical ranges for the entirety of 2020 (Figure 14, Figure 15). Turbidity ranged from 0.1 to 3.5 NTU in Quabbin Reservoir Core monitoring tributary and from 0.45 to 6.4 NTU in Ware River watershed tributaries (Table 11, Table 12). Turbidity levels in Core tributary monitoring sites in the Quabbin Reservoir watershed remained below the five NTU SWTR requirement for the entirety of 2020. Turbidity levels exceeded five NTU on a single date at DSWP site 121B in the Ware River watershed in 2020 (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 2020, or high flow events in either watershed.

Turbidity levels in 2020 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 2.3 to 3.3 NTU) than in Quabbin Reservoir tributaries (generally < 1 NTU). Variability in turbidity dynamics observed across sites may be attributed to land use differences across sites, localized meteorological effects, and sub-catchment hydrology, and is not necessarily indicative of long-term trends. Turbidity levels observed in 2020 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 2020. Censored data were substituted with one-half the detection limit for calculations. * Note: 215 was not sampled from August 4 to December 9, 2020 due to a lack of flowing water.

Site	Season	Turbidity (NTU)				
		Count	Min	Med	Avg	Max
211	Spring	2	0.27	0.34	0.34	0.40
	Summer	4	0.36	0.43	0.43	0.50
	Fall	7	0.26	0.30	0.44	1.20
	Winter	6	0.21	0.30	0.28	0.34
212	Spring	2	0.45	0.62	0.62	0.79
	Summer	4	0.99	1.15	1.12	1.20
	Fall	7	0.35	0.53	0.87	2.50
	Winter	6	0.34	0.59	0.53	0.65
213	Spring	2	0.58	0.77	0.77	0.96
	Summer	4	0.90	0.94	0.95	1.00
	Fall	7	0.43	0.62	0.68	1.00
	Winter	6	0.42	0.53	0.54	0.66
215	Spring	2	0.45	0.55	0.55	0.65
	Summer	3	0.86	1.60	1.45	1.90
	Fall*	0	-	-	-	-
	Winter	6	0.37	0.40	0.41	0.52
216	Spring	2	0.47	0.600	0.60	0.73
	Summer	4	0.62	0.72	1.02	2.00
	Fall	7	0.41	0.57	0.60	0.93
	Winter	6	0.47	0.52	0.52	0.57

Site	Season	Turbidity (NTU)				
		Count	Min	Med	Avg	Max
GB	Spring	2	0.15	0.26	0.26	0.37
	Summer	4	0.14	0.16	0.18	0.27
	Fall	7	0.11	0.26	0.26	0.61
	Winter	6	0.10	0.16	0.21	0.37
BC	Spring	2	0.80	1.00	1.00	1.20
	Summer	2	0.72	1.01	1.01	1.30
	Fall	4	0.16	0.55	0.62	1.20
	Winter	6	0.99	1.25	1.77	3.50

Table 12: Descriptive statistics (minimum, median, average, and maximum) for turbidity in Core tributary monitoring sites in the Ware River watershed during 2020.

Site	Season	Turbidity (NTU)				
		Count	Min	Med	Avg	Max
101	Spring	2	0.56	0.93	0.93	1.30
	Summer	4	2.10	2.35	2.45	3.00
	Fall	6	1.10	1.20	1.22	1.50
	Winter	7	0.51	0.56	0.82	1.60
103A	Spring	2	0.53	0.82	0.82	1.10
	Summer	4	1.90	2.25	2.20	2.40
	Fall	6	0.77	1.10	1.21	1.80
	Winter	7	0.45	0.52	0.60	0.86
107A	Spring	2	0.57	0.79	0.79	1.00
	Summer	4	1.20	1.55	1.65	2.30
	Fall	6	0.68	1.05	0.98	1.20
	Winter	7	0.47	0.53	0.69	1.20
108	Spring	2	0.64	0.92	0.92	1.20
	Summer	4	2.30	2.45	2.55	3.00
	Fall	6	0.91	1.55	1.50	2.00
	Winter	7	0.49	0.76	0.79	1.30
121B	Spring	2	0.56	0.78	0.78	1.00
	Summer	4	1.90	2.35	2.48	3.30
	Fall	4	0.68	1.13	2.34	6.40
	Winter	7	0.49	0.58	0.89	2.70

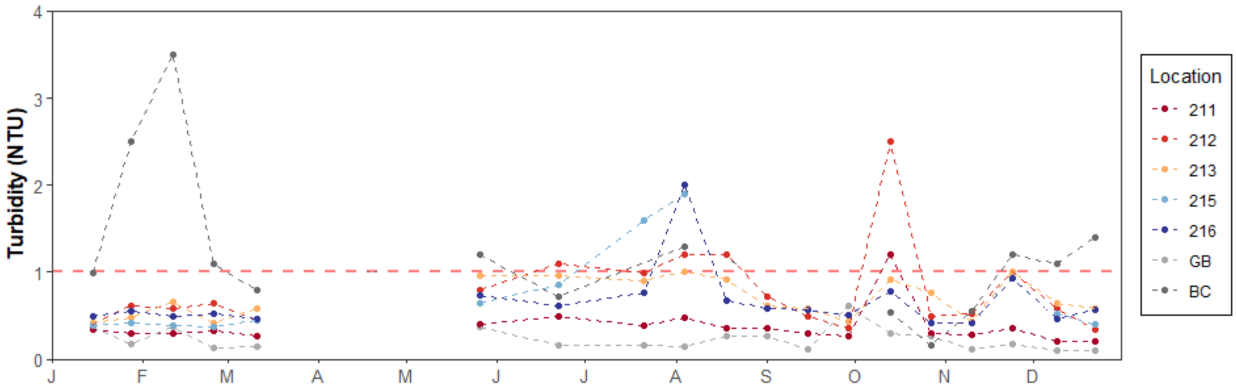

Figure 14: Time series depicting the temporal variations in turbidity observed In Quabbin Reservoir watershed Core tributary monitoring sites in 2020. The red dashed line represents the one NTU MassDEP standard.

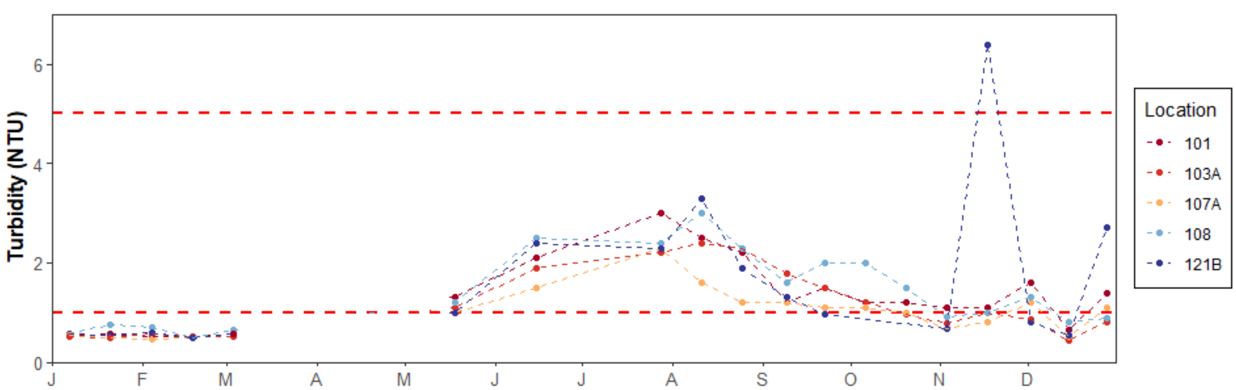

Figure 15: Time series depicting the temporal variations in turbidity observed In Ware River watershed Core tributary monitoring sites in 2020. The red dashed lines represent the 5 NTU SWTR standard and the one NTU MassDEP standard.

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 in Core tributaries in the Quabbin Reservoir and Ware River watersheds was not performed in 2020.

Elevated bacteria results from Quabbin Reservoir and Ware River tributaries that exceed the upper bounds of seasonal normals (75th percentiles) and that cannot be attributed to a recent meteorological event are followed up with site inspection and re-sampling for *E. coli* concentrations. Historically, follow-up sampling has previously attributed elevated *E. coli* concentrations to wildlife activity, recent precipitation, or findings were inconclusive. No follow-up samples were collected in 2020.

3.2.4.1 Total Coliform

Variability in total coliform concentrations observed in Core tributaries in Quabbin Reservoir and Ware River watersheds largely mirrored that of stream temperature throughout 2020 (Section 3.2.1). Total coliform in Quabbin Reservoir watershed Core monitoring tributaries ranged from 189 to greater than 24,200 MPN/100-mL (Table 13) and from 155 to greater than 24,200 MPN/100-mL in Core monitoring tributaries in the Ware River watershed in 2020 (Table 14). Median total coliform concentrations for samples collected during June through August 2020 generally exceeded the summer median for the period of record at each site but remained within an order of magnitude of the seasonal median for all sites aside from Boat Cove Brook (Quabbin Reservoir watershed). Median total coliform concentrations for Core monitoring sites during fall and winter months were typically comparable to that of the period of record for each site. Historical seasonal maximum total coliform concentrations were not observed in 2020 (Appendix C).

Table 13: Descriptive statistics (minimum, median, average, and maximum) for total coliform in Core tributary monitoring sites in the Quabbin Reservoir watershed during 2020. 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	2	488	874	874	1,260
	Summer	4	3,450	5,045	5203	7,270
	Fall	7	727	1,840	4094	19,900
	Winter	6	211	310.5	326	441
212	Spring	2	455	862.5	863	1,270
	Summer	4	4,350	4,610	4,925	6,130
	Fall	7	393	2,140	5,225	24,200
	Winter	6	399	500	519	697
213	Spring	2	399	2,025	2,025	3,650
	Summer	4	4,110	5,420	5,555	7,270
	Fall	7	677	1,720	5,061	24,200
	Winter	6	199	303.5	295	383
215	Spring	2	428	2,394	2,394	4,360
	Summer	3	4,610	9,210	8,107	10,500
	Fall	0	-	-	-	-
	Winter	6	246	344.5	456	1,080
216	Spring	2	388	1,289	1,289	2,190
	Summer	4	4,110	5,240	9,698	24,200
	Fall	7	373	1,660	2,220	6,490
	Winter	6	317	383.5	407	537
GB	Spring	2	1,040	1,525	1,525	2,010
	Summer	4	3,870	5,505	5,645	7,700
	Fall	7	435	2,600	2,955	9,210
	Winter	6	189	409.5	425	697
BC	Spring	2	471	2,171	2,171	3,870
	Summer	2	9,800	17,000	17,000	24,200
	Fall	4	1,250	2,350	7,538	24,200
	Winter	6	313	559	537	743

Table 14: Descriptive statistics (minimum, median, average, and maximum) for total coliform in Core tributary monitoring sites in the Ware River watershed during 2020. Results are reported as MPN/100-mL.

Site	Season	Total Coliform (MPN/100-mL)				
		Count	Min	Med	Avg	Max
101	Spring	2	262	961	961	1,660
	Summer	4	2,280	7,225	9,158	19,900
	Fall	6	1180	2,525	3,055	5,790
	Winter	7	155	309	937	2,990
103A	Spring	2	201	1,061	1,061	1,920
	Summer	4	2,310	10,605	9,130	13,000
	Fall	6	888	2,445	2,463	4,350
	Winter	7	292	359	813	2,610
107A	Spring	2	309	1,695	1,695	3,080
	Summer	4	3,450	9,065	9,270	15,500
	Fall	6	1480	2,080	2,942	6,870
	Winter	7	275	487	815	2,140
108	Spring	2	262	519	519	776
	Summer	4	2,720	5,960	5,700	8,160
	Fall	6	754	1,920	1,827	2,490
	Winter	7	171	309	772	2,250
121B	Spring	2	1450	3,620	3,620	5,790
	Summer	4	5,790	20,750	17,873	>24,200
	Fall	4	3,260	6,155	6,518	10,500
	Winter	7	388	759	1350	4,110

The timing of seasonally elevated total coliform concentrations in 2020 coincided with an extended period of below-normal streamflow, high temperatures, and dry antecedent conditions across DWSP watersheds (Section 3.1). However, seasonal descriptive statistics corresponding to spring and summer months may also have been impacted by decreased sampling frequencies associated with restrictions posed by the COVID-19 state of emergency in Massachusetts in 2020. No samples were collected by DWSP for total coliform analysis from March 11 through May 18, 2020. Total coliform was analyzed at a monthly frequency at each site thereafter until August 2020 when sampling frequencies returned to biweekly. Subsequently, both streamflow and antecedent precipitation remained low throughout fall 2020. Thus, sampling frequency effects on seasonal descriptive statistics for spring and summer of 2020 should not be discounted entirely. DWSP will continue biweekly monitoring of total coliform in Core tributaries throughout 2021.

3.2.4.2 E. coli

E. coli results corresponding to Core monitoring tributaries in the Quabbin Reservoir watershed and Ware River watershed were compared to the Class A standards for non-intake waters, and annual geometric means were compared to those of previous years. *E. coli* concentrations ranged from less than 10 to 4,110 MPN/100-mL in Quabbin Reservoir watershed tributaries and from less than 10 to 556 MPN/100-mL in the Ware River watershed tributaries in 2020 (Table 16). Of the 213 samples collected from Core tributaries and analyzed for *E. coli* in 2020, approximately 30% (n=66) were below detection limits (<10 MPN/100-mL).

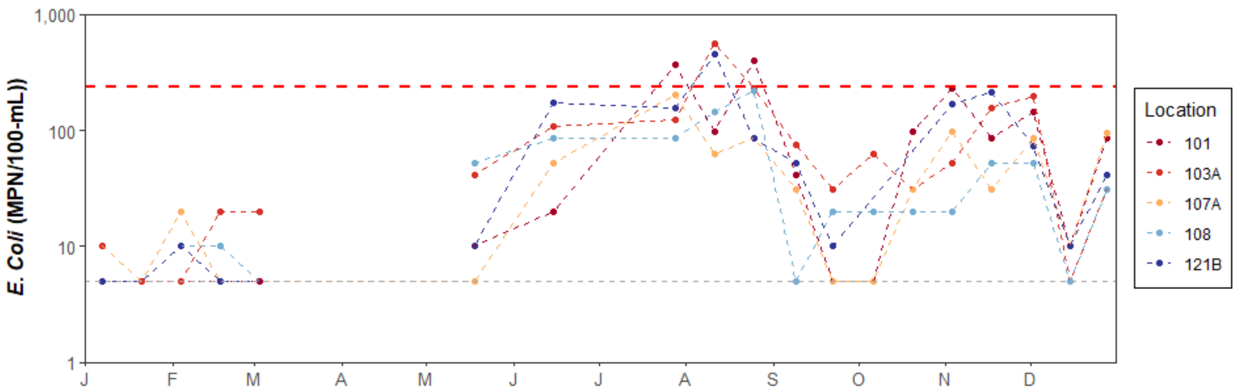

Figure 16: Time series of *E. coli* measured in Quabbin Reservoir watershed core tributary sites in 2020. Dashed lines correspond to Class A standard for *E. coli* (235 MPN/100-mL), and one-half the greatest laboratory detection limit (5 MPN/100-mL).

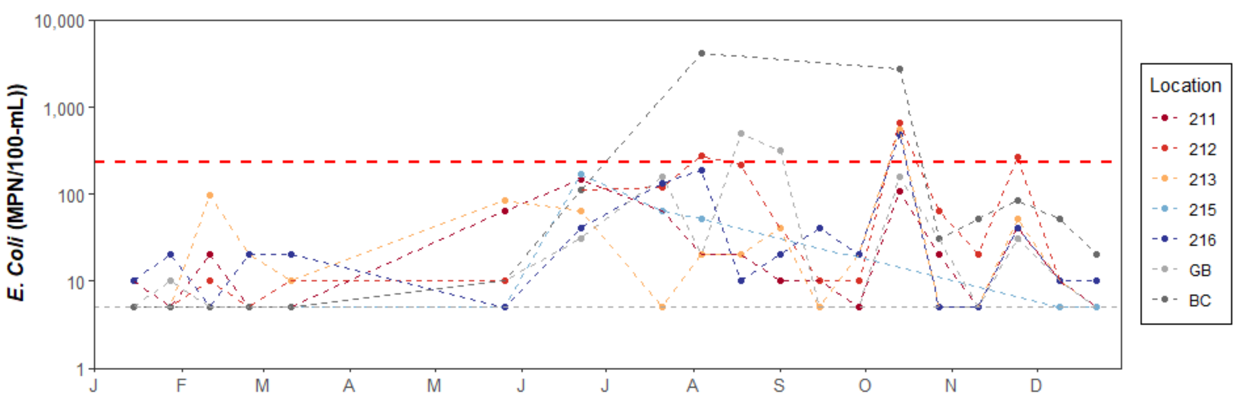

Figure 17: Time series of *E. coli* measured in Ware River watershed core tributary sites in 2020. Dashed lines correspond to Class A standard for *E. coli* (235 MPN/100-mL), and one-half the greatest minimum laboratory detection limit (5 MPN/100-mL).

Thirteen total 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 in 2020. Observations of *E. coli* concentrations in excess of 235 MPN/100-

mL occurred during the latter half of 2020 in either watershed (

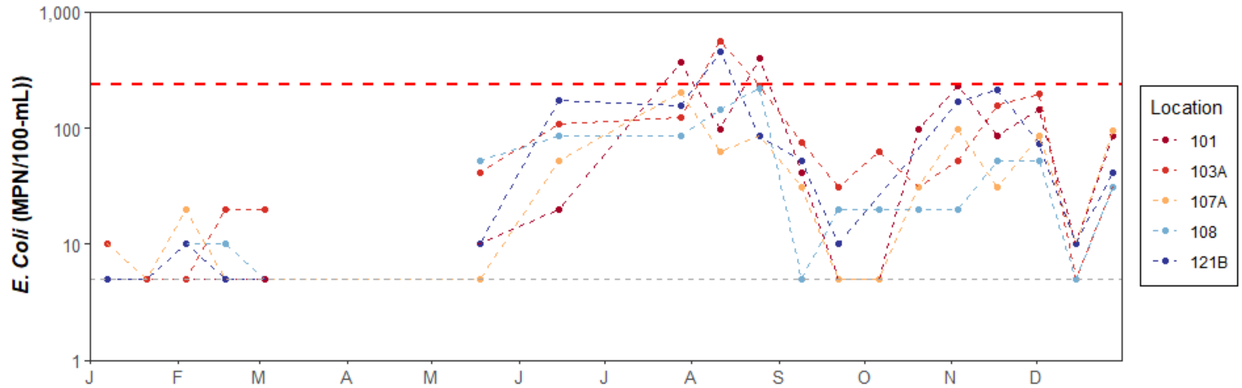

Figure 16, Figure 17), following precipitation events in all instances except two samples collected from Gates Brook (August 18 and September 01, 2020). It was during this time the region experienced moderate to severe drought (Section 3.1.1.2), and direct field observations indicated that several sample sites exhibited stagnant waters or had dried completely. No potential source of pollution were observed during or following sample collection, and *E. coli* concentrations decreased in subsequent samples (

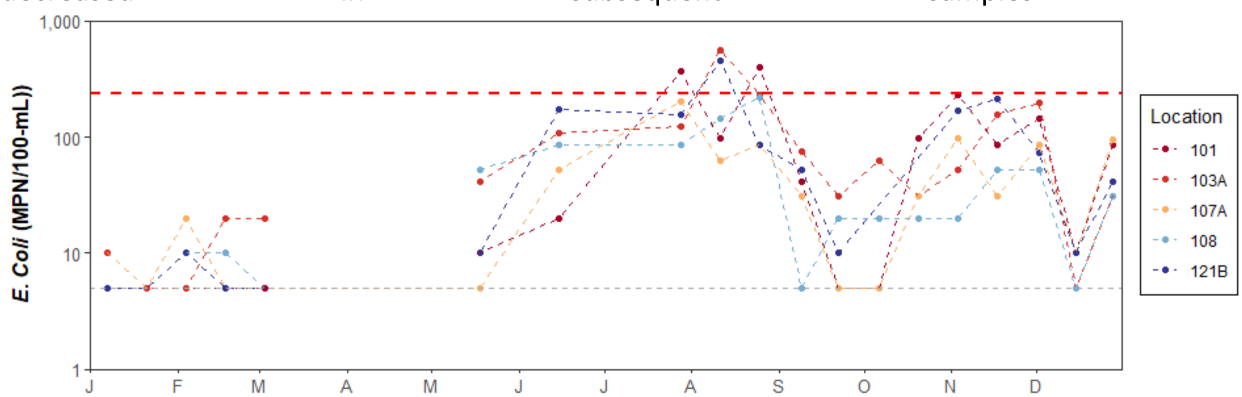

Figure 16, Figure 17).

The annual geometric mean *E. coli* concentration remained below 126 MPN/100-mL and the Class A standards for all Core monitoring sites in 2020 (Table 15). Annual geometric means corresponding to 2020 were greater than those observed during 2019 in all Core monitoring sites, aside from sites 213 and 108 in the Quabbin Reservoir and Ware River watersheds, respectively (Table 15). Relative to the 2016 geometric mean - corresponding to the last documented occurrence of prolonged significant drought in MA (DWSP, 2017) - annual geometric mean *E. coli* concentrations in Gates Brook (Quabbin Reservoir watershed) were greater in 2020. In contrast, annual geometric mean *E. coli* concentrations of sites in the Ware River watershed were typically greater for 2020 relative to 2016 (with the exclusion of site 108). This contrast may reflect the timing of sample collection relative to precipitation events in 2020, differences in the degree to which the two watersheds may have been impacted by drought, or variations in factors controlling the sources of *E. coli* to the watersheds.

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 the detection limit (MassDEP, 2018). Results are reported as MPN/100-mL. * Routine monitoring began at site 101 in 2012.

Watershed	Site	Annual Geometric Mean *E. coli* (MPN/100 mL)										
		2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Quabbin Reservoir Watershed	211	23.23	16.87	19.39	17.7	18.52	17.71	35.90	18.47	24.81	14.30	19.77
	212	28.68	27.46	27.66	21.51	23.35	43.47	60.88	28.07	40.94	18.94	32.94
	213	60.57	48.36	49.44	42.75	43.3	37.35	43.85	30.55	43.04	29.34	23.34
	215	23.56	21.60	22.84	20.74	22.12	16.60	39.21	22.07	24.20	15.27	17.78
	216	23.1	31.20	18.75	20.44	18.68	17.76	27.76	17.53	25.40	13.35	24.62
	BC	34.5	20.05	31.95	24.77	31.95	35.54	64.53	80.54	46.00	41.40	45.78
	GB	25.79	18.24	24.18	18.61	16.18	17.59	20.04	14.63	15.54	17.24	24.47
Ware River Watershed	101*	-	-	32.77	30.06	22.61	23.49	21.97	35.05	37.94	25.19	35.47
	103A	39.17	28.80	25.20	28.94	39.53	37.73	42.78	39.80	58.54	41.18	47.14
	107A	24.19	21.01	21.89	24.67	21.95	27.20	21.78	28.63	37.36	20.63	27.81
	108	34.40	35.48	23.61	32.22	25.44	29.24	27.8	36.20	41.72	30.04	27.04
	121B	60.51	31.37	47.4	27.67	24.83	32.79	36.47	38.16	33.51	22.56	37.60

Table 16: Descriptive statistics (minimum, median, average, and maximum) for *E. coli* in Core tributary monitoring sites in the Quabbin Reservoir watershed during 2020. 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	2	<10	34	34	63
	Summer	4	20	42	63	148
	Fall	7	<10	10	29	109
	Winter	6	<10	8	9	20
212	Spring	2	10	10	10	10
	Summer	4	110	167	180	275
	Fall	7	10	41	151	650
	Winter	6	<10	<10	7	10
213	Spring	2	10	48	48	86
	Summer	4	<10	20	27	63
	Fall	7	<10	20	96	546
	Winter	6	<10	8	24	98
215	Spring	2	<10	<10	5	<10
	Summer	3	52	63	95	171

	Fall	0	-	-	-	-
	Winter	6	<10	<10	5	<10
216	Spring	2	<10	13	13	20
	Summer	4	10	88	93	187
	Fall	7	<10	20	88	487
	Winter	6	<10	10	13	20
GB	Spring	2	<10	8	8	10
	Summer	4	20	96	177	496
	Fall	7	<10	31	79	315
	Winter	6	<10	<10	7	10
BC	Spring	2	<10	8	8	10
	Summer	2	110	2,110	2,110	4,110
	Fall	4	31	69	732	2,760
	Winter	6	<10	<10	15	52

Table 17: Descriptive statistics (minimum, median, average, and maximum) for *E. coli* in Core tributary monitoring sites in the Ware River watershed during 2020. 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	2	<10	8	8	10
	Summer	4	20	234	221	395
	Fall	6	<10	63	78	231
	Winter	7	<10	10	38	146
103A	Spring	2	20	31	31	41
	Summer	4	107	178	255	556
	Fall	6	31	58	68	156
	Winter	7	<10	10	39	197
107A	Spring	2	<10	<10	5	<10
	Summer	4	52	75	101	203
	Fall	6	<10	31	34	98
	Winter	7	<10	10	33	96
108	Spring	2	<10	29	29	52
	Summer	4	85	116	134	218
	Fall	6	<10	20	23	52
	Winter	7	<10	10	17	52
121B	Spring	2	<10	8	8	10
	Summer	4	86	166	217	450
	Fall	4	10	112	112	213
	Winter	7	<10	10	21	73

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 2020 were comparable to those of the prior two years (40, 41.4, and 45.78 MPN/100-mL for 2018, 2019, and 2020). Work to assess potential bacteria sources near this sample location has been described in previous reports (DWSP, 2018c).

Ultimately, *E. coli* concentrations in excess of the Class A Standard for single samples were largely attributed to flushing processes following storm events preceding sample collection dates. Disruptions to sampling frequency during the spring and summer months coupled with region-wide drought conditions present during 2020 may have contributed to much of the temporal variability observed in 2020. *E coli* concentrations in Core tributaries in Quabbin Reservoir and Ware River watersheds 2020 continued to demonstrate a high sanitary quality.

3.2.5 Nutrient Dynamics

3.2.5.1 Nitrogen Species

3.2.5.1.1 ***Ammonia-Nitrogen***

Concentrations of ammonia (NH_3-N) in Quabbin Reservoir and Ware River Watershed tributaries have routinely been below detection limits (48% of samples from Core tributaries in 2020). Concentrations of NH_3-N in Quabbin Reservoir and Ware River watershed Core monitoring tributaries ranged from <0.005 to 0.114 mg/L and <0.005 to 0.248 mg/L, respectively, in 2020 (

Table 18, Table 19). Concentrations of NH_3-N were generally within historical ranges for most Core tributary sites in 2020, with exceedances of previous seasonal maximum concentrations observed at several sites. Concentrations of NH_3-N in Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds were below the MA acute and chronic aquatic life criteria (17 mg/L and 1.9 mg/L, respectively) and the WHO taste and odor thresholds for drinking water (1.5 mg/L and 1.9 mg/L) for the entirety of 2020.

Concentrations of NH_3-N measured at site 215 in the Quabbin Reservoir watershed in 2020 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 noted a marked decrease in channel velocity and water clarity, and corresponding increase in relative stream stage for Fever Brook (215) in 2019, 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 2020 suggest that the development of beaver dam downstream from this sampling site in early 2019 may have continued to impact N-cycling in the upstream reaches of this particular sub-watershed during 2020 (DWSP, 2019a).

2020 marked the first year of biweekly monitoring of NH_3-N in Core tributaries. The increased monitoring frequency likely impacted seasonal descriptive statistics, as well as intra-annual and site-to-site variability (Jones et al., 2012; Elwan et al., 2018). For example, the range of concentrations of NH_3-N observed biweekly at site 211 in summer 2020 was greater than the range of concentrations across all seasons for the period of record (<0.005 to 0.0821 mg/L vs. <0.005 to 0.016 mg/L, respectively). As different factors may play variable roles in terrestrial aquatic N-cycling across watersheds (e.g., 211, vs. 215, vs. Boat Cove Brook; Quabbin Reservoir watershed vs. Ware River watershed), the insights on controls on riverine N-loading to Quabbin Reservoir derived from the introduction of biweekly analyses of NH_3-N may also vary. Namely, NH_3-N was below laboratory detection limits for the entirety of 2020 in Gates Brook. In contrast, concentrations of NH_3-N varied over several orders of magnitude in samples collected during the summer at sites 211 and 215. Site 108 and 121B in the Ware River watershed also demonstrated distinct intra-seasonal variability in concentrations of NH_3-N in 2020. Despite the intra-seasonal variability introduced by increased monitoring frequency, NH_3-N concentrations observed in Ware River watershed tributaries exhibited a comparable seasonal variability to large tributaries in the Quabbin Reservoir watershed (e.g., 211, 212, 213, 215, and 216) in 2020. The general timing of annual increases in instream NH_3-N concentrations was consistent across watersheds (Figure 19, Figure 21).

3.2.5.1.2 Nitrate-Nitrogen

Concentrations of nitrate (NO_3-N) ranged from <0.005 to 0.114 mg/L in Quabbin Reservoir watershed core sites in 2020 (Table 18). Concentrations of NO_3-N observed in Ware River watershed during 2020 ranged from <0.005 to 0.15 mg/L (Table 19). Concentrations of NO_3-N observed in Core tributary monitoring sites in Quabbin Reservoir and Ware River Watersheds during 2020 were largely within historical seasonal ranges but revealed differences in seasonal median concentrations when compared to those for the period of record for most sites. Seasonal concentration ranges of NO_3-N were generally similar in Core tributaries in the Ware River watershed compared to Core tributaries in the Quabbin Reservoir watershed. Variations in concentrations of NO_3-N across Core tributaries likely reflects differences in watershed characteristics combined with land use and management across the two watersheds. Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds were below the EPA MCL for drinking water of 10 mg/L for the entirety of 2020. 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 2020.

Concentrations of NO_3-N in Quabbin Reservoir and Ware River watersheds followed expected seasonal patterns in 2020, with the greatest concentrations of NO_3-N observed in samples collected from most Core tributaries in spring and winter months, and subsequent depletion in summer and fall, where uptake or increases in denitrification rates likely contributed to NO_3-N removal/reduction. Small Core tributaries in the Quabbin Reservoir watershed (e.g., Gates Brook and Boat Cove Brook) did not follow these patterns, rather these locations favored greater concentrations during low flows (e.g., summer) and relative depletion of NO_3-N concentrations during spring and winter high flows (Figure 19, Figure 21). The latter indicates key differences in controls on biogeochemical N-cycling in small low-order tributaries compared to higher-order (larger) tributaries to the Quabbin Reservoir and those in the Ware River watershed. Median winter NO_3-N concentrations in 2020 were greater than those for the period of record for most Core tributary sites, regardless of designated watershed (Appendix C). Several sample collection dates (in either watershed) during January and December 2020 occurred coincident with high streamflow events (Figure 7) resulting from large precipitation events, including a number of rain-on-snow events (Section 3.1.1.2). Increases in stream NO_3-N concentrations during different stages of snowmelt may suggest flushing of NO_3-N rich waters from shallow subsurface flow paths or atmospherically-derived NO_3-N from the snowpack (Kendall et al., 1995; Ohte et al., 2004; Pellerin et al., 2011)

Table 18: Descriptive statistics (minimum, median, average, and maximum) for nutrients (a) NO_3-N, NH_3-N, and b) TKN and TP) in Core tributary monitoring sites in the Quabbin Reservoir watershed during 2020. Results are reported as mg/L. Censored data were substituted with one-half the detection limit for calculations.

a)

Site	Season	NO_3-N (mg/L)					NH_3-N (mg/L)				
		Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max
211	Spring	5	<0.005	0.010	0.011	0.020	5	<0.005	<0.005	0.003	<0.005
	Summer	6	0.040	0.094	0.085	0.112	6	<0.005	0.012	0.021	0.082
	Fall	7	0.013	0.025	0.042	0.100	7	<0.005	<0.005	0.004	0.010
	Winter	6	0.017	0.024	0.024	0.034	6	<0.005	<0.005	0.003	0.006
212	Spring	5	0.025	0.028	0.034	0.057	5	<0.005	<0.005	0.004	0.008
	Summer	6	0.039	0.079	0.075	0.107	6	<0.005	0.005	0.005	0.009
	Fall	7	<0.005	0.020	0.018	0.037	7	<0.005	<0.005	0.003	0.008
	Winter	6	0.038	0.064	0.062	0.089	6	<0.005	<0.005	0.003	0.006
213	Spring	5	0.013	0.038	0.033	0.047	5	<0.005	<0.005	0.007	0.016
	Summer	6	<0.005	0.011	0.010	0.014	6	0.006	0.019	0.017	0.022
	Fall	7	<0.005	0.011	0.017	0.058	7	0.007	0.012	0.011	0.015
	Winter	6	0.054	0.084	0.080	0.110	6	<0.005	0.004	0.006	0.012
215	Spring	5	<0.005	<0.005	0.003	0.006	5	<0.005	<0.005	0.004	0.007
	Summer	5	0.006	0.012	0.011	0.015	5	0.028	0.059	0.065	0.114
	Fall	0	-	-	-	-	0	-	-	-	-
	Winter	6	0.007	0.018	0.018	0.024	6	<0.005	0.009	0.008	0.013
216	Spring	5	0.015	0.022	0.025	0.042	5	<0.005	<0.005	0.004	0.008
	Summer	6	0.033	0.037	0.046	0.096	6	<0.005	0.007	0.007	0.014
	Fall	7	<0.005	0.006	0.007	0.011	7	<0.005	<0.005	0.005	0.013
	Winter	6	0.036	0.062	0.058	0.080	6	<0.005	0.004	0.011	0.046
GB	Spring	5	<0.005	<0.005	0.003	0.003	5	<0.005	<0.005	0.003	0.003
	Summer	6	<0.005	0.015	0.017	0.041	6	<0.005	<0.005	0.003	0.006
	Fall	7	<0.005	<0.005	0.011	0.027	7	<0.005	<0.005	0.003	0.007
	Winter	6	<0.005	<0.005	0.005	0.011	6	<0.005	<0.005	0.003	0.003
BC	Spring	5	<0.005	0.006	0.006	0.009	5	<0.005	<0.005	0.003	0.007
	Summer	4	0.020	0.060	0.053	0.072	4	<0.005	0.007	0.007	0.011
	Fall	4	<0.005	0.016	0.037	0.114	4	<0.005	<0.005	0.005	0.012
	Winter	6	0.008	0.015	0.017	0.030	6	<0.005	<0.005	0.005	0.015

b)

Site	Season	TKN (mg/L)					TP (mg/L)				
		Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max
211	Spring	5	0.080	0.097	0.121	0.192	5	0.016	0.032	0.030	0.043
	Summer	6	0.124	0.149	0.152	0.186	6	0.034	0.041	0.041	0.048
	Fall	8	0.099	0.147	0.146	0.196	8	0.021	0.033	0.034	0.050
	Winter	6	0.084	0.094	0.094	0.109	6	0.017	0.029	0.027	0.029
212	Spring	5	0.065	0.090	0.118	0.182	5	0.023	0.047	0.042	0.052
	Summer	6	0.142	0.154	0.169	0.229	6	0.041	0.049	0.050	0.063
	Fall	8	0.076	0.128	0.151	0.277	8	0.024	0.040	0.040	0.057
	Winter	6	0.073	0.093	0.092	0.108	6	0.019	0.034	0.032	0.039
213	Spring	5	0.124	0.144	0.181	0.252	5	0.020	0.032	0.033	0.045
	Summer	6	0.272	0.323	0.327	0.382	6	0.038	0.043	0.046	0.058
	Fall	8	0.203	0.268	0.274	0.377	8	0.022	0.034	0.034	0.043
	Winter	6	0.115	0.136	0.142	0.172	6	0.018	0.028	0.028	0.035
215	Spring	5	0.172	0.203	0.231	0.362	5	0.018	0.020	0.027	0.040
	Summer	5	0.432	0.501	0.490	0.538	5	0.027	0.039	0.040	0.060
	Fall	0	-	-	-	-	0	-	-	-	-
	Winter	6	0.170	0.183	0.223	0.326	6	0.017	0.028	0.027	0.032
216	Spring	5	0.124	0.180	0.203	0.314	5	0.018	0.034	0.032	0.043
	Summer	6	0.181	0.278	0.277	0.383	6	0.027	0.034	0.038	0.064
	Fall	8	0.167	0.219	0.226	0.287	8	0.019	0.026	0.028	0.040
	Winter	6	0.148	0.162	0.184	0.245	6	0.021	0.029	0.028	0.031
GB	Spring	5	0.049	0.066	0.086	0.144	5	0.021	0.045	0.041	0.053
	Summer	6	0.066	0.099	0.116	0.182	6	0.049	0.060	0.061	0.079
	Fall	8	0.069	0.125	0.107	0.137	8	0.027	0.043	0.042	0.051
	Winter	6	0.058	0.066	0.066	0.074	6	0.018	0.034	0.033	0.043
BC	Spring	5	0.098	0.118	0.133	0.197	5	0.054	0.067	0.064	0.073
	Summer	4	0.145	0.171	0.169	0.189	4	0.077	0.083	0.088	0.109
	Fall	5	0.185	0.306	0.300	0.450	5	0.058	0.071	0.068	0.073
	Winter	6	0.101	0.114	0.151	0.262	6	0.044	0.049	0.049	0.057

Table 19: Descriptive statistics (minimum, median, average, and maximum) for nutrients (a) NO_3-N, NH_3-N, and b) TKN and TP) in Core tributary monitoring sites in the Ware River watershed during 2020. Results are reported as mg/L. Censored data were substituted with one-half the detection limit for calculations.

a)

Site	Season	NO_3-N (mg/L)					NH_3-N (mg/L)				
		Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max
101	Spring	4	<0.005	0.008	0.014	0.036	4	<0.005	<0.005	0.004	0.006
	Summer	7	0.014	0.018	0.025	0.048	7	<0.005	0.008	0.009	0.016
	Fall	6	<0.005	0.008	0.007	0.010	6	<0.005	0.006	0.005	0.007
	Winter	7	0.013	0.043	0.042	0.054	7	<0.005	0.006	0.006	0.013
103A	Spring	4	0.012	0.026	0.035	0.075	4	<0.005	<0.005	0.004	0.007
	Summer	7	0.024	0.042	0.043	0.071	7	<0.005	0.006	0.008	0.017
	Fall	6	<0.005	0.007	0.006	0.012	6	<0.005	0.007	0.006	0.011
	Winter	7	0.013	0.070	0.066	0.084	7	<0.005	0.006	0.009	0.027
107A	Spring	4	<0.005	0.005	0.017	0.057	4	<0.005	<0.005	0.003	0.003
	Summer	7	0.009	0.019	0.020	0.036	7	<0.005	0.006	0.007	0.014
	Fall	6	0.003	0.006	0.012	0.035	6	<0.005	0.008	0.008	0.017
	Winter	7	0.011	0.045	0.038	0.055	7	0.006	0.007	0.008	0.012
108	Spring	4	0.010	0.015	0.022	0.048	4	<0.005	<0.005	0.003	0.003
	Summer	7	0.016	0.037	0.039	0.082	7	<0.005	0.021	0.017	0.034
	Fall	6	<0.005	0.009	0.009	0.019	6	<0.005	0.011	0.009	0.017
	Winter	7	0.012	0.053	0.043	0.062	7	0.005	0.008	0.026	0.123
121B	Spring	4	<0.005	<0.005	0.020	0.072	4	<0.005	<0.005	0.005	0.011
	Summer	7	<0.005	<0.005	0.003	0.008	7	0.003	0.021	0.025	0.065
	Fall	4	<0.005	0.010	0.011	0.022	4	0.018	0.052	0.065	0.137
	Winter	7	0.021	0.108	0.094	0.150	7	0.01	0.045	0.064	0.248

b)

Site	Season	TKN (mg/L)					TP (mg/L)				
		Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max
101	Spring	4	0.168	0.194	0.201	0.250	4	0.018	0.026	0.026	0.034
	Summer	7	0.248	0.289	0.309	0.402	7	0.025	0.039	0.039	0.050
	Fall	6	0.127	0.253	0.244	0.388	6	0.019	0.032	0.031	0.042
	Winter	7	0.151	0.181	0.220	0.358	7	0.021	0.029	0.030	0.038
103A	Spring	4	0.159	0.182	0.181	0.201	4	0.018	0.026	0.026	0.034
	Summer	7	0.248	0.307	0.306	0.365	7	0.023	0.041	0.040	0.048
	Fall	6	0.156	0.231	0.237	0.334	6	0.017	0.032	0.031	0.041
	Winter	7	0.120	0.158	0.190	0.318	7	0.018	0.027	0.028	0.038
107A	Spring	4	0.201	0.235	0.241	0.291	4	0.019	0.027	0.028	0.037
	Summer	7	0.330	0.342	0.389	0.517	7	0.020	0.038	0.036	0.047
	Fall	6	0.307	0.409	0.399	0.469	6	0.017	0.032	0.032	0.042
	Winter	7	0.178	0.231	0.269	0.424	7	0.022	0.031	0.032	0.044
108	Spring	4	0.181	0.193	0.198	0.227	4	0.017	0.022	0.023	0.030
	Summer	7	0.318	0.366	0.374	0.453	7	0.019	0.041	0.036	0.050
	Fall	6	0.255	0.299	0.296	0.324	6	0.021	0.031	0.031	0.040
	Winter	7	0.149	0.190	0.222	0.335	7	0.015	0.027	0.027	0.042
121B	Spring	4	0.182	0.264	0.262	0.340	4	0.012	0.018	0.018	0.024
	Summer	7	0.465	0.510	0.522	0.583	7	0.024	0.039	0.036	0.046
	Fall	4	0.380	0.405	0.406	0.433	4	0.015	0.023	0.027	0.048
	Winter	7	0.199	0.244	0.272	0.39	7	0.017	0.026	0.025	0.034

Biweekly analyses of NO_3-N in 2020 revealed several key patterns not presented by single quarterly (seasonal) results. Temporally, within a seasonal period, in-stream NO_3-N concentrations may vary from below 25th percentile concentrations to maximum concentrations observed for the period of record (Appendix C). This is to be expected, given the dynamic controls on NO_3-N transport across terrestrial aquatic ecosystems. Other sites offered little to no intra-seasonal variability in NO_3-N concentrations at a biweekly monitoring frequency. The latter typically occurred at locations which NO_3-N concentrations remained below laboratory detection limits for the entire three-month window (e.g., 121B and GB) and ultimately serves to provide meaningful information relative to N-loading in small tributary systems. Furthermore, seasonal median NO_3-N concentrations for some sites in 2020 illustrated seasonality distinct patterns from that presented by seasonal medians for the period of record. This observation may also have been impacted by the drought conditions during summer and fall months, discussed previously. Although, this pattern was most notable in samples collected during the spring of 2020 in Quabbin Reservoir watershed Core tributaries. Biweekly monitoring of NO_3-N over the next several years may provide additional insights toward the implications of the increase in monitoring frequency of nutrients in Core tributaries in the Quabbin Reservoir watershed and Ware River watershed. Higher frequency sampling of nutrients in surface waters generally results in more accurate annual load estimates (Jones et al., 2012; Elwan et al 2018). As variations in NO_3-N concentrations may drastically impact estimates of N-loading, thoroughly understanding the processes controlling NO_3-N concentrations – including typical intra- and interannual variability - is critical for deriving accurate estimates of N-delivery to Quabbin Reservoir.

3.2.5.1.3 Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen (TKN) concentrations in Quabbin Reservoir watershed core tributary monitoring sites ranged from 0.049 to 0.538 mg/L in 2020 (Table 18). TKN concentrations in 2020 exceeded historical seasonal maximums for select sites in the Quabbin Reservoir watershed in samples (n=3) following large precipitation events that occurred during the spring, or preceded by an extended period of drought in the fall, and rain-on-snow events (Figure 18, Figure 19; Section 3.1.2). TKN concentrations in Ware River watershed core tributary monitoring sites ranged from 0.12 to 0.583 mg/L during 2020 (Table 19). TKN concentrations observed in Ware River tributaries in 2020 were within historical seasonal ranges (Figure 20, Figure 21). TKN concentrations measured in 2020 in most Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds fell within established ranges for local ecoregional background concentrations (0.1 – 0.3 mg/L; Appendix A), except for sample sites with a greater percentage of wetland cover or immediately downstream of a wetland area (e.g., 215 in the Quabbin Reservoir watershed and 121B in the Ware River watershed).

TKN dynamics in Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds loosely mirrored that of other N-species (NO_3-N, NH_3-N), TP, and organic content (Figure 22, Figure 23), with relative enrichment during summer (Section 3.2.6). Similar to patterns presented by biweekly concentrations of other N-species in 2020, TKN concentrations exhibited considerable variability for select Core sites within seasons (Figure 18). Organic nitrogen (TKN – NH_3-N) was the most abundant nitrogen form in Core tributaries in either Quabbin Reservoir watershed or Ware River watershed in 2020. Dominance of organic nitrogen in headwater streams in the US has been documented previously (Scott et al., 2007). Notably, the fraction of total nitrogen (TN) comprised of organic nitrogen (TKN - NH_3-N) did not increase ubiquitously with hydrologic events (Figure 19, Figure 21), suggesting that the increase in TN during high flows is driven predominantly by increases in inorganic N-species (namely, NO_3-N and NH_3-N) and further corroborated by observed patterns in concentrations of in stream inorganic N-forms during 2020. These relationships were elucidated more clearly in 2020 relative to prior years, in part due to the increased monitoring frequency of all N-forms for both watersheds.

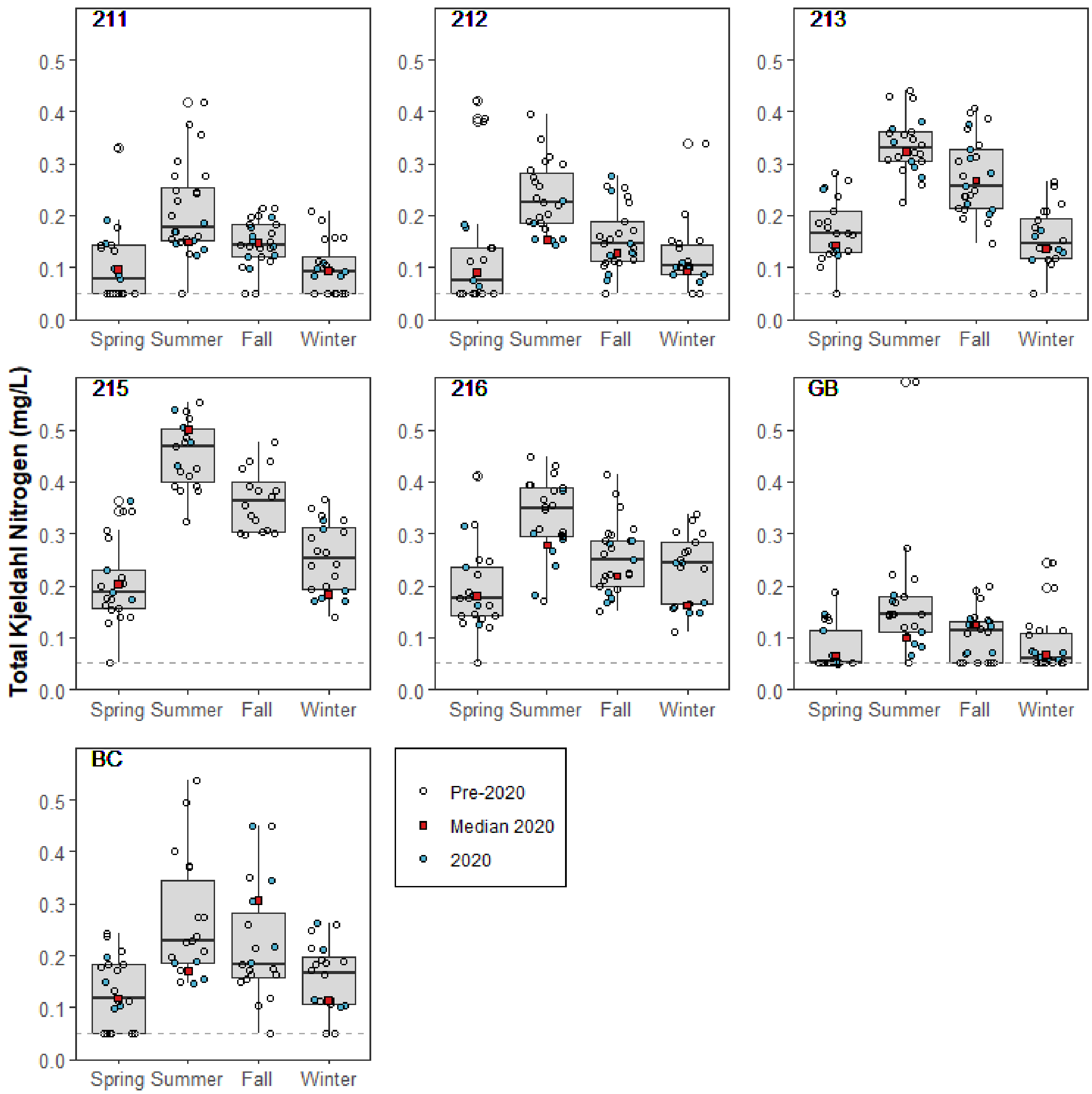

Figure 18: Boxplots depicting the seasonal distributions of TKN observed In Quabbin Reservoir watershed Core tributary monitoring sites. Results corresponding to samples collected in 2020 are signified by the blue points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. The dashed horizontal line represents one-half of the greatest laboratory detection limit (0.05 mg/L)

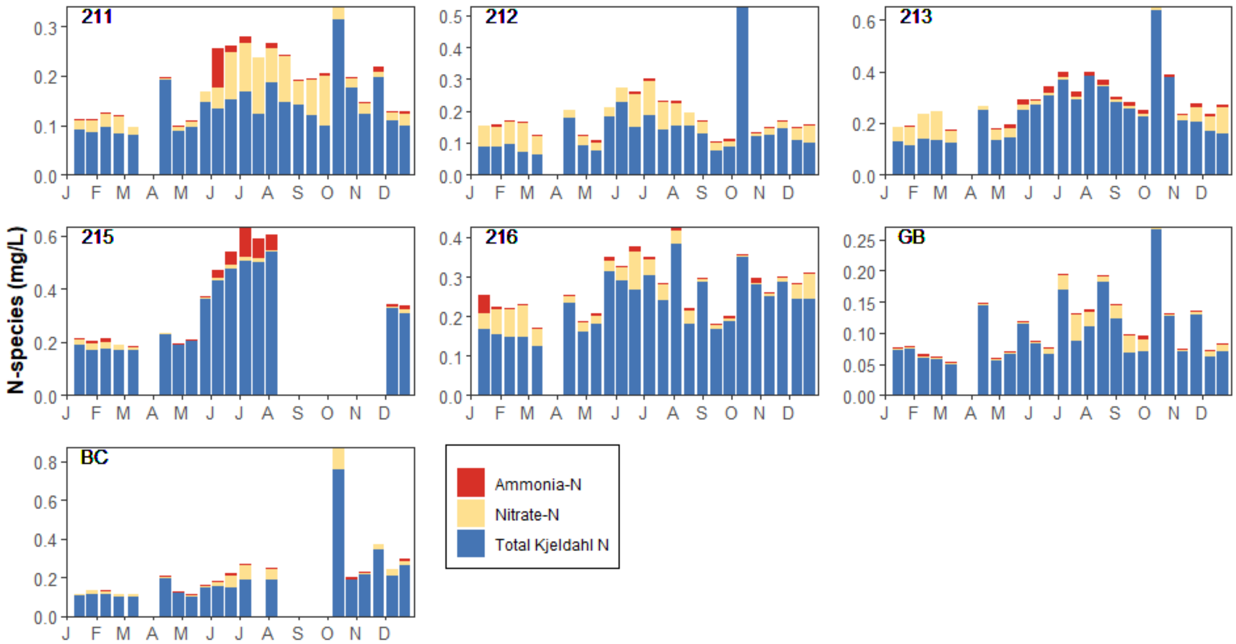

Figure 19: Bar plots depicting the temporal distributions of nitrogen species observed In Quabbin Reservoir watershed Core tributary monitoring sites during 2020. Note: y-axes vary.

Lastly, analytical methods for TKN were modified in 2020. Prior to January 1, 2020, TKN concentration data for Quabbin Reservoir and Ware River watershed tributaries were derived via EPA Method 351.2 (O'Dell, 1993a). Beginning January 1, 2020, analysis shifted to Valderrama (1981) to facilitate biweekly monitoring frequencies of N-species and TP in Core tributaries. Results were reported as total nitrogen (TN) thereafter. TKN concentrations for 2020 were derived by subtracting corresponding concentrations of NO_3-N and NO_2-N from TN data. Concentrations below laboratory detection limits were substituted with one-half the detection limit. NO_2-N has been measured previously (2005 through 2011, 2013, 2015, and 2019), in tributaries in the Quabbin Reservoir and Ware River watershed and was below laboratory detection limits in all but four samples (n=2,005 total measurements). Thus, for the purposes of deriving estimates of TKN concentrations from TN data, NO_2-N was assumed to remain below laboratory detection limits (<0.005 mg/L) in all samples. DWSP did not modify sample collection methods, thus uncertainty associated with 2020 TKN concentration data is limited to assumptions made during calculations (e.g., substitutions of concentration data for one-half laboratory detection limits) and/or sensitivity of different analytical methods. The detection limits for TN via Valderrama (1981) were 0.0034 mg/L.

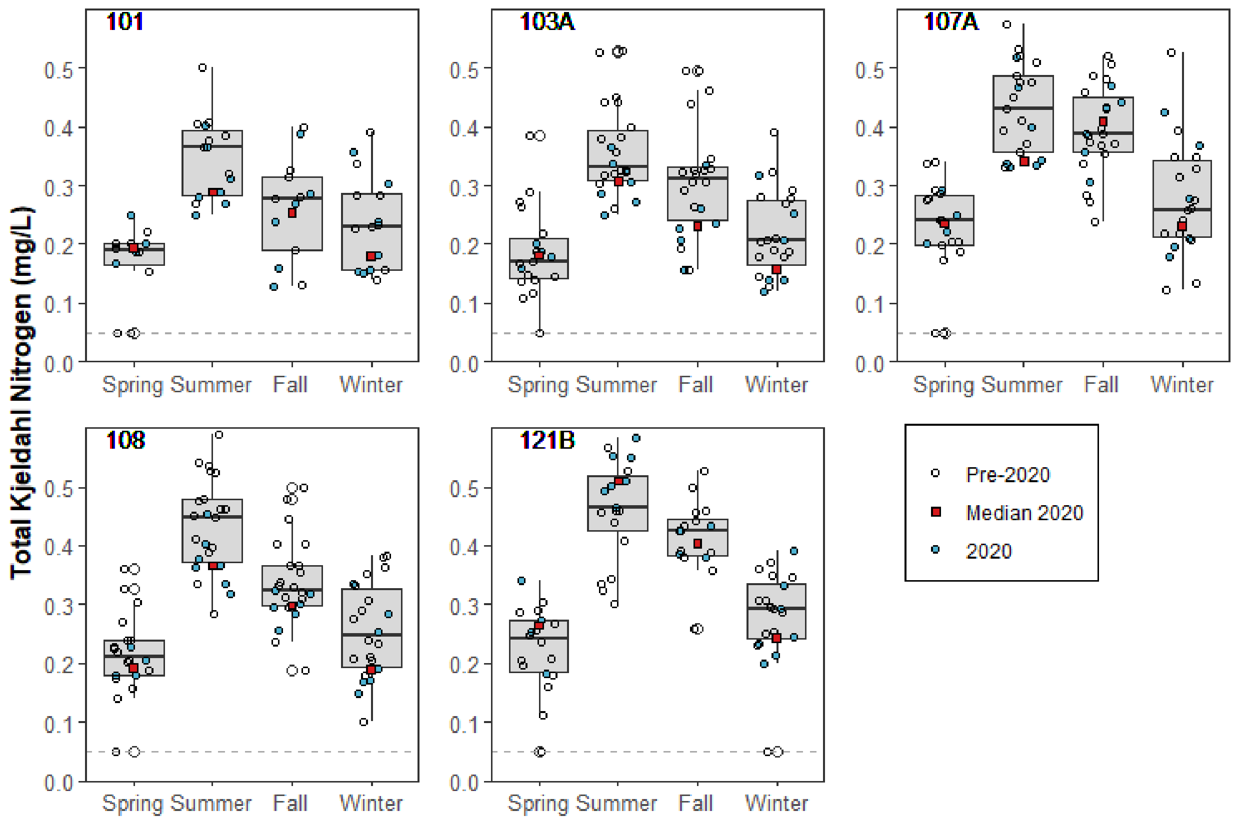

Figure 20: Boxplots depicting the seasonal distributions of TKN observed In Ware River watershed Core tributary monitoring sites. Results corresponding to samples collected in 2020 are signified by the blue points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. The dashed horizontal line represents one-half of the greatest laboratory detection limit (0.05 mg/L).

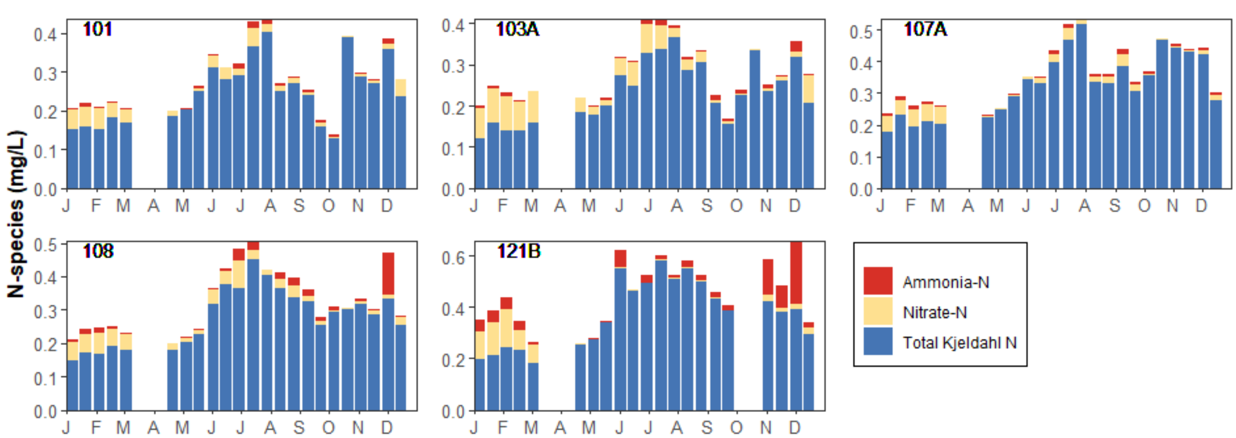

Figure 21: Bar plots depicting the temporal distributions of nitrogen species observed In Ware River watershed Core tributary monitoring sites during 2020. Note: y-axes vary.

Furthermore, in-stream biogeochemical cycles can be sensitive to impacts from drought, with mixed responses driven by a multitude of interacting factors related to channel characteristics (e.g., geomorphology, riparian structure, organic-content of stream sediments), watershed characteristics (catchment size, land cover, etc.) and/or the presence of point/diffuse nutrient sources. Drought scenarios in northern river networks may result in decreased in-stream NO_3-N concentrations, as rates of denitrification increase in response to stagnant waters, warmer temperatures, or increased residence times (Gómez-Gener et al., 2020). Streams impacted by agricultural or urban runoff may exhibit decreasing nutrient concentrations during drought, owing to a reduction in runoff containing high concentrations of nutrients (Mosley, 2015). Alternatively, the absence of dilution of nutrient-laden groundwater inputs may seve to elevate in-stream nutrient concentrations during drought conditions (Sprague, 2005). Thus, the divergence of concentrations of N-species in 2020 from typical seasonal distributions, may also have been driven, in part, by the increased stream water residence time, and subsequent denitrification rates, lack of groundwater dilution via recent precipitation, and/or reduction in inputs associated with moderate to severe drought conditions that were present during 2020 (Section 3.1). Following the drought (e.g., December 2020), nutrient concentrations typically increased – as rewetting of sediments mobilized nutrients into stream channels.

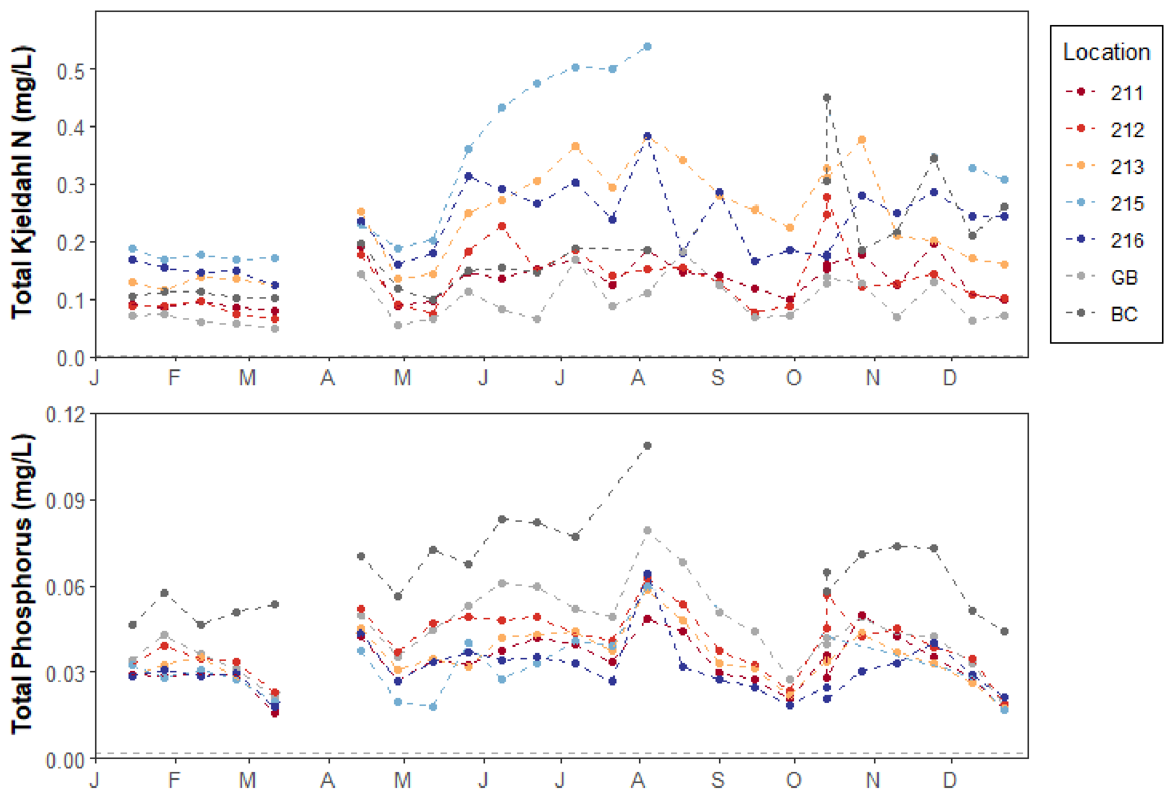

Figure 22: Time series depicting the seasonal variations in TKN and TP observed In Quabbin Reservoir watershed Core tributary monitoring sites. The dashed horizontal lines represent one-half of the greatest laboratory detection limits for TKN and TP (0.05 mg/L, and 0.0017 mg/L, respectively).

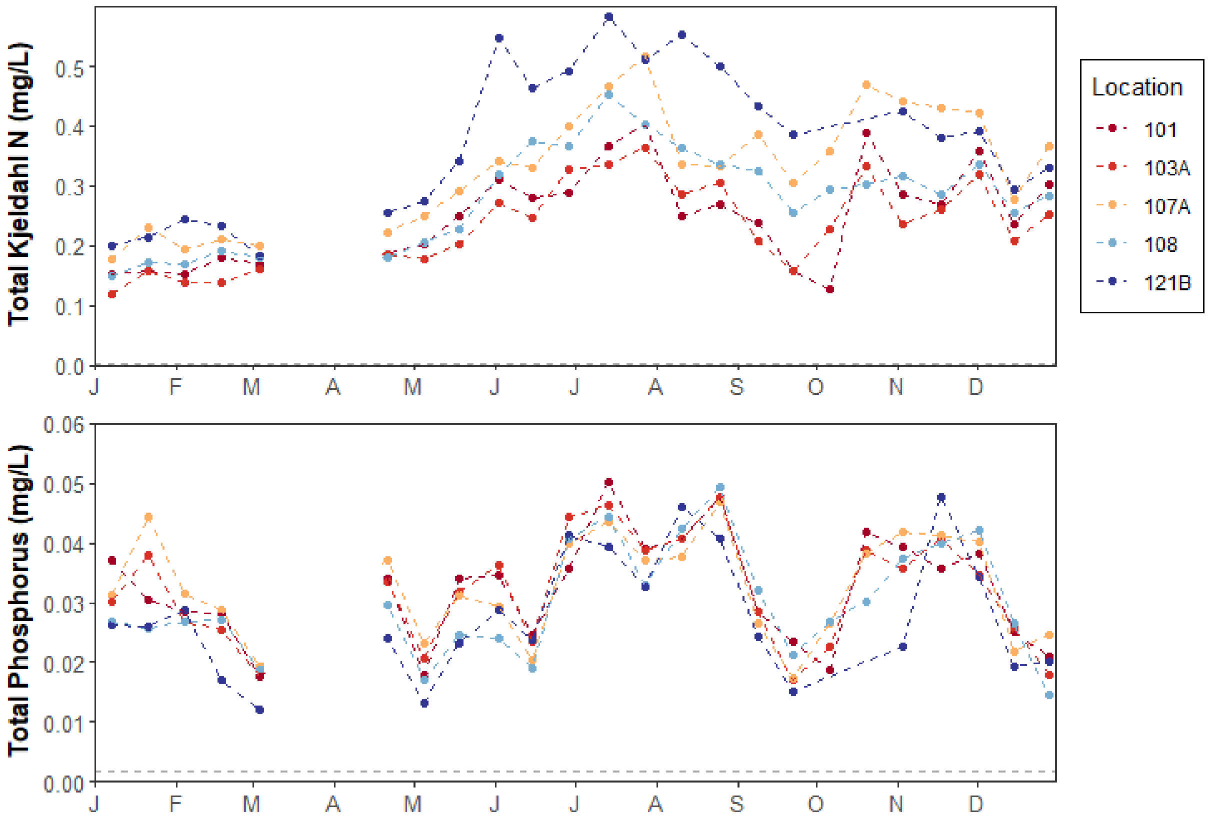

Figure 23: Time series depicting the seasonal variations in TKN and TP observed In Ware River watershed Core tributary monitoring sites. The dashed horizontal lines represent one-half of the greatest laboratory detection limits for TKN and TP (0.05 mg/L, and 0.0017 mg/L, respectively).

3.2.5.2 Total Phosphorus

Total phosphorus (TP) concentrations measured in Core monitoring tributaries in the Quabbin Reservoir during 2020 ranged from 0.016 to 0.109 mg/L (Figure 24). TP concentrations were above the seasonal median for the period of record for all sites and seasons in 2020. Despite this, concentrations of TP in Core tributaries in the Quabbin Reservoir watershed exhibited typical season dynamics (e.g., enrichment in summer/fall and relative depletion during winter/spring) observed previously (DWSP, 2020a). Relative site-to-site variability was consistent with prior monitoring periods. TP concentrations in Core tributary monitoring locations in the Quabbin Reservoir watershed exceeded EPA ecoregional background TP concentrations for Region VIII - Subregion 58 and Region XIV - Subregion 59 (0.012 mg/L and 0.024 mg/L) on select dates during 2020.

In the Ware River watershed, TP concentrations were between 0.017 to 0.05 mg/L in 2020 (Figure 25). Similar to patterns observed in the Quabbin Reservoir watershed during 2020, TP concentrations exceeded the seasonal median for the period of record at all sites and during all seasons in 2020, while following expected seasonal dynamics. Despite an overall shift in measured TP concentrations during 2020, relationships between TP and TKN were preserved from previous years, and site-to-site variability in TP concentrations was relatively consistent with that of the period of record (Figure 22, Figure 23). EPA ecoregional background TP concentrations for Region VIII - Subregion 58 and Region XIV - Subregion 59 (0.012 mg/L and 0.024 mg/L) were exceeded by Core tributaries in the Ware River watershed for much of 2020.

TP concentrations exhibited distinct seasonality for select Core sites in both watersheds (Figure 24, Figure 25). In tributaries in the Quabbin Reservoir watershed and Ware River watershed, TP concentrations were greatest during the summer and fall and comparatively lower during the spring and winter, behavior consistent with other forested headwater catchments in the NE USA (Lisboa et al., 2016). The observed gradient in TP concentrations across Quabbin Reservoir and Ware River watersheds may be partially attributed to variations in land cover, wetland connectivity, groundwater contributions, and timing of sample collection relative to large hydrometeorological events (Reddy et al., 1999; Lisboa et al., 2016). A precipitation event totaling 0.41-in (USC00190562) on August 3, 2020 following several months of below normal precipitation resulted in an observable peak in stream TP concentrations on August 4, 2020 in Core tributaries in the Quabbin Reservoir watershed (Figure 22), demonstrating process-driven loading of TP to Quabbin Reservoir (Morris et al. 2014, Lisboa et al., 2016). Similar events during October and November 2020 resulted in a comparable response in some Core tributaries (Figure 22). The biweekly monitoring of TP in 2020 allowed for observation of these relationships.

Analytical methods for TP in Core and EQA site in Quabbin Reservoir and Ware River watersheds were modified in 2020. TP concentration data for Quabbin Reservoir and Ware River watershed tributaries were derived via EPA Method 365.1 (O'Dell, 1993b) until January 1, 2020. Analysis was performed via Valderrama (1981) thereafter to facilitate biweekly monitoring frequencies of TP in Core tributaries in Quabbin Reservoir and Ware River watersheds. Uncertainty associated with TP concentration data for 2020 is limited to sensitivity of different analytical methods, as sample collection and storage were not altered in 2020. Although near-ubiquitous increases in concentrations of TP in surface water across the US have been observed previously, these changes were gradual – occurring over decades (Stoddard et al., 2016). No other parameters demonstrated an instantaneous increase in 2020, and the shift in concentrations was preserved across all sites/seasons in the absence of new point/diffuse sources of TP across Quabbin Reservoir and Ware River watersheds. Thus, it is unlikely that the shift in concentrations observed in 2020 resulted from environmental factors. Furthermore, a step change in TP concentrations was not observed for sites that analytical methods were not altered. Concentrations of TP were derived via EPA 265.1 for the entirety of 2020 at long-term forestry monitoring sites - EBU and MBD on Prescott Peninsula - and Shaft 1 in the Wachusett Reservoir watershed during 2020. TP concentrations remained within established background ranges at unaffected sites (DWSP, 2021). DWSP will perform duplicate analyses for TP (via Valderrama, 1981 and EPA 265.1) in routine samples collected from tributaries and the Quabbin Reservoir in 2021 to better understand the impact that modifications to analytical methods may have on resultant concentration data and long-term monitoring.

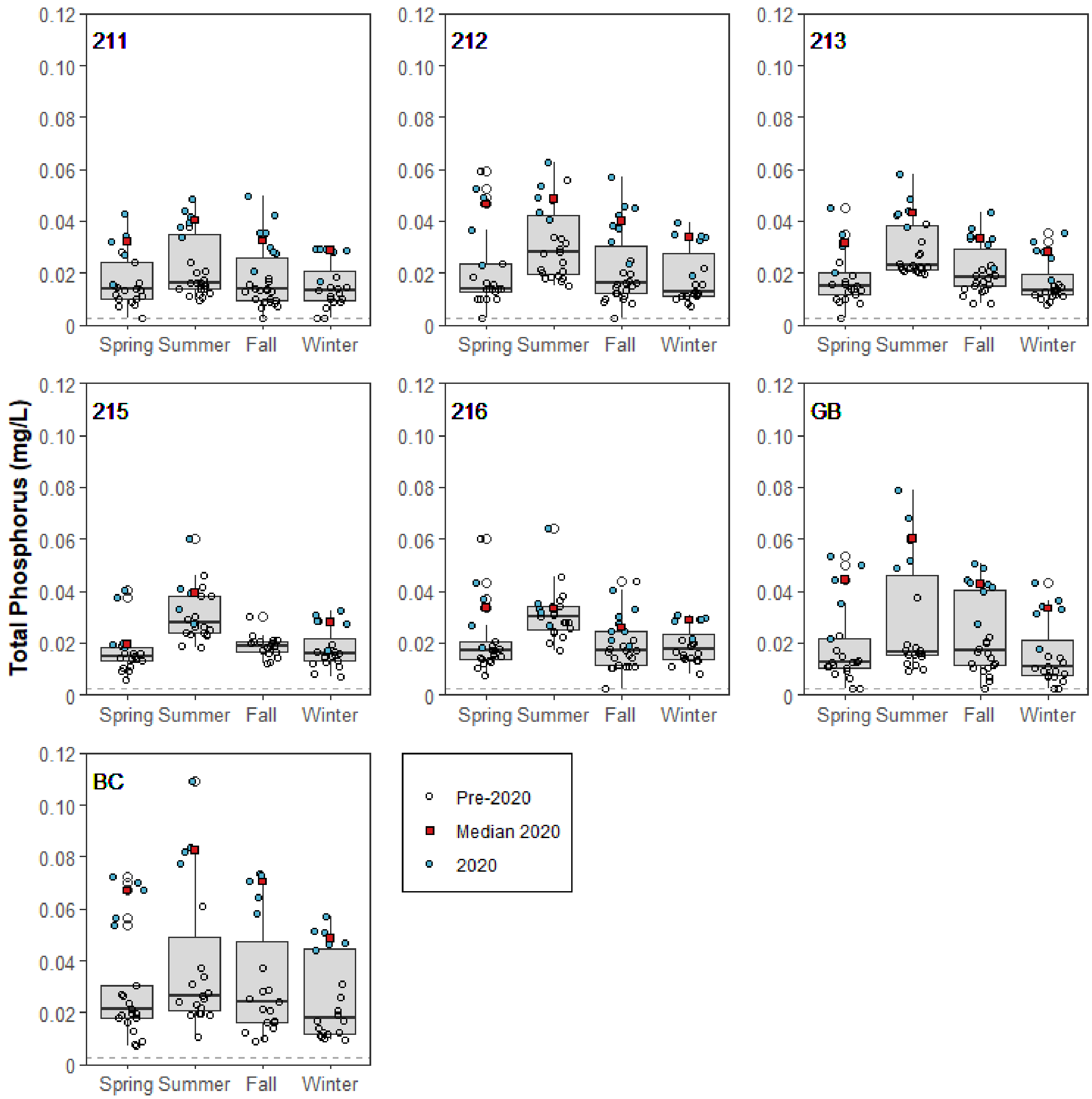

Figure 24: Boxplots depicting the seasonal distributions of total phosphorus (TP) observed In Quabbin Reservoir watershed Core tributary monitoring sites. Results corresponding to samples collected in 2020 are signified by the blue points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. The dashed horizontal lines represent one-half of the greatest laboratory detection limits for TP (0.0017 mg/L).

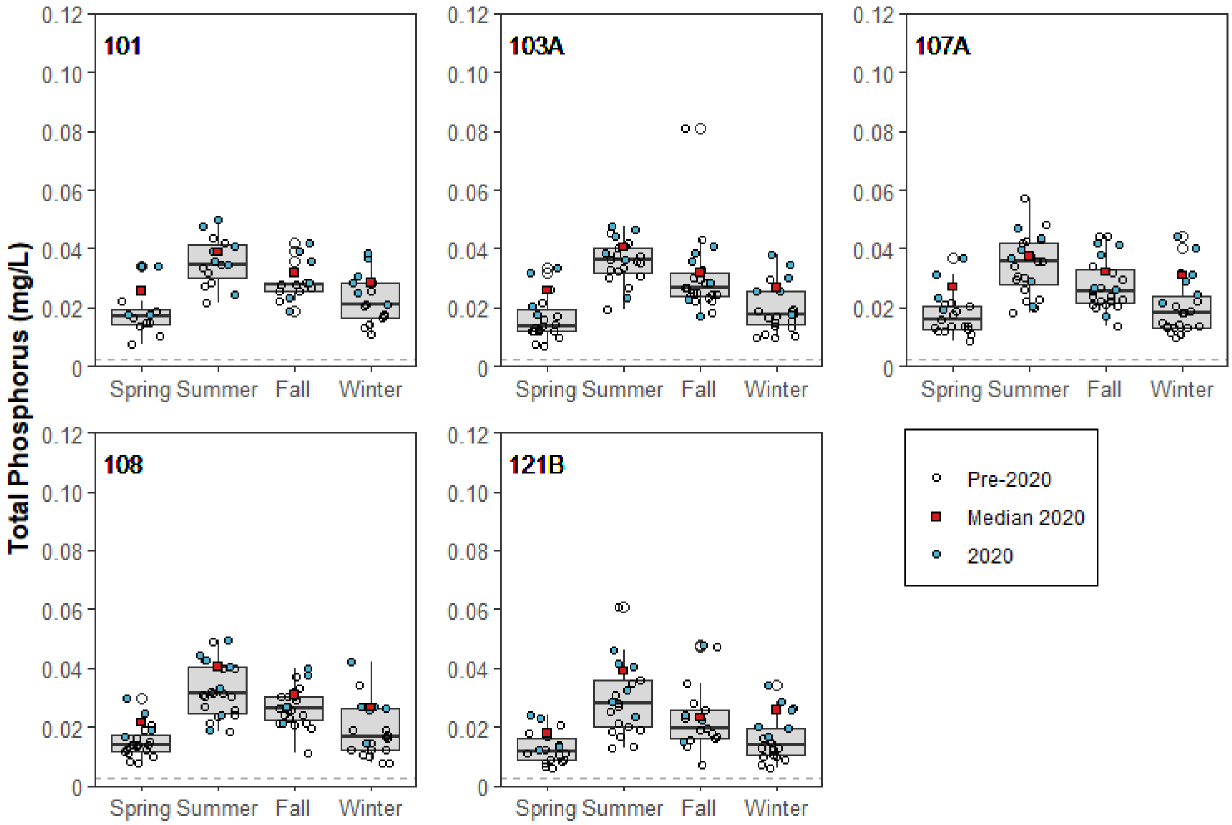

Figure 25: Boxplots depicting the seasonal distributions of total phosphorus (TP) observed In Ware River watershed Core tributary monitoring sites. Results corresponding to samples collected in 2020 are signified by the blue points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. The dashed horizontal lines represent one-half of the greatest laboratory detection limits for TP (0.0017 mg/L).

3.2.6 UV_{254}

UV_{254} absorbance in Quabbin Reservoir Watershed Core tributary monitoring sites ranged from 0.048 to 0.409 ABU/cm in 2020 (Table 20). UV_{254} was lower in tributaries along the west arm of the Quabbin Reservoir and on Prescott Peninsula (e.g., GB, 211, 212) than those located within the northernmost reaches of the watershed (e.g., 212, 215) or on the east arm (216, BC). These tributaries (213, 215, and 216) have a higher relative percentage of wetlands and a lower proportion of DWSP-owned and managed land in upstream contributing areas than those along the west arm and in the Winsor basin area (e.g., 211, 212, GB, and BC) (Table 4), which may serve to alter organic matter (OM) processing to that which is favorable for greater OM transport and delivery to Quabbin Reservoir (Hosen et al., 2017). Differences in UV_{254} dynamics across tributaries additionally reflects variations in watershed characteristics such as wetland connectivity, channel morphology and streambed material, as well as land cover characteristics and hydrologic factors controlling the source and transport of organic matter (Larson et al., 2007;

Laudon et al., 2011; Lynch et al., 2019). As TOC has not been measured in tributaries to the Quabbin Reservoir, UV_{254} data cannot be used to derive actual estimates of OM loading across the watersheds, rather are more likely reflective of relative contributions of OM (or variations in the aromaticity of OM) to the Quabbin Reservoir (Weishaar et al., 2003; Golea et al., 2017).

Seasonal dynamics in UV_{254} absorbance measured in Core tributaries in the Quabbin Reservoir watershed were comparable to that of the period of record for the majority of Core tributary monitoring sites in the watershed during 2020 (Figure 26). The Core sites located along the west arm of the Quabbin Reservoir and on Prescott Peninsula (GB, 211, 212) demonstrated a greater deviation from historical seasonal medians during months when drought conditions prevailed (Section 3.1). Following snowmelt and rain-on-snow events, UV_{254} increased above 75th percentile seasonal values at select sites (Figure 26). Prior to 2020, UV_{254} was measured quarterly in Quabbin Reservoir watershed Core tributaries (DWSP, 2019a). Thus, some of the variability in UV_{254} observed in 2020 relative to historical seasonal ranges may be attributed to differences in sample frequencies, with more frequent samples more likely to capture hydrologic-driven variability in stream UV_{254} dynamics. Deviations from the seasonal medians for each site for the periods of record may also be attributed to the distinct hydrologic conditions presented in 2020 (e.g., drought followed by rapid rewetting. rain-on-snow events, etc.).

UV_{254} absorbance in Ware River watershed Core tributary monitoring sites ranged from 0.082 to 0.65 ABU/cm in 2020 (Table 21). Median UV_{254} in Core monitoring tributaries in the Ware River watershed in 2020 trended near or below seasonal medians for the period across seasons for most Core sites (Figure 27). Monitoring frequency for UV_{254} in Core tributaries in the Ware River watershed did not change in 2020. UV_{254} was generally greater in Core tributaries in the Ware River watershed compare to Core tributaries in the Quabbin Reservoir watershed. A greater percentage of wetlands comprises the upstream reaches of Core tributaries in the Ware River watershed (Table 4). The timing of seasonal variability in absorbance values of UV_{254} was comparable between Ware River and Quabbin Reservoir watersheds for 2020 (e.g., UV_{254} absorbance peaked during summer months for both watersheds, coincident with warmer water temperatures). Furthermore, historical variations in sampling frequencies (e.g., quarterly vs. biweekly) in Core monitoring tributaries in the Quabbin Reservoir watershed compared to those in the Ware River watershed may serve to mask inter-watershed differences in pre-2020 data.

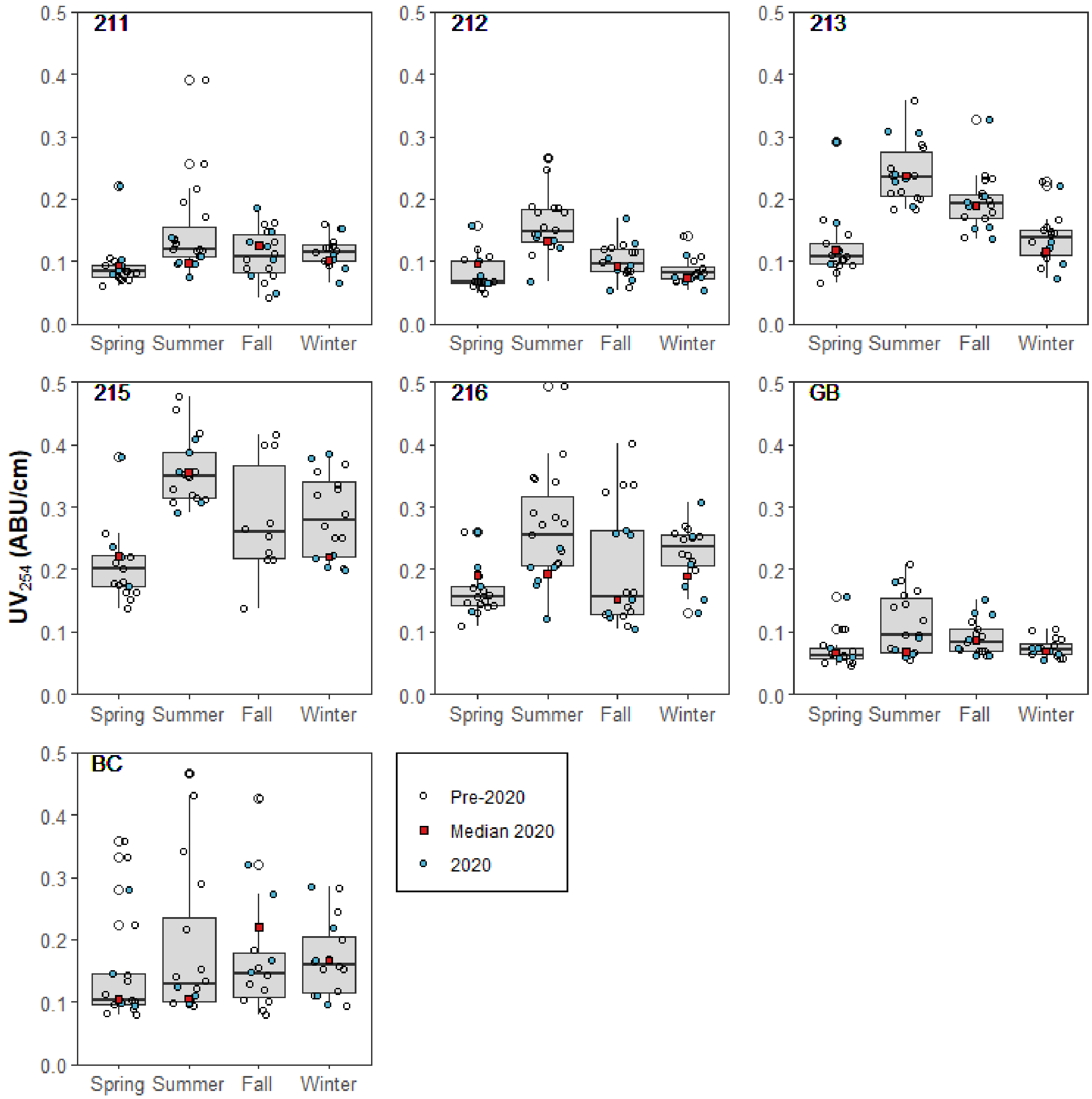

Figure 26: Boxplots depicting the seasonal distributions of UV_{254} observed In Quabbin Reservoir watershed Core tributary monitoring sites. Results corresponding to samples collected in 2020 are signified by the blue points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

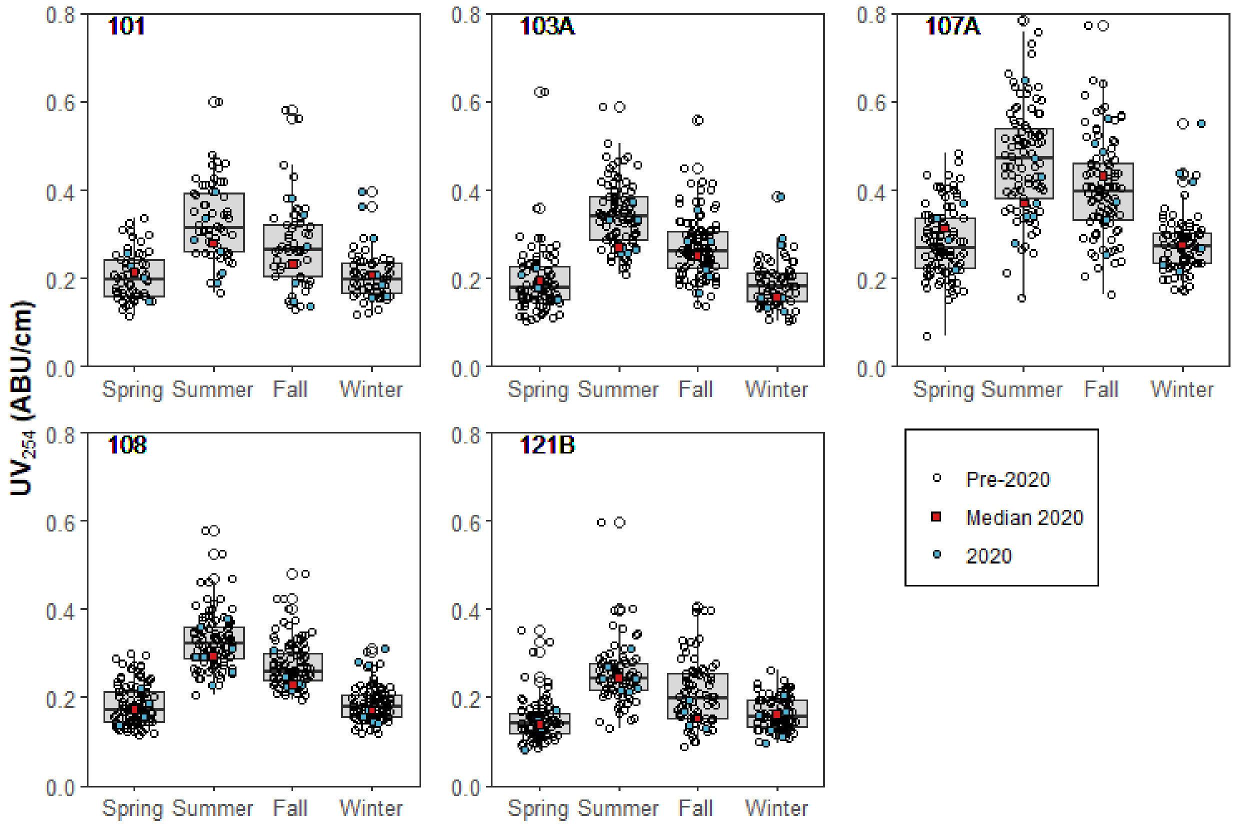

Figure 27: Boxplots depicting the seasonal distributions of UV_{254} observed In Ware River watershed Core tributary monitoring sites. Results corresponding to samples collected in 2020 are signified by the blue points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

Table 20: Descriptive statistics (minimum, median, average, and maximum) for UV_{254} in Core tributary monitoring sites in the Quabbin Reservoir watershed during 2020.

Site	Season	UV_{254} (ABU/cm)				
		Count	Min	Med	Avg	Max
211	Spring	5	0.080	0.094	0.117	0.221
	Summer	6	0.076	0.097	0.102	0.137
	Fall	7	0.048	0.125	0.117	0.185
	Winter	6	0.066	0.101	0.103	0.153
212	Spring	5	0.066	0.096	0.099	0.157
	Summer	6	0.067	0.132	0.122	0.142
	Fall	7	0.052	0.093	0.101	0.170
	Winter	6	0.053	0.073	0.076	0.111
213	Spring	5	0.095	0.118	0.157	0.292
	Summer	6	0.187	0.237	0.251	0.309
	Fall	7	0.135	0.188	0.194	0.327
	Winter	6	0.072	0.117	0.126	0.222
215	Spring	5	0.173	0.221	0.246	0.380
	Summer	5	0.291	0.356	0.350	0.409
	Fall	0	-	-	-	-
	Winter	6	0.198	0.219	0.267	0.386
216	Spring	5	0.132	0.190	0.191	0.260
	Summer	6	0.121	0.193	0.187	0.234
	Fall	7	0.103	0.152	0.184	0.263
	Winter	6	0.130	0.190	0.204	0.308
GB	Spring	5	0.058	0.066	0.082	0.156
	Summer	6	0.059	0.068	0.087	0.179
	Fall	7	0.062	0.087	0.099	0.151
	Winter	6	0.054	0.069	0.067	0.074
BC	Spring	5	0.095	0.104	0.144	0.279
	Summer	4	0.099	0.106	0.109	0.124
	Fall	4	0.149	0.219	0.227	0.320
	Winter	6	0.097	0.167	0.174	0.285

Table 21: Descriptive statistics (minimum, median, average, and maximum) for UV_{254} in Core tributary monitoring sites in the Ware River watershed during 2020.

Site	Season	UV_{254} (ABU/cm)				
		Count	Min	Med	Avg	Max
101	Spring	4	0.148	0.213	0.208	0.258
	Summer	7	0.190	0.280	0.281	0.397
	Fall	6	0.136	0.232	0.246	0.380
	Winter	7	0.157	0.208	0.252	0.398
103A	Spring	4	0.153	0.194	0.191	0.222
	Summer	7	0.257	0.270	0.299	0.376
	Fall	6	0.167	0.251	0.252	0.354
	Winter	7	0.125	0.157	0.217	0.384
107A	Spring	4	0.220	0.313	0.304	0.370
	Summer	7	0.282	0.370	0.412	0.650
	Fall	6	0.253	0.431	0.419	0.563
	Winter	7	0.215	0.276	0.343	0.550
108	Spring	4	0.138	0.173	0.176	0.220
	Summer	7	0.227	0.294	0.304	0.378
	Fall	6	0.216	0.231	0.243	0.307
	Winter	7	0.142	0.171	0.212	0.312
121B	Spring	4	0.082	0.139	0.133	0.170
	Summer	7	0.212	0.244	0.246	0.312
	Fall	4	0.130	0.152	0.157	0.194
	Winter	7	0.095	0.162	0.148	0.204

3.2.7 Calcium, Alkalinity, and pH

3.2.7.1 Calcium

Calcium (Ca) monitoring in Quabbin Reservoir watershed tributaries began in 2010 to assess the risk of colonization by aquatic invasive organisms (e.g., zebra mussels). 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 2020 ranged from 0.84 to 14.6 mg/L (Appendix C). The range of Ca observed in Core monitoring tributaries in the Ware River watershed was 2.14 to 14.8 mg/L Ca (Appendix C). The 12 mg/L Ca threshold was exceeded at Boat Cove Brook in the Quabbin Reservoir watershed in samples collected during the summer and fall months and at site 121B in the Ware River watershed throughout the year. pH at both locations was consistently below 7.4 during this time, thus these sites remain at low risk for colonization by zebra mussels. Ca concentrations in Core tributary monitoring sites were generally elevated during summer months (June through August), relative to samples collected in either spring or winter. The timing of seasonally elevated stream Ca concentrations relative to low streamflow conditions suggests that groundwater contributions may be a source of elevated calcium to streams in the watershed (Appendix C). Continued monitoring of Ca in streams in the Quabbin Reservoir and Ware River watersheds will serve to better inform the drivers behind the seasonal dynamics and long-term trends in calcium concentrations observed in tributaries to the Quabbin Reservoir and Ware River.

3.2.7.2 Alkalinity

Alkalinity of Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds ranged from 0.93 to 25.8 mg/L and from 1.16 to 24 mg/L, respectively, in 2020. Maximum annual alkalinity for each site was typically recorded in samples collected during the summer (June) or fall (September). Temporal changes in alkalinity concentrations in surface water may be attributed to a variety of factors (e.g., natural geogenic variability, urbanization and associated chemical weathering of the built environment, acid rain inputs, or changes in or introduced during sample collection and analysis). Thus, much of the heterogeneity of alkalinity concentrations observed in tributaries within the Quabbin Reservoir watershed and Ware River watershed is likely the result of the interactions of multiple variable forces, rather than readily attributable to a single direct cause.

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 MA. The ARM criteria are based on average results for the month of April (Godfrey et al., 1996). Surface waters with Average April alkalinity concentrations less than 5.0 mg/L are classified as Endangered with regard to sensitivity to acidification using the ARM criteria. The majority of Core monitoring tributaries in the Ware River watershed were within the sensitivity category indicative of surface waters that are endangered by acid deposition (alkalinity of 2-5 mg/L) established under the UMass ARM Project, with only alkalinity measured at site 121B falling within the range of alkalinities corresponding to the Highly Sensitive category (alkalinity of 5-10 mg/L). The observed alkalinity concentration at site 103A in April 2020 resulted in a relative improvement in sensitivity classification for this site, compared to long-term averages (e.g., from Critical to Endangered). Sensitivity classifications for all other Core tributary monitoring sites in the Ware River watershed during 2020 were consistent with that for the period of record. Conversely, in Core tributaries in the Quabbin Reservoir watershed, concentrations of alkalinity in 2020 were typically greater than seasonal medians for the period of record, oftentimes exceeding seasonal 75th percentile concentrations (Appendix C). This may in part be related to an extended period of below-normal streamflow that impacted the region throughout much of the latter half of 2020 (Section 3.1.2).

The results of applying the ARM sensitivity classifications for alkalinity concentrations to samples collected in the spring of 2020 from Core tributaries within the Quabbin Reservoir Watershed suggests that sensitivity to acid deposition has improved relative to the period of record for several sites (namely, 211, 212, and 213), while falling within previous classifications for the remaining sites (215, 216, BC, and GB). With alkalinity concentrations of <2 mg/L in April 2020, sites 215 and GB fell within the most sensitive category (Critical), as outlined by Godfrey et al. (1996). The remaining sites were deemed less susceptible to the effects of acid deposition based on these criteria.

3.2.7.3 pH

The pH in Core monitoring tributaries ranged from 4.25 to 7.06 in the Quabbin Reservoir watershed and 4.8 to 7.21 in the Ware River watershed in 2020. Median pH values observed in Core monitoring tributaries in the Quabbin Reservoir and Ware River watersheds typically approached or fell below the minimum established standards for Class A inland waters as established by MassDEP (6.5 to 8.3) in 2020, consistent with prior observations throughout the period of record (DWSP, 2020a). The annual precipitation-weighted mean pH of rainfall within the Quabbin Reservoir watershed has increased steadily over the past several decades (NADP, 2021). The established pattern of inter-site variability in pH was preserved in the 2020 record, relative to prior years. Spatial variability in surface water pH across the Quabbin Reservoir and Ware River watersheds may be attributed to variations in watershed characteristics and meteorological drivers.

Seasonal median pH of Core monitoring tributaries was generally greater in 2020 than the median pH for each site for the period of record, aside from pH observed during winter months, which exhibited notably lower seasonal medians at most sites relative to the period of record (Appendix C). The decline in winter median pH at Core tributary monitoring sites may have been driven by a series of rain-on-snow events that primarily occurred during December 2020. This response was most evident in the Ware River tributary records generated from December 28, 2020 sampling – following a two-day window (December 25 through 26, 2020) where nearly two inches of precipitation fell as rain, coupled with a maximum daily air temperature ranging from

42°F to 59°F observed at the Belchertown monitoring station (Section 3.1.1). These large influxes of recent precipitation combined with rapidly generated meltwater from an established snowpack could have been sufficient to drastically shift instream pH levels below that of typical seasonal distributions for each site (Fuss et al., 2015). A series of comparable events occurred (either direct rain-on-snow or melting of recent snowfall) throughout January and February 2020, likely further contributing to the markedly lower winter median pH values observed for Core tributary monitoring sites in 2020.

3.2.8 Special Investigations

3.2.8.1 Forestry Water Quality Monitoring

3.2.8.1.1 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 2020.

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 2020 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, sample and data collection during five events, and associated data analysis. Timber harvest operations began within the EBU watershed on December 18, 2019, and was about two-thirds complete by March 11, 2020. Harvesting was paused from April 1 through June 1, 2020, due to unfavorable (wet) conditions. Work resumed within the EBU watershed after June 1, with the majority of the harvesting completed between August 26 to October 11, 2020. Of the five events sampled by DWSP, four occurred during active harvest operations, while one event (November 2020) represents the first post-harvest event-based sample collection. Monthly samples at EBU and MBD were collected for the entirety of 2020. Event-based sample collection at MBD and EBU for at least four events will be conducted in 2021.

3.2.8.1.2 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 2020. Field review of proposed DWSP timber lots was conducted in the Ware River and Quabbin Reservoir watersheds. Post-harvest monitoring for turbidity occurred at two sites in the Quabbin Reservoir watershed in 2020 (Appendix C). No issues were identified in 2020.

3.2.8.2 Environmental Quality Assessments

3.2.8.2.1 East Branch Swift River Sanitary District

Water quality in surface water in the East Branch Swift River sanitary district in 2020 was generally comparable to that of previous monitoring periods, with some exceptions (Appendix B). Data collected in 2020 were compared to data collected in 2018, 2015, 2014, and 2010. Despite several consecutive months of below normal streamflow observed in 2020, specific conductance was not significantly greater in 2020 than in 2010 at any tributary sites in the East Branch Sanitary District. Notably, turbidity has decreased steadily at 216D (which represents the outlet of Connor Pond) during each monitoring year since 2010 monitoring. Concentrations of total phosphorus (TP) measured in surface water monitoring sites within the East Branch Swift River sanitary district in 2020 were significantly different than those of prior monitoring periods, aside from those corresponding to site 216I-X. The observed changes in TP coincide with the timing of a change in analytical methods (Section 3.2.5.2), thus it is unlikely that this pattern represents increased loading of phosphorus to Quabbin Reservoir, as no other related parameters exhibited ubiquitous changes from prior monitoring periods. No other parameters were affected by changes in analytical methods for the intervals compared.

Surface water samples collected in 2020 throughout the East Branch Swift River sanitary district ultimately revealed no widespread indicators of impairment/degradation of water quality. Monitoring of EQA sites in the Quabbin Reservoir watershed will shift to sites in the Quabbin Northwest sanitary district in 2021. Monitoring of tributaries in the East Branch Swift River sanitary district is anticipated to resume in 2025.

3.2.8.2.2 East Branch Ware River Sanitary District

Water quality in surface water in the East Branch Ware River sanitary district in 2020 was generally comparable to that of previous monitoring periods, with several noteworthy exceptions (Appendix B). Data collected in 2020 were compared to data collected in 2019, 2015, and 2011. Most pronounced, annual median specific conductance was significantly greater in 2020 than 2011 monitoring periods at all surface water quality monitoring locations in the East Branch Ware

River sanitary district. Additionally, annual median concentrations of total phosphorus (TP) observed in all surface water monitoring sites within each sanitary district were significantly different than those of prior monitoring periods. The latter is likely attributable to a change in analytical methods that occurred at the beginning of 2020 (Section 3.2.5.2), rather than an actual disruption of factors controlling the phosphorus cycle within the sanitary district, as no other related parameters exhibited widespread significant changes from prior monitoring periods. TP concentrations in surface water in the East Branch Ware River sanitary district exhibited typical seasonal variations.

Surface water samples collected in 2020 throughout the East Branch Ware River sanitary district ultimately revealed no widespread indicators of impairment/degradation of water quality, aside from increasing conductivity at select locations. Monitoring of EQA sites in the Ware River watershed will shift to sites within the Coldbrook and Longmeadow sanitary district in 2021. Monitoring of EQA sites in the East Branch Ware River sanitary district will resume in 2025.

3.2.8.3 Water Quality Database

Over 40,000 individual historical data records (spanning 2007-2017) and over 35,000 individual records from 2020 were imported into the water quality Access database following quality assurance and quality control (QA/QC) procedures in 2020. 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. Digitized historical phytoplankton density data were assessed for QA/QC and imported to the Access database via import-scripts generated in R. Additional R-scripts were revised in 2020 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 coupled with discharge data and converted to event loads for import into the Access database. In 2021, the Microsoft Access database will be migrated to SQL Server. The SQL database allows for cloud-based storage of DWSP records. Data generated from Quabbin and Ware River watershed monitoring in 2020 and prior years are available upon request. Work related to DWSP data management and integration of historical records (prior to 2010) remains ongoing.

3.3 Reservoir Monitoring

Water quality of the Quabbin Reservoir in 2020 continued to meet the stringent source water quality criteria stipulated under the SWTR and associated filtration avoidance waiver. The following sections provide a detailed summary of DWSP monitoring efforts conducted in 2020 for the purpose of evaluating the physical, chemical, and biological dynamics of the Quabbin Reservoir.

Depth profiles of physiochemical parameters reveal general patterns in water column characteristics such as the timing of seasonal turnover and stratification, the relative position of the epilimnion, metalimnion, and hypolimnion, the general degree of mixing within the water column, and the timing and location of relative increases in primary productivity. Several complete depth profiles of various physiochemical water quality parameters (temperature, pH, dissolved oxygen, specific conductance, pH, chlorophyll *a*, and phycocyanin) from each site were selected to demonstrate changes in seasonal conditions, and show periods of peak primary productivity (**Error! Reference source not found.**). Phycocyanin was not collected July 6 to September 3, 2020 due to sensor malfunction and extended delay in repairs as a result of COVID-19. Seasonal descriptive statistics were calculated for each site to summarize the variation of conditions throughout 2020, relative to prior monitoring conditions (Table 22, Appendices).

3.3.1 Water Temperature

Water column temperature profiles indicate the timing of seasonal changes in stratification throughout the Quabbin Reservoir (Figure 28). Shifts in the timing and extent of the various stages of stratification may have profound implications on water quality, ecology, and primary productivity. The water column was fully mixed through the winter months, reaching a minimum temperature of 2.04 °C at site 202 (Table 22). The reservoir did not fully freeze over in 2020. Stratification began building in May as the epilimnion warmed and was achieved (≥1 °C change per 1-m) by June 1, 2020. Surface water temperatures reached a maximum of 26.7 °C at site 202 in the summer, then began decreasing in September. Fall turnover began in November, as indicated by the deepening epilimnion and diminishing metalimnion. The water column was fully mixed by winter sampling performed on December 16, 2020. Consistent with previous years, average (and median) spring, summer, and fall temperatures for the full water column were greater at 206 than 202, and greatest at Den Hill (Appendices), with average temperatures generally increasing at shallower depths. The timing of reservoir stratification and mixing during 2020 was consistent with previous years.

3.3.2 Chlorophyll *a*

Chlorophyll *a* may be used to estimate the overall biomass of the phytoplankton community. DWSP staff reference *in-situ* measurements of chlorophyll *a* (in addition to concentrations of dissolved oxygen) to determine the location in the water column where samples are collected for phytoplankton enumeration on a given date. On average, chlorophyll *a* concentrations in the reservoir are low, typical for low-productivity oligotrophic systems in New England. The greatest concentration of chlorophyll *a* observed in Quabbin Reservoir in 2020 was measured at site 202, during the spring aggregation of the chrysophyte *Dinobryon* (Section 3.3.9). The maximum chlorophyll *a* reading at site 202 was 6.29 µg/L (May 7, 2020), much lower than the 2019 maximum of 24.34 µg/L (DWSP, 2020a) at site 202 that occurred in August, in association with a *Chrysosphaerella* aggregation. Similar to previous years, average chlorophyll *a* levels were lowest at site 202, and highest at Den Hill (Table 22, Appendices), potentially due to the different nutrient concentrations across sites.

3.3.3 Dissolved Oxygen

Concentrations of dissolved oxygen in Quabbin Reservoir followed expected seasonal patterns in 2020. Changes in concentrations of dissolved oxygen in Quabbin Reservoir generally coincided with changes in water temperatures, followed stratification stages, and/or rose with relative increases in phytoplankton abundance (Figure 28). Average dissolved oxygen was highest in the spring, likely explained by the cold temperatures during this season. Concentrations of dissolved oxygen in surface water decreased with stratification, as the warmer water in the epilimnion became unable to hold as much oxygen as colder deep water. Once stratified, dissolved oxygen levels below the thermocline became elevated alongside an increase in phytoplankton activity in July at both sampling sites 202 and 206, and persisted just below the epilimmion until mid-September (Figure 28 - July profile).

Following typical seasonal patterns for Quabbin Reservoir, dissolved oxygen depletion was most pronounced during the late stages of stratification, with dissolved oxygen concentrations declining with depth. This was particularly distinct for water below the thermocline that remains isolated from atmospheric influence, and where rates of decomposition, a process that consumes oxygen, exceed photosynthesis. The minimum dissolved oxygen concentration in 2020 was 2.51 mg/L, observed at 18 m in the fall at Den Hill (Appendices). Following fall turnover in late November to early December, oxygen was able to circulate through the water column again, reaching an average of 11.2 mg/L throughout the water column on December 16, 2020 at site 202. The mean dissolved oxygen concentrations in 2020 remained well above 6 mg/L at all sites (Table 22, Appendices), sustaining concentrations required to support cold water aquatic species (MassDEP 314 CMR 314 4.05(3)(a)1).

Table 22: Descriptive statistics (minimum, median, average, and maximum) for physical water quality parameters monitored in Quabbin Reservoir during 2020 at DWSP monitoring site 202. Statistics provided include measurements conducted in conjunction with monthly Quabbin Reservoir water quality monitoring and routine phytoplankton sampling (January through December 2020). Sample dates without corresponding complete water column profiles (n=2) were excluded from calculations to avoid introducing bias inherent with incomplete water column profiles. Phycocyanin was not recorded from July 6 to September 3, 2020. Negative phycocyanin concentrations (n=3) were excluded from calculations for descriptive statistics, as they likely represent sensor interference. Dissolved oxygen concentrations measured on October 14, 2020 were excluded due to documented sensor malfunction. Erroneous optical datapoints collected 1-m above the reservoir bottom on June 23, July 29, September 9, and December 16 2020 were also excluded from calculations, as these measurements likely reflect artificial introduction of turbidity during instrument deployment, and thus do not accurately reflect undisturbed water column conditions.

Analyte	Season	Count	Min	Med	Avg	Max
Water Temperature (°C)	Winter	121	2.04	4.29	4.81	7.83
Water Temperature (°C)	Spring	177	2.62	5.66	5.71	8.94
Water Temperature (°C)	Summer	422	7.23	10.2	13.2	26.7
Water Temperature (°C)	Fall	291	8.23	12.2	13.5	22.9
Chlorophyll *a* (µg/L)	Winter	121	0.85	2.44	2.34	4.43
Chlorophyll *a* (µg/L)	Spring	177	0.55	3.32	3.09	6.29
Chlorophyll *a* (µg/L)	Summer	422	0.24	1.33	1.45	4.31
Chlorophyll *a* (µg/L)	Fall	291	0.54	1.38	1.39	3.01
Phycocyanin (µg/L)	Winter	121	1.04	1.54	1.58	3.18
Phycocyanin (µg/L)	Spring	177	0.88	1.60	1.62	3.78
Phycocyanin (µg/L)	Summer	166	0.80	1.24	1.26	4.01
Phycocyanin (µg/L)	Fall	291	0.37	1.43	1.46	5.21
Dissolved Oxygen (mg/L)	Winter	121	11.2	12.6	12.5	13.9
Dissolved Oxygen (mg/L)	Spring	177	13.4	13.7	13.8	14.0
Dissolved Oxygen (mg/L)	Summer	422	8.28	10.8	10.7	12.9
Dissolved Oxygen (mg/L)	Fall	249	6.39	9.31	9.29	11.8
Oxygen Saturation (% Sat.)	Winter	121	95.3	99.8	99.36	104
Oxygen Saturation (% Sat.)	Spring	177	104	112	112	119
Oxygen Saturation (% Sat.)	Summer	422	75.4	105	103	121
Oxygen Saturation (% Sat.)	Fall	249	56.4	95.5	91.0	123
pH	Winter	121	6.32	6.52	6.63	7.54
pH	Spring	177	6.27	6.61	6.68	7.57
pH	Summer	422	5.47	6.42	6.41	7.26
pH	Fall	291	5.35	6.3	6.36	7.76
Specific Conductance (µS/cm)	Winter	121	44.9	47.7	46.84	47.9
Specific Conductance (µS/cm)	Spring	177	44.5	46.2	46.16	47.6
Specific Conductance (µS/cm)	Summer	422	42.2	47	46.82	49.3
Specific Conductance (µS/cm)	Fall	291	46.2	47.1	47.24	48.3

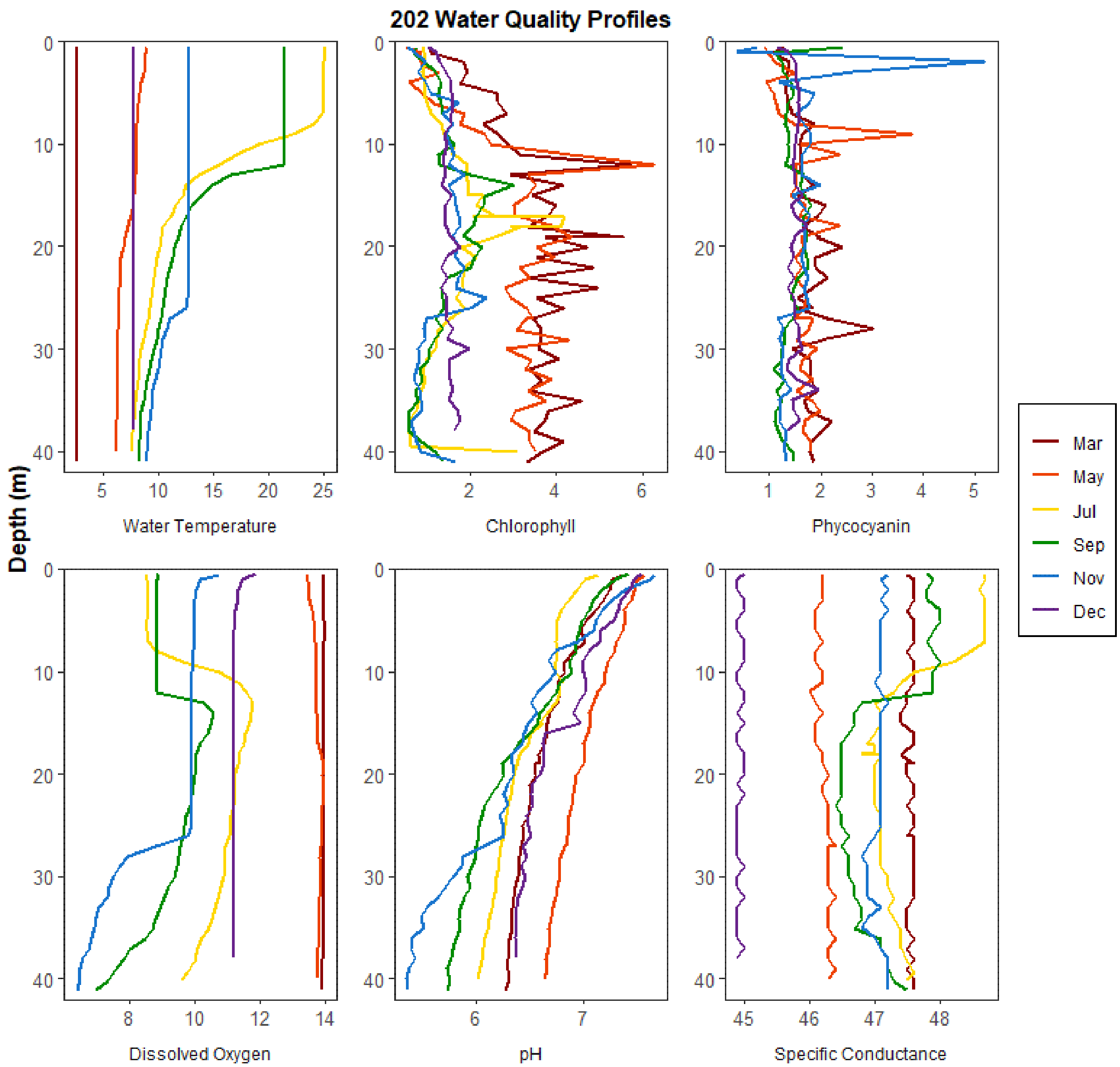

Figure 28: Select depth profiles of temperature (°C), chlorophyll *a* (µg/L), phycocyanin (µg/L), dissolved oxygen (mg/L), pH, and specific conductance (µS/cm) collected by DWSP at Quabbin Reservoir monitoring site 202 in 2020. (See Appendix C for depth profiles on select dates for DWSP monitoring sites 206 and Den Hill). March 2020 profile corresponds to spring isothermy, which existed from March through April. It also demonstrates the spring proliferation of *Dinobryon* throughout the water column (chlorophyll a profile). The May 2020 profile corresponds to the beginning of stratification of Quabbin Reservoir and continued elevated chlorophyll *a* concentrations in association with the persisting *Dinobryon* growth. The July profile signifies full thermal stratification, and lower chlorophyll *a* concentrations. The September profile shows continued stratification through the fall months despite cooling surface water temperatures, and the November profile signifies the beginning of fall turnover. The December profile indicates a return to isothermy.

3.3.4 Alkalinity and pH

The dynamics of pH in Quabbin Reservoir are largely governed by the exchange of inorganic carbon between the atmosphere and water (carbon dioxide-bicarbonate-carbonate buffering). The pH of Quabbin Reservoir generally decreases with depth and may vary with changes in photosynthesis and respiration, and contributions from various weather events (e.g., freshwater inputs). Generally, pH within Quabbin Reservoir is unremarkable, ranging from 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 5.35 to 7.76 in 2020 (**Error! Reference source not found.**).

Overall, alkalinity in Quabbin Reservoir remained low (<5 mg/L as $CaCO_3$) throughout 2020 and exhibited little variability with depth, changes in stratification, or seasonality (Appendices). Alkalinity was generally greatest at Den Hill in 2020, relative to other routine monitoring sites in Quabbin Reservoir. This pattern was consistent with previous years during which alkalinity concentrations were reported via titration to a pH 4.2 endpoint (Standard Methods 2320B). Overall, alkalinity measured in Quabbin Reservoir was higher in 2020 than historical medians, particularly in the spring and summer, but remained within the established range of values for each site. Alkalinity concentrations corresponding to samples collected from the Quabbin Reservoir were historically reported by titration to pH of 4.5 endpoint via Standard Method 2320B (DWSP, 2018c). Additionally, the pH (annual precipitation-weighted mean) of rainfall within the Quabbin Reservoir watershed has been increasing steadily for decades (NADP, 2021). Temporal changes in alkalinity concentrations in lakes and reservoirs in New England may be attributed to interactions of multiple factors (e.g., natural geogenic variability, urbanization and associated chemical weathering of the built environment, acid rain inputs, or changes in or introduced during sample collection and analysis).

3.3.5 Specific Conductance and Dissolved Salts

Specific conductance measured in the Quabbin Reservoir has historically been quite low, relative to other water bodies in the northeastern United States, which may exceed 1,000 µS/cm in highly urbanized watersheds. The relatively low observed specific conductance in Quabbin Reservoir waters 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 but does demonstrate a slight stratification. During these periods, specific conductance is greatest at the surface, declining with depth. Specific conductance measured in Quabbin Reservoir waters was within the historical ranges during 2020, ranging from a minimum of 42.2 µS/cm at site 202 in the summer, to an annual maximum of 53 µS/cm at Den Hill in the summer (Appendices).

2020 marked the first year that concentrations of sodium and chloride were routinely measured in Quabbin Reservoir. Sodium concentrations ranged from a minimum of 5.13 mg/L at the surface of site 202, to a maximum of 6.16 at the surface of Den Hill (Table 23, Appendices). Chloride concentrations ranged from a minimum of 7.74 at site 202 to a maximum of 9.04 mg/L at Den

Hill. Sodium and chloride concentrations varied little with season, or with depth in the reservoir. Similar to other analytes, concentrations of both sodium and chloride were typically highest at Den Hill (Appendices). Neither ORS guidelines for Na (20 mg/L) or the SMCL for Cl (250 mg/L) were exceeded in Quabbin Reservoir in 2020.

Table 23: Descriptive statistics (minimum, median, average, and maximum) for sodium and chloride monitored in Quabbin Reservoir, DWSP monitoring site 202, for 2020 monitoring period.

Analyte	Season	Count	Min	Med	Avg	Max
Na (mg/L)	Surface	5	5.13	5.52	5.49	5.79
	Mid	5	5.48	5.55	5.58	5.74
	Deep	5	5.61	5.75	5.77	6.00
Cl (mg/L)	Surface	5	7.74	7.93	7.97	8.31
	Mid	5	7.83	7.91	7.97	8.26
	Deep	5	7.74	7.88	7.97	8.37

3.3.6 Turbidity

Turbidity levels measured in the Quabbin Reservoir were low and relatively stable throughout the year, reflective of the low productivity of the reservoir and coincident with drought conditions observed through parts of 2020 (Section 3.1.1). Contributions from major tributaries to the Quabbin Reservoir during high streamflow, wind-driven and hydrodynamic currents, and shoreline erosion may contribute to instances of elevated turbidity measured in Quabbin Reservoir. The highest turbidity levels were observed in the spring across all sites and depths (Table 24, Appendices). This may have been a result of above average streamflow events that occurred in April and May, along with a spring proliferation of phytoplankton throughout the water column at all three core monitoring sites (Appendices). The maximum turbidity observed in 2020 (0.8 NTU) was measured on May 11, 2020 at 202. An extended period of drought and below average streamflow during the summer and fall of 2020 may account for the relatively low variability observed in turbidity levels of Quabbin Reservoir in 2020 (Section 3.1.2). Additionally, ice cover may minimize wind-driven mixing and subsequent effects on in-reservoir turbidity. Turbidity levels in Quabbin Reservoir ranged from 0.18 to 0.8 NTU during 2020 (Table 24, Appendices), falling within the historical range of turbidity observed at DWSP monitoring sites. Turbidity levels in Quabbin Reservoir remained below 1 NTU for the entirety of 2020.

Table 24: Descriptive statistics (minimum, median, average, and maximum) for turbidity monitored in Quabbin Reservoir, DWSP monitoring site 202, for 2020 monitoring period. Detection limits were <0.05 NTU for turbidity.

Turbidity (NTU)					
Depth	Count	Min	Med	Avg	Max
Surface	8	0.18	0.25	0.26	0.39
Mid	8	0.22	0.26	0.30	0.55
Deep	8	0.23	0.30	0.39	0.80

3.3.7 Secchi Disk Depth/Transparency

Water in the Quabbin Reservoir continued to demonstrate exceptional clarity in 2020, with a mean Secchi depth of 10.2 m across all sites. Secchi disk transparency in Quabbin Reservoir during 2020 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 5.6 m at Den Hill site on May 11, 2020, to a maximum of 13.8 m at site 206 on September 3, 2020 (Figure 29). Transparency at Den Hill monitoring site was 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 29). 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 spring months in 2020 may have been influenced by elevated concentrations of the chrysophyte, *Dinobryon* (Section 3.3.9). Overall, Secchi depths remained high through the summer, as phytoplankton densities remained low, and drought conditions resulted in lower than average riverine inputs. Following this period of drought, large rain events and higher than average stream inputs in November and December may have resulted in the lower Secchi readings observed during those months.

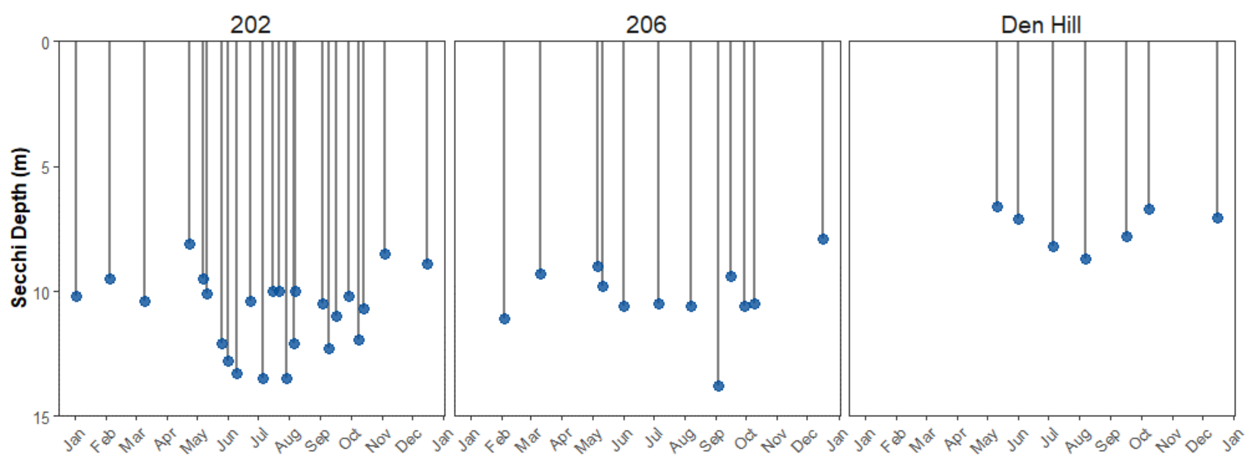

Figure 29: Secchi disk transparencies measured in 2020 in Quabbin Reservoir at DWSP monitoring sites 202 (maximum depth 42 m), 206 (maximum depth 28 m), and Den Hill (maximum depth 19 m).

3.3.8 Nutrient Dynamics

Patterns of nutrient distributions in Quabbin Reservoir in 2020 were generally consistent with those documented previously by Worden (2000) and historical ranges observed in Quabbin Reservoir. Prominent seasonal, spatial, and vertical variations were present, likely due to the interactions of demand by phytoplankton in the epilimnion and metalimnion, the decomposition of organic matter in the hypolimnion, and the timing and extent of terrestrial-derived sources of nutrients delivered via riverine loading to the Quabbin Reservoir. With only a few exceptions of large streamflow events, 2020 experienced abnormally dry to drought conditions for six consecutive months, resulting in lower than typical inflows in to the Quabbin Reservoir (Section 3.1.2).

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

Concentrations of nitrate (NO_3-N) and ammonia (NH_3-N) ranged from <0.005 to 0.029 mg/L and from <0.005 to 0.022 mg/L, respectively (Appendices), in Quabbin Reservoir. Overall concentrations of NO_3-N and NH_3-N followed the vertical and temporal variation presented by historical medians for each site. Concentrations of NO_3-N and NH_3-N were generally elevated in the hypolimnion and at Den Hill relative to other sites. NO_3-N and NH_3-N were below detection limits (<0.005 mg/L) in all samples collected in the spring and summer, with two exceptions of low concentrations in the hypolimnion at sites 206 and Den Hill in the summer (Appendices). NO_3-N and NH_3-N are typically low in the spring. As is typically observed, NO_3-N and NH_3-N levels rose slightly in the hypolimnion in the fall at all sites, likely coincident with decomposition. Monthly sampling performed through the fall revealed slight variation of concentrations of NO_3-N and NH_3-N, however all samples remained within the historical range of values. Following fall turnover in the reservoir, NO_3-N and NH_3-N concentrations increased, homogenizing across depths, for each site. Winter concentrations of NO_3-N were consistent with historical medians, while NH_3-N winter concentrations were higher than the historical medians at sites 202 and 206.

Methods for the analysis of Total Kjeldahl Nitrogen (TKN) in samples collected from Quabbin Reservoir were modified in 2020. Prior to January 1, 2020, TKN concentration data for Quabbin Reservoir was derived via EPA Method 351.2 (O'Dell, 1993a). Beginning in May 2020, analysis shifted to Valderrama (1981) to facilitate monthly monitoring frequencies of N-species and TP in Core sites. Results were reported as total nitrogen (TN) in 2020. TKN concentrations for 2020 were derived by subtracting corresponding concentrations of NO_3-N and NO_2-N from TN data. Concentrations below laboratory detection limits were substituted with one-half the detection limit. NO_2-N has been measured previously (2010), in samples collected from Core sites in the Quabbin Reservoir and was below laboratory detection limits in all samples (n=18 total measurements). Thus, for the purposes of deriving estimates of TKN concentrations from TN data, NO_2-N was assumed to remain below laboratory detection limits (<0.005 mg/L) in all samples collected in 2020. DWSP did not modify sample collection methods. The detection limits for TN via Valderrama (1981) were 0.0034 mg/L. The monitoring frequency of TKN in Quabbin Reservoir Core sites also changed from quarterly in 2019 and preceding years to monthly in 2020.

Concentrations of TKN in Quabbin Reservoir Core sites ranged from 0.096 to 0.226 mg/L in 2020 (Table 25). Concentrations of TKN in Quabbin Reservoir exhibited little temporal variability in 2020 and were typically slightly elevated in samples collected at Den Hill, relative to 202 and 206, similar to spatial patterns exhibited by other nutrients. Seasonal concentrations of TKN in Quabbin Reservoir in spring of 2020 were below historical seasonal median concentrations at all depths. Concentrations of TKN in samples collected during the remainder of the calendar year were comparable to respective seasonal medians, with the exception a high (relative to 25th to

75th percentile concentations) concentration observed in the hypolimnion at Den Hill in August (0.231 mg/L), and in the metalimnion at 206 in June (0.182 mg/L). A proportion of the variability in concentrations of TKN observed within seasons for each site, when compared to the historical records, may be attributed to assumptions made during calculations of TKN concentrations for 2020 data (e.g., substituting one-half the detection limit of NO_2-N), or related to differences in sensitivity of different laboratory methods (e.g., the detection limits for TN via Valderrama (1981) were lower than that of EPA 351.2 used previously). Additional variability within seasonal TKN concentrations could also be related to the increased monitoring frequency of this nutrient in 2020, as demonstrated by patterns presented by other N-species, TP, and Si. Monitoring of TKN will continue monthly during calendar year 2021. Additional years of monthly data may better reveal key drivers in TKN dynamics in Quabbin Reservoir.

Table 25: 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 2020 monitoring period. Detection limits were <0.005 mg/L for NO_3-N and NH_3-N. TP was measured via Valderrama (1981) with a detection limit of 0.0034 mg/L, a different method from previous years. TKN concentrations for 2020 were calculated by subtracting half the detection limit of NO_2-N (0.0025 mg/L) plus the reported NO_3-N concentration from measured concentrations of TN (detection limit 0.0226 mg/L). NO_2-N were analyzed previously in Quabbin Reservoir (DWSP, 2011) and were below laboratory detection limits in all samples. 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	8	<0.005	<0.005	0.004	0.009
	Mid	8	<0.005	<0.005	0.004	0.009
	Deep	8	<0.005	0.006	0.011	0.029
NH_3-N (mg/L)	Surface	8	<0.005	<0.005	0.003	0.008
	Mid	8	<0.005	<0.005	0.004	0.009
	Deep	8	<0.005	0.006	0.009	0.022
TKN (mg/L)	Surface	9	0.105	0.134	0.130	0.144
	Mid	9	0.112	0.134	0.132	0.144
	Deep	9	0.100	0.134	0.130	0.163
TP (mg/L)	Surface	9	<0.0034	0.011	0.010	0.0165
	Mid	9	<0.0034	0.0106	0.0086	0.0137
	Deep	9	0.004	0.0129	0.011	0.0166
Ca (mg/L)	Surface	3	2.00	2.06	2.13	2.33
	Mid	5	1.96	2.04	2.10	2.37
	Deep	3	2.08	2.16	2.17	2.26
Si (mg/L)	Surface	8	1.66	1.8	1.83	2.06
	Mid	8	1.61	1.83	1.87	2.13
	Deep	8	2.01	2.22	2.21	2.42

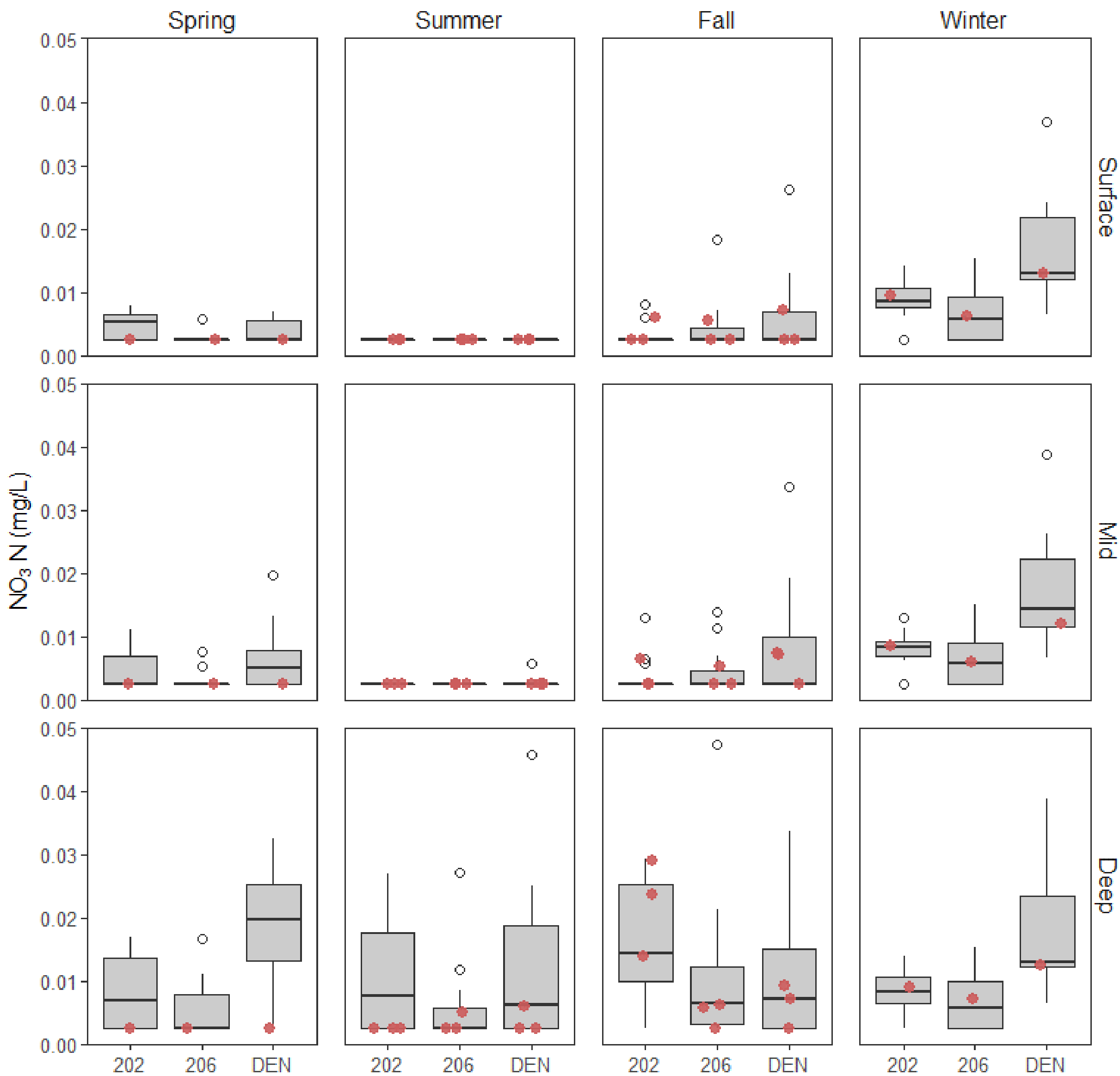

Figure 30: Boxplots depicting the seasonal and vertical distributions of NO_3-N observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected in 2020 are signified by the red points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. The scale has been adjusted to best display 2020 variation, and thus excludes the following outlier: 0.0757 mg/L at Den Hill deep from 2011.

3.3.8.2 Total Phosphorus

Total Phosphorus (TP) was measured in samples collected from the Quabbin Reservoir via a different method than that used previous for the 2020 sampling season. Concentrations of TP in samples collect from Core sites in the Quabbin Reservoir were derived via EPA Method 365.1 (O'Dell, 1993b) until December 31, 2019. Analysis was performed via Valderrama (1981) beginning in May 2020 to facilitate monthly monitoring frequencies of TP in Core sites. Uncertainty associated with TP concentration data for 2020 may be attributed to either the sensitivity of different analytical methods, variability revealed by increased frequencies, or a combination of these two factors. DWSP will perform duplicate analyses for TP (via Valderrama, 1981 and EPA 365.1) in routine samples collected from the Quabbin Reservoir in 2021 to isolate the impacts that modifications to analytical methods and/or sampling frequencies may have had on resultant concentration data and long-term monitoring.

Concentrations of TP in Quabbin Reservoir derived during 2020 via Valderrama (1981) appear to be higher than historical seasonal concentrations for each site. However, an increase in TP concentrations was not observed for sites that analytical methods were not altered. Concentrations of TP were derived via EPA 365.1 for the entirety of 2020 at Shaft 1 in the Wachusett Reservoir watershed. As Shaft 1 represents the outlet of the Quabbin Aqueduct to the Wachusett Reservoir, and was unaffected by this change in methods (DWSP, 2021), it may act as a baseline for TP concentrations during this time. Concentrations of TP observed at Shaft 1 in 2020 fell within established seasonal ranges (DWSP, 2021).

Despite this, vertical and spatial patterns in TP concentrations observed in Quabbin Reservoir remained consistent with those previously observed. Measured concentrations of TP in 2020 ranged from <0.0035 to 0.0270 mg/L in 2020 (Table 25). Consistent with previous intra-annual variation, TP was slightly elevated in the spring compared to other seasons and was higher at Den Hill compared to the other sampling sites (Appendices). In contrast to previous years, there was a mid-summer increase in TP across all sites. Following the initial spring and heightened August concentrations, TP decreased through the following months, particularly in the euphotic zones. The lowest recorded TP concentrations occurred at all sites during the fall season. TP increased following fall turnover but did not return to the relatively higher levels measured during the spring. TP concentrations in all 2020 samples remained well below the 10 µg/L threshold for classification as an oligotrophic water body (Carlson, 1977).

Depletion of nitrogen species and TP in the epilimnion during summer and fall may be attributed to seasonal uptake by phytoplankton (Section 3.3.9). NH_3-N and TP depletion may serve to limit phytoplankton growth in Quabbin Reservoir, as TP may act as the limiting nutrient in lakes in temperate climates (Worden, 2000). Elevated concentrations of nutrients observed in the hypolimnion likely reflects natural microbial decomposition of organic matter and sedimentation from the water column.

3.3.8.3 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 exhibited a limited range from a minimum of 1.66 to a maximum of 2.37 mg/L in 2020 (Appendices). Consistent with historical trends, calcium concentrations were slightly higher in winter across all sites (Appendices). Additional sampling performed in the surface and deep layers of the reservoir revealed little variation in calcium concentrations across depths. Calcium concentrations observed in 2020 in Quabbin Reservoir continue to demonstrate a low risk of zebra mussel colonization.

Silica is utilized by phytoplankton, particularly diatoms and chrysophytes (Reynolds, 2006). In contrast to quarterly silica concentrations in Quabbin Reservoir during 2019 that exceeded seasonal median concentrations, observed ranges of monthly silica concentrations in 2020 approached historical medians, and generally fell within seasonal interquartile ranges for each site/collection depth (Figure 31**Error! Reference source not found.**). The change in sampling frequency may have contributed to this pattern. Silica monitoring in Quabbin Reservoir will continue at a monthly frequency in 2021. Concentrations of dissolved silica in Quabbin Reservoir exhibited spatial and temporal gradients consistent with seasonal productivity and subsequent riverine loading of dissolved silica to the Quabbin Reservoir. Dissolved silica concentrations were greatest at Den Hill, similar to patterns observed in turbidity and UV_{254} across monitoring sites and is likely the result of the proximity of Den Hill to the confluence of the East Branch Swift River with the Quabbin Reservoir. Silica concentrations in the Quabbin Reservoir were generally lower in the epilimnion and metalimnion during the summer and fall, consistent with previous results and likely attributed to uptake by phytoplankton (e.g., diatoms) and lack of substantial riverine inputs during an extended period of below-normal streamflow observed during the summer and fall of 2020 (Section 3.1.2).

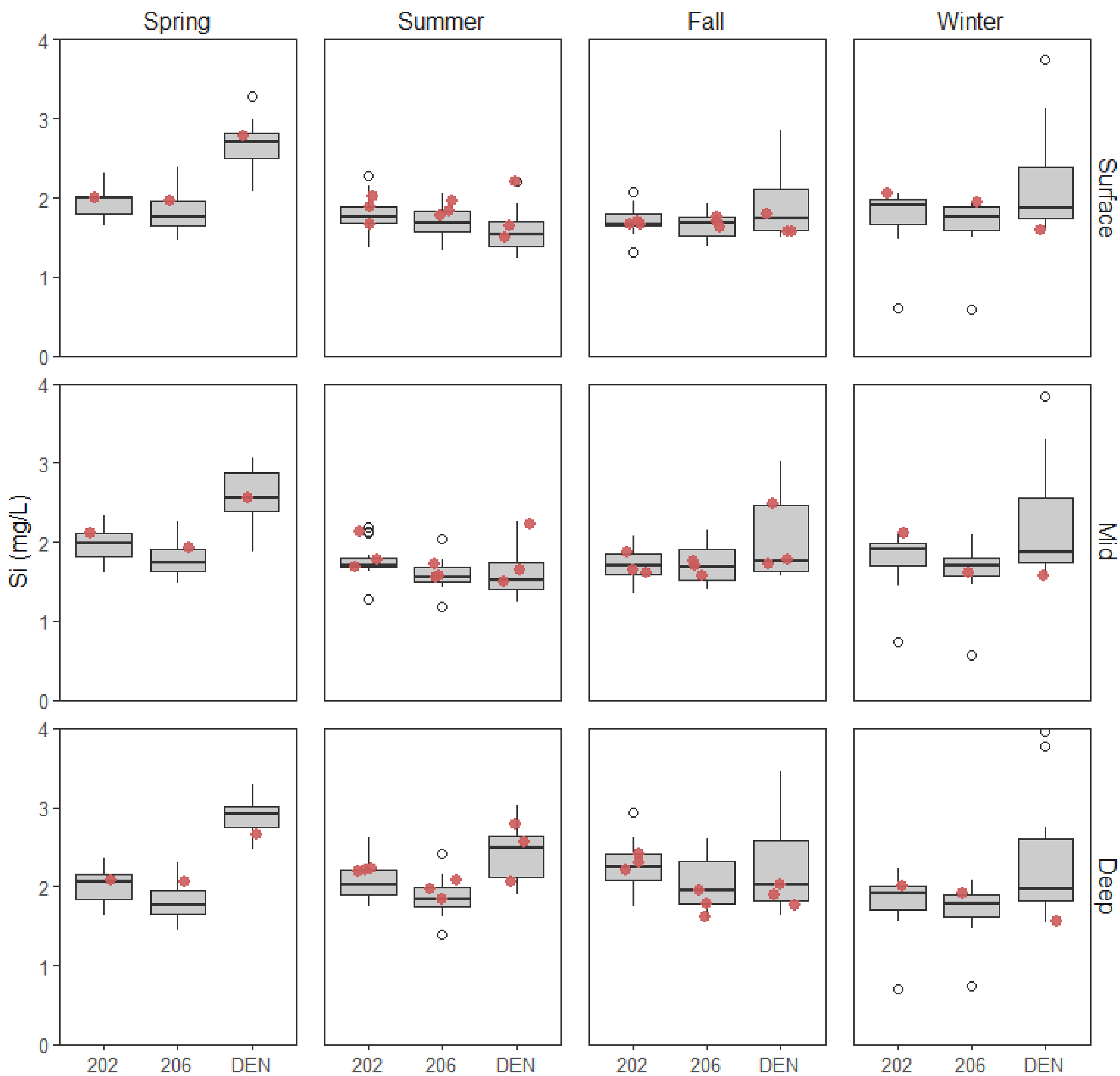

Figure 31: Boxplots depicting the seasonal and vertical distributions of silica observed in Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected in 2020 are signified by the red points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

3.3.8.4 UV_{254} and Total Organic Carbon

UV_{254} 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). UV_{254} was greatest at Den Hill and displayed little seasonal variation in 2020 samples (Appendices). 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 below average streamflow conditions during the summer and fall sampling events, resulting in a lower influx of organic matter. UV_{254} in Quabbin Reservoir ranged from 0.021 to 0.029 ABU/cm at sampling site 202 (Appendices). Unlike the 2019 UV_{254} readings that exceeded seasonal medians for the period of record, overall UV_{254} concentrations remained closer to the historical mean in 2020.

Routine monitoring for total organic carbon (TOC) in Quabbin Reservoir began in 2020. TOC concentrations ranged from a minimum of 1.6 mg/L from 202 deep to a maximum of 3.01 mg/L at Den Hill surface (Appendices). Overall, TOC exhibited little variability with depth or changes in stratification. Consistent with UV_{254} and other parameters, TOC concentrations were highest at Den Hill, compared to 202 and 206 (Appendices). TOC concentrations in the Quabbin Reservoir in 2020 were lower than global mean concentrations for deep lakes (3.463 mg/L), and north temperate lakes (5.809 mg/L; Chen *et al.*, 2015).

Table 26: Descriptive statistics (minimum, median, average, and maximum) for UV_{254} monitored in Quabbin Reservoir, DWSP monitoring site 202, for 2020 monitoring period. Detect limits were <0.0001 ABU/cm for UV_{254}.

UV_{254} (ABU/cm)					
Depth	**Count**	**Min**	**Med**	**Avg**	**Max**
Surface	8	0.0216	0.0234	0.0237	0.0267
Mid	8	0.0215	0.0267	0.0255	0.0285
Deep	8	0.0216	0.0256	0.0253	0.0269

Table 27: Descriptive statistics (minimum, median, average, and maximum) for total organic carbon monitored in Quabbin Reservoir, DWSP monitoring site 202, for 2020 monitoring period.

Total Organic Carbon (mg/L)					
Depth	**Count**	**Min**	**Med**	**Avg**	**Max**
Surface	8	1.89	2.10	2.12	2.39
Mid	8	1.74	2.09	2.14	2.79
Deep	8	1.60	2.02	2.00	2.36

3.3.9 Phytoplankton

Samples for phytoplankton enumeration were collected from Quabbin Reservoir core monitoring sites 202 and 206 on 21 and 10 days in 2020, respectively.

Table 28. Phytoplankton survey dates in 2020 and explanations for deviations from the standard sampling plan.

Sampling Site	Season	Sampling Date	Frequency Summary	Reason for Deviation
202	Winter	1/2/2020 2/4/2020	Monthly	n/a
	Spring	3/10/2020 3/24/2020 4/23/2020 5/7/2020 5/26/2020	Biweekly, apart from COVID-19 interuption	Increased to weekly in response to elevated densities of Dinobryon observed on March 10, 2020. COVID-19 state of emergency prevented sampling March 24 to April 23, 2020.
	Summer	6/9/2020 6/23/2020 7/6/2020 7/22/2020	Biweekly	n/a
		7/29/2020 8/6/2020 8/12/2020 8/19/2020 8/26/2020	Weekly	Increased to weekly frequency, following July 29, 2020 results in response to elevated densities of *Chrysosphaerella.*
	Fall	9/3/2020 9/9/2020 9/16/2020	Weekly	Maintained at weekly to monitor taxa of concern and perform special investigations.
		9/29/2020 10/14/2020	Biweekly	Sampling ended October 14, 2020 due to staffing constraints.
206	Winter	1/2/2020 2/4/2020	Monthly	n/a
	Spring	3/10/2020 5/7/2020	Monthly	COVID-19 state of emergency prevented sampling March 24 to April 23, 2020.
	Summer	6/1/2020	Monthly	n/a
		7/6/2020 7/15/2020	Weekly	Increased to weekly frequency following July 6, 2020 in response to elevated densities of *Chrysosphaerella*.
		8/6/2020	Monthly	n/a
	Fall	9/3/2020 9/29/2020	Monthly	Sampling ended September 29, 2020 due to staffing constraints.

Samples were collected from two to three depths: 1) from 1 to 5 m corresponding with the epilimnion, 2) at the chlorophyll *a* maximum reading with simultaneous high dissolved oxygen, typically within the metalimnion and, when necessary, 3) near intake(s) to closely monitor phytoplankton community composition and potential taste and odor impacts (DWSP, 2020a). This sampling was performed to maintain a regular record of phytoplankton densities that directly influence the quality of water flowing into the Chicopee Valley Aqueduct (CVA) Intake (site 202) or into the Quabbin Aqueduct, toward Wachusett Reservoir (site 206). Samples were periodically collected at additional depths based on concentrations of chlorophyll *a*, phycocyanin and dissolved oxygen observed via in situ readings.

Phytoplankton densities at both Quabbin Reservoir core monitoring sites in 2020 followed the seasonal patterns that have been observed in the phytoplankton communities present in the Quabbin Reservoir for the past ten years (Figure 32). Overall, elevated spring densities of phytoplankton began slightly earlier and were elevated, relative to the historical averages for each site. Total densities were generally below historical averages in July through October, likely coincident with lower than average streamflow (and thus, subsequent N and P delivery to the reservoir) during this time (Section 3.1.2).

Both sampling sites exhibited similar overall trends to each other in total phytoplankton densities. At both sampling sites, total phytoplankton densities were moderate (around 300 ASU/mL) in the winter months, then rose to a maximum of 1,055 ASU/mL at 202, and 777 ASU/mL at 206 on March 10, 2020 (Figure 33, Figure 34). Total phytoplankton densities decreased at both sites following stratification of the water column in May, to below 250 ASU/mL, and remained low for the remainder of the sampling period. Densities at different sampling depths also exhibited similar trends across sites. Epilimnion samples typically had lower densities than meta- or hypolimnion samples. Phytoplankton densities in samples collected from 18 to 20 m at site 202 demonstrated similar seasonal shifts in phytoplankton community composition to the other depths sampled for site 202.

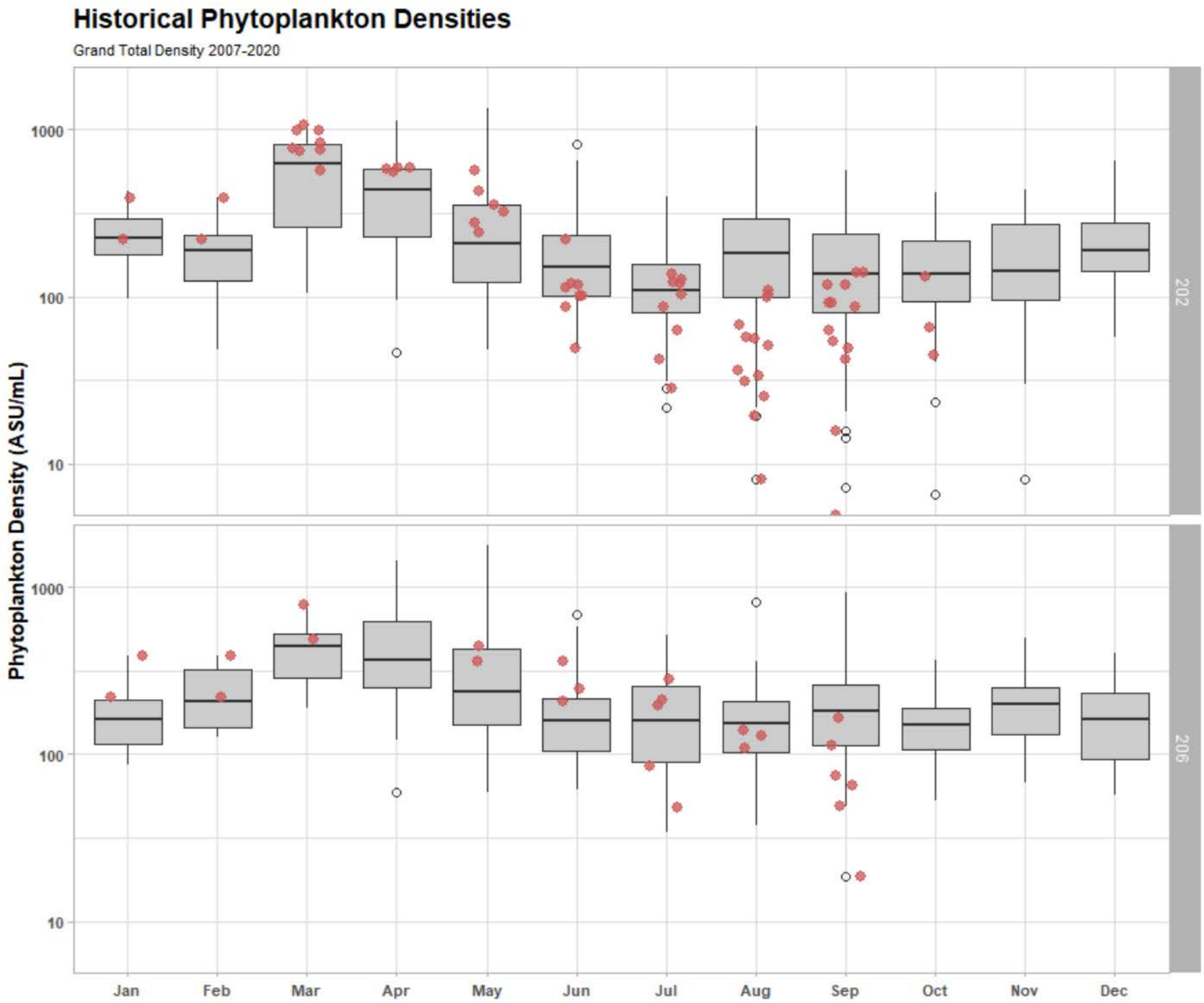

Figure 32: Boxplot depicting the monthly variation of grand total phytoplankton in Quabbin Reservoir DWSP monitoring sites 202 and 206. Note: y-axis is plotted as log-scale. Results corresponding to samples collected in 2020 are signified by the red points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

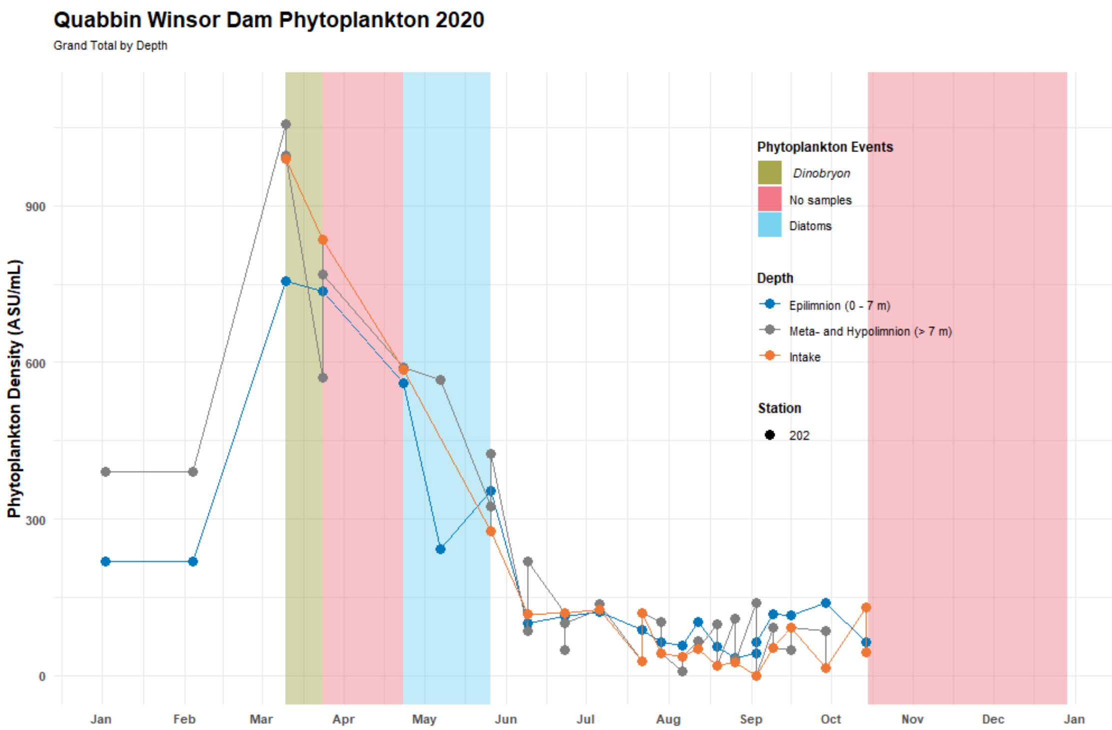

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Figure 33: Grand total phytoplankton densities observed in routine samples collected from the epilimnion and metalimnion, Quabbin Reservoir site 202, during 2020.

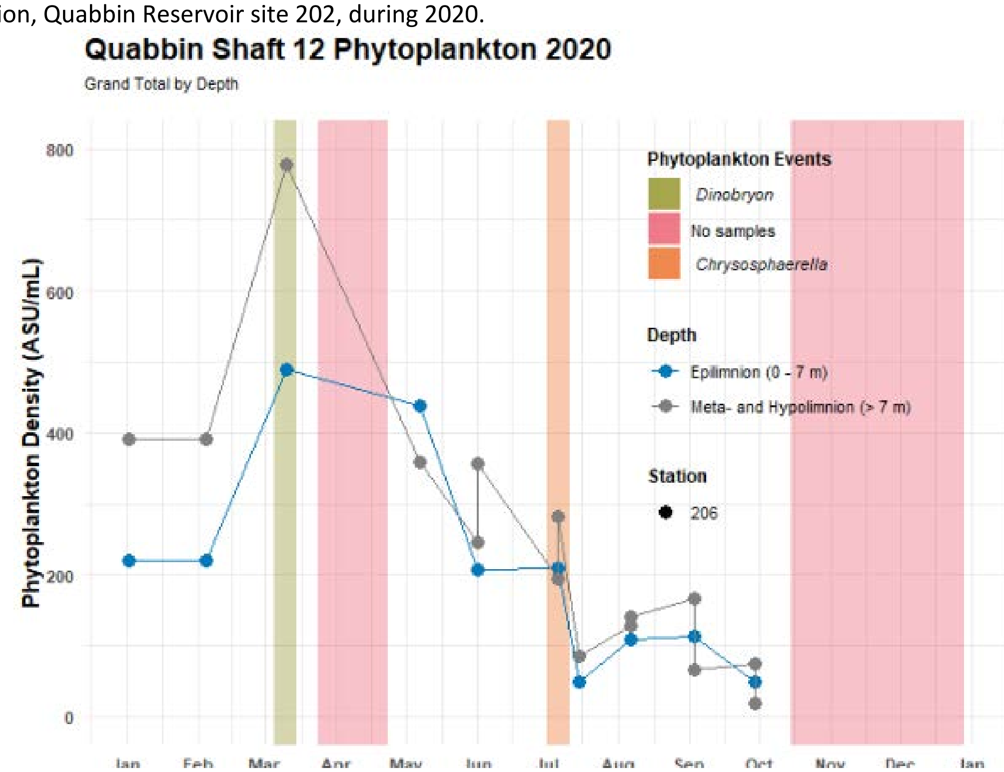

Figure 34: Grand total phytoplankton densities observed in routine samples collected from the epilimnion and metalimnion, Quabbin Reservoir site 206, during 2020.

Changes in phytoplankton community composition throughout 2020 followed patterns typical of seasonal succession historically observed in the Quabbin Reservoir at both core sampling sites (Worden, 2000; Figure 35). Diatoms were dominant at both sampling sites from January through June 2020, with the exception of two sampling events when Chrysophytes were dominant at site 202 (March 10 and 24, 2020), and one sampling event when Chrysophytes were dominant at site 206 (March 10, 2020). Initial warming temperatures, an increase in sunlight duration and intensity, and access to a greater abundance of dissolved silica, relative abundance of other nutrients, and lower light conditions often result in spring diatom dominance in freshwater systems (Cole and Weihe, 2016). Diatoms are ubiquitous in freshwater environments, able to live in a wide variety of habitats (Wehr, Sheath and Kociolek, 2015). The most common diatoms observed in the Quabbin Reservoir in 2020 were *Asterionella* and *Cyclotella.* Similar to diatoms, some chrysophytes use silica in their cell structure, and higher spring abundance in nutrients may result in chrysophyte growth. Quabbin Reservoir water is characterized by low productivity, alkalinity (<60 mg/L), pH (<7) and conductivity (specific conductance <50 µS/cm), creating conditions ideal for chrysophytes (Nicholls and Wujek, 2015; USGS, 2020). The most common chrysophytes observed in Quabbin Reservoir in 2020 were *Dinobryon* and *Chrysosphaerella*.

Beginning in June and through August, total densities decreased at both sites as diatom and chrysophyte populations declined. This is likely explained by a depletion of available nutrients limiting growth, and increasing competition, resulting in a shift in community composition (Cole and Weihe, 2016; Section 3.3.8). Species diversity increased along with a decrease in total densities into June, favoring chlorophytes (most common species were *Gloeocystis* and *Staurodesmus*) through the end of the summer. Samples collected in September and October were marginally dominated by cyanobacteria. The most common cyanobacteria in 2020 were *Microcystis* and *Aphanocapsa.* A transition to cyanobacteria dominance in late summer into fall is also a typical succession of phytoplankton (Cole and Weihe, 2016). This is explained by their heightened performance in warm water compared to other phytoplankton (Whitton, 2012). Overall, the seasonal changes in composition observed in the Quabbin Reservoir in 2020 were typical of temperate freshwater systems.

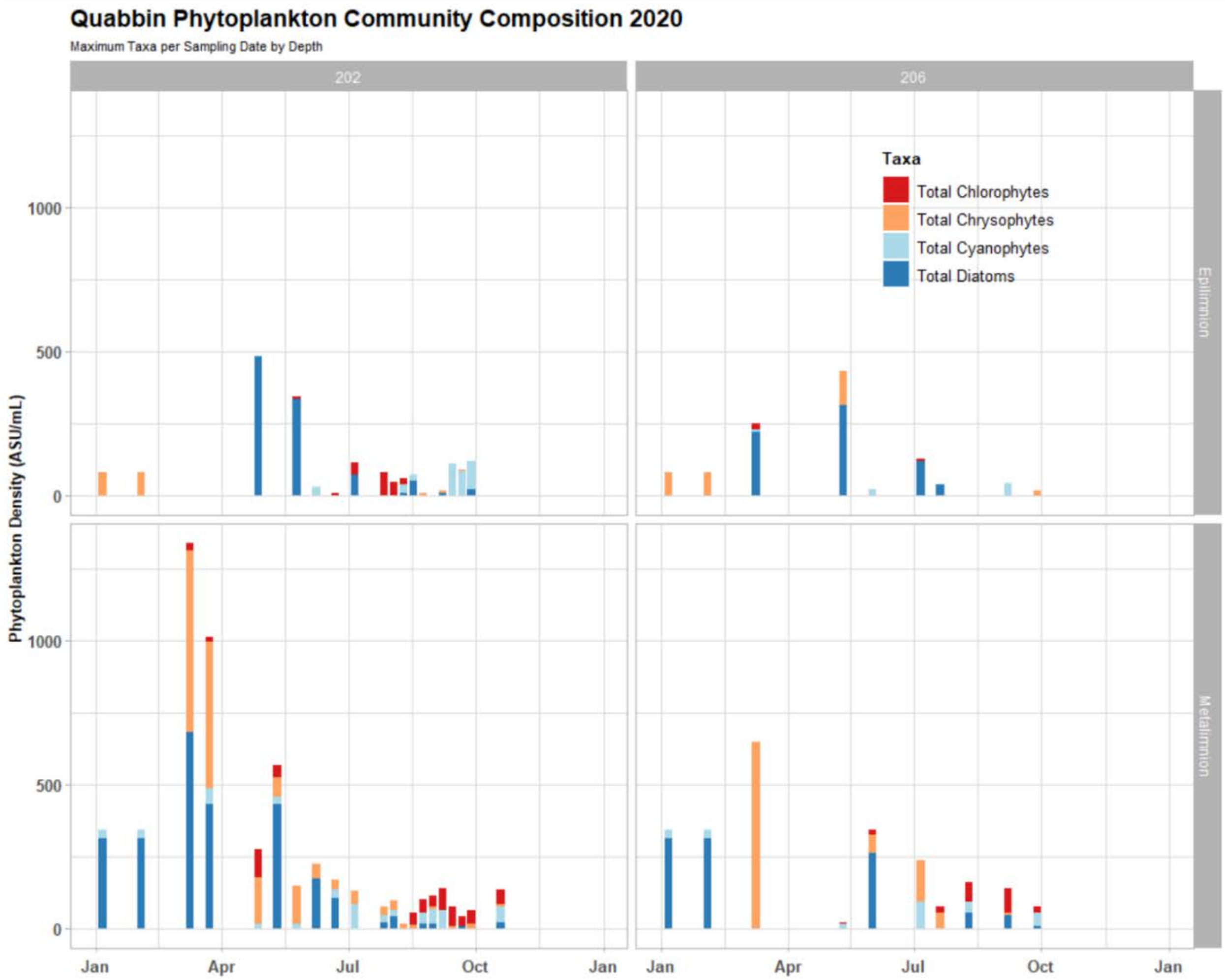

Figure 35: Phytoplankton community composition, collected from the epilimnion and metalimnion, Quabbin Reservoir sites 202 and 206, during 2020 sampling.

3.3.9.1 Taste and Odor Taxa

Several nuisance taxa are closely monitored by DWSP to best inform the source of potential undesirable taste and odor characteristics or cyanotoxin impacts to drinking water supply. Density thresholds for early monitoring and treatment consideration levels have been set for four chrysophytes and one cyanobacteria taxa (Figure 36, Table 29). The cyanobacteria, *Dolichospermum,* was observed at countable densities in only two samples collected in 2020; one at 202 and one at 206, but remained below the early monitoring trigger (15 ASU/mL).

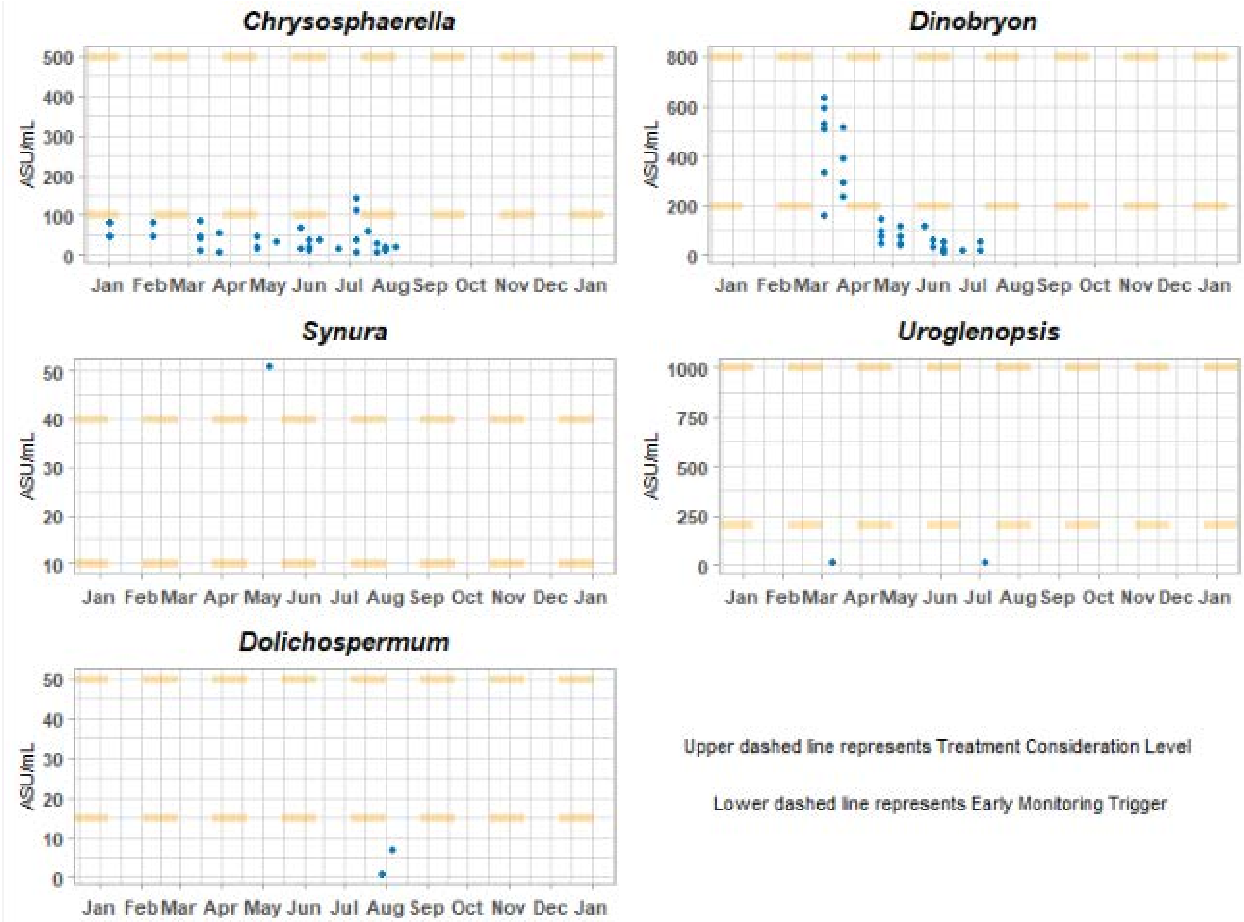

Figure 36: Occurrence of nuisance taxa at both core monitoring sites 202 and 206 during 2020. Upper dashed line represents the treatment consideration level, and the lower dashed line represents the early monitoring trigger.

Table 29: 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 elevated total phytoplankton densities observed in March (Figure 33, Figure 34), were driven by a *Dinobryon* aggregation throughout the water column. Samples from all depths on two sampling events in March 2020 exceeded the early monitoring threshold for *Dinobryon* (200 ASU/mL). The *Dinobryon* aggregation fully dissipated with the onset of stratification in May. *Dinobryon* densities did not exceed treatment consideration levels in 2020. The greater

Dinobryon densities observed in Quabbin Reservoir in the spring were not associated with a subsequent increase in the frequency of taste and odor complaints originating from CVA communities, despite elevated densities at the intake depths on two dates (525.4 ASU/mL on March 10 and 510.7 ASU/mL on March 24, 2020, both from 21 m).

In contrast to 2019 when an aggregation of *Chrysosphaerella* persisted from August through October, *Chrysosphaerella* exceeded the early monitoring threshold (100 ASU/mL) only on July 6, 2020, and only at site 206. Though *Chrysosphaerella* did not exhibit similar growth patterns to 2019, this taxa was present at countable densities in samples from January through August of 2020. *Synura* was detected at levels above the treatment consideration level (40 ASU/mL) for one sample on May 7, 2020 at site 206, but remained below countable densities for the remainder of the sampling season. *Uroglenopsis* remained below the early monitoring threshold (200 ASU/mL) for all sampling dates at both sites in 2020.

Chrysophyte levels in 2020 and 2019 exceeded typical densities observed in Quabbin Reservoir. The 2020 *Dinobryon* aggregation occurred in the spring before stratification, and thus was more distributed in the water column compared to aggregations that occur under stratified conditions. This is in contrast to the *Chrysosphaerella* aggregation that occurred primarily at depth, during stratified conditions, late summer into fall. Though the *Dinobryon* proliferation was different from the *Chrysosphaerella* aggregation of 2019 in time of year and depth distribution, it was likely influenced by similar factors (low phosphorous, alkalinity, pH and productivity) (Nicholls et al., 1977; Nicholls and Wujek, 2015). In addition to the general water quality characteristics previously described leading to favorable conditions for chrysophytes in Quabbin Reservoir, several climatic and hydrologic drivers in recent years may have also contributed to the greater than typical densities observed in 2020.

Monitoring for phytoplankton in Quabbin Reservoir will be conducted monthly (October-April) or biweekly (May-September) at site 202, and monthly at site 206 in 2021. In the instance that an exceedance of an early monitoring trigger is observed, phytoplankton monitoring will be increased, as appropriate.

3.3.10 Bacteria and Turbidity Monitoring for SWTR Compliance

A population of waterfowl that roost on Quabbin Reservoir during fall and winter months have been identified as the primary sources of fecal coliform and *E. coli* to the Quabbin Reservoir (Wolfram, 1996). Additional sources may include semi-aquatic wildlife, and inputs from major tributaries to the reservoir. Fecal coliform and *E. coli* levels in Quabbin Reservoir are historically low, reflecting microbial die-off and predation. Fecal coliform ranged from <1 to 3 CFU/100-mL in samples collected by DWSP from Quabbin Reservoir in 2020 (n=72). *E. coli* was detected at 10 MPN/100-mL samples collected at the median depth of the metalimnion, and approximately 1-m above the reservoir bottom in October at site 202 and in November at Den Hill. *E. coli* remained below 10 MPN/100-mL in the remainder of samples collected by DWSP from Quabbin Reservoir in 2020 (n=72).

The MWRA monitors bacteria levels and turbidity of Quabbin Reservoir water daily prior to disinfection to ensure compliance with the SWTR. Monitoring is performed by MWRA at the BWTF in Ware, MA.

Turbidity is monitored daily by MWRA via an in-line turbidity meter inside the BWTF. Average and maximum daily turbidity levels in Quabbin Reservoir source water measured at the BWTF ranged between 0.22 to 0.36 NTU and 0.24 to 0.96 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 2020 (Figure 37). Fecal coliform bacteria were not detected above 20 CFU/100-mL in samples collected at the BWTF (Figure 37). 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 (0.74 and 0.5 CFU/100 mL, respectively). Neither *Cryptosporidium* nor *Giardia* were detected in biweekly samples (n=26) of raw water at the BWTF in 2020. 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 2020.

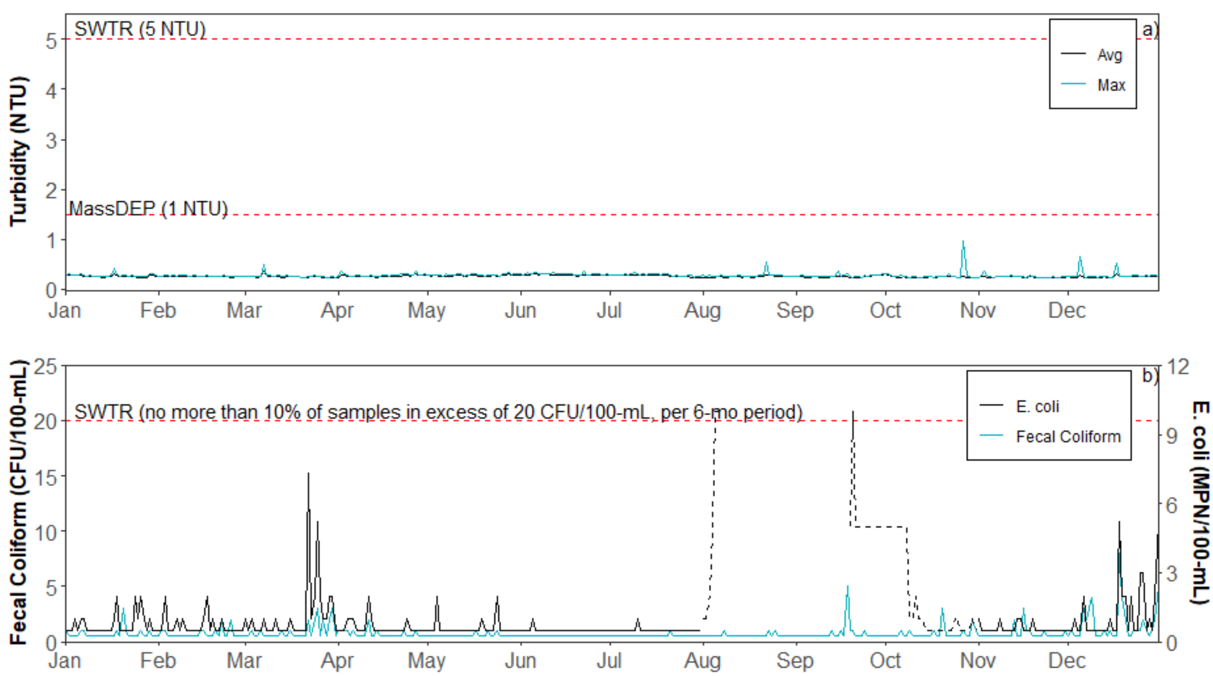

Figure 37: a) Results of daily average and maximum turbidity, and b) fecal coliform and *E. coli* monitoring of Quabbin Reservoir source water, Winsor Dam Intake, collected at BTWF. Note: Detection limits for *E. coli* in source water ranged from <2 MPN/100-mL to <100 MPN/100-mL from August 1 through October 31, 2020, thus fecal coliform served as a better indicator of the sanitary quality of Quabbin Reservoir source water during this interval. *E. coli* remained below minimum laboratory detection limits in source water for the entirety of this affected interval. Data that were affected by the change in minimum detection limits are symbolized using a dashed line in panel b. Data below laboratory detection limits were replaced with one-half the detection limit.

3.4 Aquatic Invasive Species Monitoring and Management

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

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

3.4.1 Invasive Aquatic Macrophyte Monitoring and Distribution

Macrophyte surveys are conducted during the growing season and have been performed periodically since 1998, and on a regular basis since 2006 and 2010 in the Quabbin Reservoir and Ware River watersheds, respectively. Shoreline assessments entail visual observations of the littoral zone via kayak, small boat, or on foot depending on water level. Some water bodies are surveyed annually, while others are surveyed every five years, on a rotating annual schedule by Sanitary District. Routine monitoring prioritizes water bodies with ramps suitable for launching trailered boats, as this type of activity increases the risk of AIS spread (Rothlisberger et al., 2011).

The following sections summarize the distribution of invasive aquatic macrophytes in the Quabbin Reservoir watershed, and the Ware River (Table 30 and Table 31, respectively). Macrophyte surveys were not performed by DWSP staff in 2020 due to staffing vacancies, however contracted surveys were conducted by ESS Group Inc.

Table 30: Aquatic Invasive Species documented presence in the Quabbin Reservoir Watershed. Dates listed mark the initial identification of the listed invasive species found within that body of water.

	Aquatic Invasive Species										
Water Body Name	*Cambomba caroliniana* (fantwort)	*Iris pseudacorus* (yellow flag)	*Lythrum salicaria* (purple loosetrife)	*Myosodis scorpiodes* (True forget-me -nots)	*Myriophyllum heterophyllum* (var. leaf milfoil)	*Najas minor* (Brittle naiad)	*Potamogeton crispus* (curly pond weed)	*Phragmites australis* (common reed)	*Rorrippa microphyllum* (one row yellowcress)	*Utricularia inflata* (swollen bladderwor)	*Cipangopaludina chinensis* (Chinese Mystery Snail)
Bassett Pond								9/6/2013			
Brown Pond				7/2/2015	8/24/2012						
Camels Hump											
Carter Pond								6/30/2015			
Connor Pond		6/26/2013	7/31/2012	6/26/2013							
Doubleday Pond								8/25/2017			
Dugway Pond								8/25/2017			
Gaston Pond				7/27/2012	7/27/2012						
Gate 36 Pond											
Gauco Pond					8/9/2017						
Harvard Pond			8/14/2017					6/26/2013			
Lake Mattawa			7/19/2011	7/17/2015	6/29/2010			8/27/2012			7/30/2013
Nichewaug Pond								7/10/2012			
O'Loughlin Pond					8/4/2011				8/22/2013		
Pepper's Mill Pond				8/16/2013	8/7/2015				8/16/2013		
Pottapaug Pond		7/7/2012	8/20/2011	7/22/2013	8/20/2011			1970s			
Prescott Pen. Ponds				9/15/2014				9/15/2014			
Raccoon Hill Pond				7/29/2015							
Sibley Swamp											

Table 31: Aquatic Invasive Species documented presence in the Ware River Watershed. Dates listed mark the initial identification of the listed invasive species found within that body of water.

	Aquatic Invasive Species										
Water Body Name	*Cambomba caroliniana* (fantwort)	*Iris pseudacorus* (yellow flag)	*Lythrum salicaria* (purple loosetrife)	*Myosodis scorpiodes* (True forget-me - nots)	*Myriophyllum heterophyllum* (var. leaf milfoil)	*Najas minor* (Brittle naiad)	*Potamogeton crispus* (curly pond weed)	*Phragmites australis* (common reed)	*Rorrippa microphyllum* (one row yellowcress)	*Utricularia inflata* (swollen bladderwor)	*Cipangopaludina chinensis* (Chinese Mystery Snail)
Bickford Reservoir								7/27/2015			
Brigham Pond			6/22/2015	8/30/2016	10/14/2010						
Cloverdale Pond			8/30/2011								
Comet Pond				8/10/2017	9/14/2018						
Cunningham Pond											
Demond Pond	8/7/2017	8/17/2017	8/6/2013	8/4/2016	8/13/2010						
Edson Pond											
Long Pond			8/19/2013	7/23/2014	8/13/2010					9/28/2017	2016
Lovewell Pond		7/26/2017			7/26/2017						
Mare Mead. Reservior								7/20/2015			
Moosehorn Pond					9/9/2011						
Moulton Pond	7/6/2012				7/6/2012			7/6/2012			
Muddy Pond				10/6/2016				7/13/2012	10/6/2016		
Natty Pond											
Queen Lake	7/30/2010		8/2/2012								
Stonebridge Pond											
Thayer Pond											
Waite Pond											
Ware River					<2007				7/8/2016		
Whitehall Pond					10/14/2010		6/26/2013			8/22/2017	
Williamsville Pond											

3.4.1.1 Contracted Aquatic Macrophyte Surveys

2020 is the eighth year in a row that MWRA has contracted with ESS Group, Inc. to carry out point-intercept surveys of DWSP/MWRA source and emergency reservoirs. No new AIS were discovered in Quabbin Reservoir during the 2020 survey. The extent and density of the *Myriophyllum heterophyllum* (variable-leaf milfoil) increased slightly in Quabbin Reservoir (observed in 2% more locations), and in the Ware River (2.15 to 2.45 acres covered) in 2020 compared to 2019 (ESS, 2021).

3.4.1.2 Myriophyllum heterophyllum

Myriophyllum heterophyllum (variable-leaf milfoil) is the most frequently encountered AIS in the watersheds and is also well distributed in portions of Quabbin Reservoir. Where *M. heterophyllum* has become established, it is abundant and widely distributed. Annual management of *M. heterophyllum* has occurred since 2016 in the basin above the Shaft 8 intake along the Ware River and in sections above the railroad bridge along the Ware River. Despite these efforts, *M. heterophyllum* remains an issue for water operations due to plant fragmentation. Control methods are currently restricted to physical removal of plants and drawdowns. Winter drawdowns may lessen the labor necessary to reduce *M. heterophyllum* in this area; however, 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 upstream of the Route 122 bridge demonstrated another year of substantial increase from the previous growing season. The large, dense beds that were established in 2019 on both the eastern and western shorelines have continued to expand (ESS Group, 2021). The *M. heterophyllum* downstream of the Route 122 bridge decreased in density in 2020 to only isolated stems in some locations, and one small continuous bed (ESS Group, 2021). Davey Resource Group was contracted by MWRA to physically remove plants via raking from land/boat in 2019 and 2020. The 2020 harvest yielded fewer gallons of removed *M. heterophyllum* compared to the previous year, indicating successful removal during the previous year's efforts (ESS Group, 2021). Though many plants continue to grow in water too deep to facilitate the typical rake harvesting, an aquatic plant rake for deeper areas was used for the first time in 2020 with reported success. Depopulating the entire river above Shaft 8 would be unpractical, daunting, and extremely expensive. This is an ongoing issue with no foreseeable permanent solution. For this reason, the focus is to keep the basin above the intake as free of *M. heterophyllum* as is feasible.

A pioneer infestation of *M. heterophyllum* was found in Comet Pond in 2018. Plants were removed via hand harvest late in the 2018 season by pond residents, with DWSP assistance. AE Commercial Diving Services, Inc., removed plants in August of 2019 using diver assisted suction harvesting (DASH). Several weeks later, DCR Lakes and Ponds divers revisited the site to remove a small number of plants that were missed due to visibility issues and/or regrowth. DCR Lakes and Ponds returned in 2020 and removed several plants by hand. Management via physical methods is anticipated to continue in 2021 to prevent further growth of this tenacious invasive.

3.4.1.3 *Phragmites australis*

Phragmites australis (common reed) is widely distributed throughout the region including within the Quabbin Reservoir and Ware River watersheds. This species spreads using three different methods: seeds, stolons, and rhizomes. As more plants mature to reproductive age, seed production and dispersal increases. Stolons, runners that grow on the top of soil, and rhizomes, 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. Once established, *Phragmites* aggressively colonizes the shoreline. Although labor intensive, pioneer or small infestations may be eradicated using physical methods such as cutting below the surface of the water, hand pulling, or covering with black plastic. Herbicide use is the least labor intensive and most effective means of reducing plant numbers but is currently not under consideration by DWSP. Some success has been documented using a combination of several different methods, especially if implemented on small and newly established stands. Ideally, small, isolated populations should be targeted for management before they become established. Early removal is far more effective, requires fewer resources and has less of an environmental impact.

3.4.1.4 *Cabomba caroliniana*

Cabomba caroliniana (fanwort) has been observed in Queen Lake in Phillipston, as well as Demond Pond and Moulton Pond in Rutland, MA. *C. caroliniana* has been present in Queen Lake for several years and distribution and density appear to be increasing each year. The Queen Lake Association contracted with SOLitude Lake Management to manage *C. caroliniana* with herbicides in 2020.

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 sufficient 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.

3.4.1.5 *Utricularia inflata*

Utricularia inflata (swollen bladderwort), was documented at Whitehall Pond in 2017 and has been found each year that a survey was conducted since. *U. inflata* was also found in nearby Long Pond in 2017. *U. inflata* was documented in Quabbin Reservoir at Boat Launch Area 2 in 2017 but has not been observed since then, despite repeated survey efforts.

3.4.1.6 *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 throughout the area. It is now found along the shores of the East Branch Swift River, in Demond, Lovewell, and Pottapaug Ponds, 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 in 2021.

3.4.1.7 Lithrum salicaria

Lithrum salicaria (purple loosestrife) has been documented in 9 out of the 40 regularly surveyed ponds in the Quabbin and Ware River watersheds and has also been found in the Quabbin Reservoir. This plant is difficult to identify when not in bloom, potentially resulting in an underestimation of population size. Ongoing annual surveys, conducted at different times of the season, may facilitate documentation of infestations not previously observed. In 2020, *L. salicaria* was scattered along the shoreline of the Quabbin Reservoir as individual plants or in small clusters (ESS Group, 2021). Compared to the main reservoir, most *L. salicaria* plants in 2020 were observed in O'Loughlin Pond.

3.4.1.8 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.

Significant increases in densities of *R. microphylla* have not been observed in water bodies where it has become established. As it is edible, this plant may be kept in check by herbivores. In the past, the latter 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 in surveyed waterbodies. It is widespread throughout the Quabbin Reservoir and Ware River watersheds as well as throughout New England and has subsequently been found in the Wachusett Reservoir watershed. *R. microphylla* is likely being transported as seeds by wildlife, water currents, and possibly with gear used by anglers.

3.4.1.9 *Myosotis scorpioides*

Myosotis scorpioides (true forget-me-not) is not truly an aquatic plant but inhabits wet, disturbed shorelines and is found throughout New England. It was first documented at Quabbin Reservoir approximately 13 years ago. 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 DWSP staff, were removed by hand pulling. Additional plants have been documented in Pottapaug Pond each year. *M. scorpioides*, along with *Phragmites australis* and *Myriophyllum heterophyllum*, is the most commonly found invasive plant in either the Quabbin Reservoir watershed and Ware River watershed. Documented populations will continue to be monitored and, if possible, removed as they are documented. *M. scorpioides* multiply by seed production and spread by an extensive and shallow underground root system. These reproductive methods make complete eradication of this invasive species difficult. Known impacts associated with this plant are minimal at this time.

3.4.1.10 *Najas minor*

Najas minor (brittle naiad) was documented by ESS Group in 2014 at O'Loughlin Pond. DWSP hypothesize that *N. minor* seeds were introduced into the pond via avian passage, as birds are known to feed on the indistinguishable native *Najas gracillima* seeds (Reynolds et al., 2015; Martin and Uhler 1939). The *N. minor* infestation in O'Loughlin Pond documented in 2014 was quickly harvested using DASH. O'Loughlin Pond was free of *N. minor* plants for the sixth year in a row in 2020.

3.4.1.11 *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 where use of large watercraft is less common. Despite ongoing efforts, this plant continues to be widely distributed throughout this water body.

3.4.2 Invasive Aquatic Fauna Monitoring and Distribution

Visual surveys for Chinese mystery snail and adult zebra mussels are performed alongside aquatic macrophyte surveys. Net tows for invasive zooplankton and the larval stages of zebra mussels began in 2009. In 2020, monthly vertical plankton tows using an 80 µm mesh net were performed at the core reservoir water quality monitoring sites (202, 206 and Den Hill). Oblique tows (3 min pull, 80 µm mesh) were also performed monthly in proximity to the Boat Launch Areas to monitor for invasive zooplankton. The following sections summarize the presence and absence of potential invasive aquatic fauna threats in the Quabbin and Ware River watersheds.

3.4.2.1 *Dreissena polymorpha*

Dreissena polymorpha (zebra mussels) were discovered in Massachusetts in 2009, leading to the development and adoption of the Quabbin Boat Decontamination Program (Section 3.4.3.1).

Since then, it has been determined that the low pH and calcium levels found the Quabbin Reservoir (Section 3.3.4, Section 3.3.8.3) make it unsuitable for zebra mussel reproduction and growth. As a result, it is unlikely to find fully mature *D. polymorpha* in the reservoir. Despite this, plankton net tows are scanned for the immature larval stages of *D. polymorpha*. To date, no immature larval stages have been found in the reservoir, however regular monitoring ensures DWSP could act quickly if this were to change.

3.4.2.2 Invasive Zooplankton

The potential invasive zooplankton of concern are *Bythotrephes longimanus* (spiny waterflea) and *Cercopagis pengoi* (fishhook waterflea). As of 2020, neither species has been documented in the Quabbin Reservoir. Vertical tows collected in September and October from the core water quality monitoring sites in the reservoir were scanned to begin establishing the current zooplankton community structure. In 2020, Cladocerans including Bosminidae, Daphniidae, and an abundance of copepods in the orders of Calanoida and Cyclopoida were documented.

3.4.2.3 Cipangopaludina chinensis

Individual *Cipangopaludina chinensis* (Chinese mystery snail) were documented during DWSP AIS surveys for the Quabbin Reservoir watershed in 2011. Numerous snails were found near the boat dock at Boat Launch Area 1 where their population density continued to be high through at least 2019. 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 in Lake Mattawa in 2017. Chinese mystery snails displace native snail species by outcompeting them for resources. Despite this, few studies have been conducted to adequately determine their impacts (Solomon et al., 2010). Snails may serve as an intermediate host for fish parasites, however their presence in waterbodies in the Quabbin Reservoir and Ware River watersheds has not been associated with negative impacts thus far.

3.4.3 AIS Management and Boat Decontamination Programs

Management of AIS within the Quabbin Reservoir and Ware River watersheds is currently limited to one *Myriophyllum heterophyllum* removal project funded by MWRA (Section 3.4.1.2) and several others funded and conducted by private lake/pond associations.

The DWSP Quabbin Reservoir/Ware River Region runs several prevention programs designed to limit the spread of aquatic invasive species (AIS) throughout the watersheds. These programs include the Quabbin Boat Seal Program for anglers on the Quabbin Reservoir. In the Ware River Watershed, there are self-certification programs at Comet Pond in Hubbardston and Long Pond in Rutland. The Quabbin Boat Decontamination program was initiated in 2009. The Self-Certification programs, in the Ware River Watershed, began in 2010.

3.4.3.1 Quabbin Boat Decontamination Program

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

The Boat Decontamination Program was developed to prevent the spread of a range of AIS including plants (variable-leaf milfoil, Eurasian milfoil, hydrilla, *etc.*), zooplankton (spiny and fish-hook water flea), and invertebrates (zebra mussels and Chinese mystery snails). Marine species and severely degraded freshwater plants pose little to no risk of being successfully introduced to the Quabbin Reservoir. Despite this, many invasive species are very well adapted to endure harsh conditions, such as periods of desiccation. Plants can spread via small seeds and small plant fragments. Zooplankton and zebra mussels are microscopic during certain life stages and can persist inside boat motors for long periods of time. The boat inspection and decontamination programs offered through DWSP serve to limit the introduction of these invasive species into the Quabbin Reservoir.

The Quabbin Boat Decontamination Program consists of two options for recreational boaters to clean their boats: warm-weather decontamination (WWD) and cold-weather quarantine (CWQ). WWD events occurred over 11 dates in 2020 throughout the fishing season. Due to initial COVID-19 related precautions, 12 dates were cancelled, however nearly all appointment holders for these dates were rescheduled prior to the delayed fishing opening day. Boaters are asked what bodies of water their boats were in last, inspected for any plant material, and cleaned. Samples of biological substances collected off boats inspected during either the WWD or CWQ programs are identified whenever possible. All parts of the boat (including hulls, all through-hull fittings, live wells, bilge, downriggers, anchors, lines, and trolling motors) in addition to the boat trailers (including rollers and bunks) are washed with warm water (140 °F) at a high pressure. Warm water is then run through the boat motor until 140 °F water runs out of the motor for 10 seconds to kill any organisms that may be present in the motor. While this program requires payment from anglers, it enables them to fish outside of the Quabbin Reservoir, then return following the completion of a decontamination event. This significantly reduces the risk of AIS introduction from other waterbodies without restricting anglers to exclusively fish at the Quabbin Reservoir. The cold-weather quarantine program occurred over 5 dates in 2020. The CWQ requires no fee. Boats are tagged at the beginning of the winter season, making sure boats remain on trailers for around four months. At least three consecutive days below 32 °F, or 46 days with an average low temperature of 30 °F is required to cause desiccation or cold thermal death for any potential AIS (McMahon et al., 1993).

In 2020, 173 boats were inspected and decontaminated through the WWD program. This is around the average number of decontaminations from the previous three years (171 WWDs from 2017-2019), despite complications due to COVID-19 restrictions. 105 boats were inspected and sealed through the CWQ program for the 2021 fishing season. This is slightly lower than the average for the previous three years (115 CWQs from 2017-2019). In 2020, around 45% of boaters used the WWD for the first time, and around 35% of boaters used the CWQ for the first time.

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

3.4.3.2 Boat Ramp Monitoring and Self-Certification Programs

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

Self-certification forms are prominently displayed at Comet and Long Ponds in boxes on the kiosks near each boat ramp, along with signage directing boaters to self-certify their watercraft as free of AIS before launching. Forms include questions about where boaters were last, how long ago, how they cleaned their boats and with what, and if they are aware of any AIS in the location they previously boated. These questions not only provide information for management purposes, but also encourage boaters to take responsibility for understanding the risk of AIS in their recreational water bodies and perhaps take an active role in preventing the spread of AIS within the region.

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

Education is the key to success for this program. By focusing on the overarching prevention of AIS introductions instead of the specific organisms of concern, boaters can think about the impacts of moving boats from one waterbody to another.

4 Conclusions and Recommendations

Data generated by DWSP in 2020 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 2020. 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 2020 were largely consistent with historical data and demonstrate continued adherence to drinking water quality standards. Infrequent individual *E. coli* concentrations above single-sample regulatory limits, attributed to flushing from storm water runoff events, returned to pre-event levels upon resampling. Biweekly results for specific conductance in Core tributaries in the Quabbin Reservoir and Ware River watersheds suggest a subtle increasing baseline in specific conductance measured in some tributaries to the Quabbin Reservoir and Ware River watersheds – a pattern ubiquitous with surface waters in the snowbelt region of the US. Routine nutrient monitoring results for Core tributary monitoring sites in 2020 revealed more detailed dynamics of terrestrial aquatic N-cycling than previously documented, largely attributed to increasing the monitoring frequency for nutrients (previously quarterly) in Core tributary sites. TP analysis in Core and EQA site in Quabbin Reservoir and Ware River watersheds was modified in 2020. Coincident with the timing of the change in analytical methods, an apparent step-change in TP concentrations was observed at affected sites. This temporal pattern in TP concentrations was not observed for sites that analytical methods were not altered (EBU and MBD on Prescott Peninsula - and Shaft 1 in the Wachusett Reservoir watershed). TP concentrations remained within established background ranges at unaffected sites (DWSP, 2021). The prevalence of drought (and subsequent low streamflow) across much of Worcester and adjacent counties in 2020 impacted the results generated by DWSP routine monitoring efforts during this year.

Results of biweekly monitoring of select water quality parameters in Quabbin Reservoir watershed and Ware River watershed in 2020 were consistent with historical data, did not suggest the presence of any new substantial point-source contributions, and ultimately demonstrated continued adherence to drinking water quality standards.

4.2 Quabbin Reservoir Water Quality

Results of routine water quality profiles collected in Quabbin Reservoir in 2020 were comparable to historical data and indicated that the timing of turnover and stratification occurred in line with prior seasons. Profile data additionally served to guide phytoplankton sampling. Phytoplankton density and composition changes observed through 2020 were consistent with prior years. Climatic and hydrologic drivers contributed to seasonal and vertical shifts in phytoplankton assemblages and nutrient dynamics. Although *Chrysosphaerella* were present at countable densities in samples collected from the Quabbin Reservoir from January through August 2020, this taxa did not exhibit similar growth patterns to those observed in 2019 (DWSP, 2020a). *Dinobryon* were elevated at site 202 on two sampling dates, however these heightened concentrations were not associated with an increase in taste and odor complaints from the CVA communities. The frequency of nutrient monitoring in Quabbin Reservoir also increased in 2020. Monthly results for concentrations of Si, N-species and TP highlighted unique spatial (lateral and vertical) and temporal dynamics of these solutes in the Reservoir, largely driven by hydrodynamics (e.g., seasonal turnover) and primary productivity. Analytical methods for TP in Core sites in the Quabbin Reservoir were shifted to accomodate increased monitoring frequencies for nutrients in 2020. DWSP will collect duplicate samples for analyses via Valderrama, 1981 and EPA 265.1 to derive TP in routine samples collected from the Quabbin Reservoir in 2021 to elucidate the impact that variations in analytical methods for TP may have on resultant concentration data and the implications for long-term monitoring. 2020 marked the first year that TOC was monitored routinely at Quabbin Reservoir Core sites. TOC concentrations in Quabbin Reservoir largely mirrored patterns in UV_{254}, highlighting the influence of the East Branch Swift River on water quality at Den Hill.

Monthly monitoring of select water quality parameters in the Quabbin Reservoir during 2020 were consistent with historical data and demonstrated continued adherence to drinking water quality standards.

4.3 Proposed Quabbin Reservoir and Ware River Watershed Monitoring Programs for 2021

The water quality sampling plan for the Quabbin Reservoir and Ware River watersheds is reviewed and modified annually to direct focus to different sub-basins within the watersheds and adapt to changing conditions (including but not limited to changes in land use/land cover and/or climate-driven hydrometeorological changes). The 2021 sampling plan retains the long-term Core sites in both watersheds and replaces the sites used to support Environmental Quality Assessment (EQA) efforts.

4.3.1 Quabbin Reservoir and Ware River Watershed Tributary Monitoring

The Quabbin Reservoir Watershed tributary monitoring program includes seven core sites and up to seven EQA sites. DCR will continue to sample biweekly at core sites (Table 2), discontinue the EQA sites (216G, 216I-X, 216E-1, 216D, and 216C) monitored in 2020, and begin biweekly monitoring of seven different EQA sites (211E, 211F, 211G, 212A, 212B, 213A, and 213B) in the Quabbin Norwest Sanitary District in 2021. Site 215G will replace 215 as the Core site along the downstream reach of the East Branch Fever Brook. Monitoring of nutrients (NO_3-N, NH_3-N, TKN, and TP) and UV_{254} in tributary core monitoring locations will remain biweekly, with the addition of TOC in core tributaries in the Quabbin Reservoir watershed, biweekly for the entirety of 2021.

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, discontinue monitoring at the EQA sites monitored in 2020 (108A, 108B, 108C, 116, and 116B) and begin biweekly monitoring at four EQA sites (105, 121H, 110, and 119P) located in the Coldbrook and Longmeadow sanitary district in 2021. Site 121 will replace 121B as the Core site along the Mill Brook reach in Rutland, MA. Site 102 (Parkers Brook) will be added as an additional Core site in the Coldbrook and Longmeadow sanitary district from 2021 onward. Monitoring of nutrients (NO_3-N, NH_3-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 2020.

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 2021, weather and reservoir conditions permitting. This monitoring will include analyses for alkalinity, turbidity, total and fecal coliform, and *E. coli*. Quarterly Quabbin Reservoir monitoring will be conducted in May, July, October, and December. In addition to the monthly analytes, quarterly monitoring will include Na, Ca, and Cl concentrations collected at three depths. DWSP monitoring of nutrients (NO_3-N, NH_3-N, TKN, TP, and Si) and UV_{254} in Quabbin Reservoir core monitoring sites will remain at a monthly frequency 2021. Monthly analyses of TOC at three depths at core sites within the Quabbin Reservoir will continue in 2021. Routine monitoring for phytoplankton will be performed by DWSP biweekly at site 202 during the growing season (May 1 through September 30, 2021), monthly at 202 outside of the growing season, and monthly at site 206. *In situ* profiles of temperature, pH, specific conductance, dissolved oxygen, turbidity, chlorophyll *a*, and phycocyanin will be collected at each monitoring site within the Quabbin Reservoir and used to determine appropriate sample collection depth and inform controls on phytoplankton dynamics in Quabbin Reservoir.

No other modifications to DWSP monitoring efforts in Quabbin Reservoir watershed or Ware River watershed are anticipated for 2021. Changes to the DWSP water quality monitoring program introduced in 2021 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

Appendix A. 2020 Watershed Monitoring Parameters and Historical Context

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

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

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

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

Ammonia-Nitrogen

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

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

Nitrate-Nitrogen

Nitrate-nitrogen (NO_3-N) is an important macro-nutrient for plants and the most abundant inorganic form of nitrogen found in water (USGS, 1999). Sources of nitrate include runoff from agricultural sites and fertilized lawns, failing on-site septic systems, atmospheric deposition, and some industrial discharges. Background concentrations of NO_3-N + NO_2-N in rivers and streams of the Quabbin Reservoir and Ware River watershed ecoregions were found to range between 0.1 mg/L and 4.12 mg/L, with the 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 25^{th} percentile value (all seasons) of 0.42 mg/L (ecoregion 58) and 0.59 mg/L (ecoregion 59), which are the reference conditions for streams and rivers recommended by the EPA for the development of numerical TN criteria for these ecoregions (US EPA, 2000; US EPA 2001a). Long-term (seasonal or annual) TN concentrations above these recommended criteria likely indicate that excess nitrogen is entering waters. Any tributaries exhibiting long-term concentrations above these recommended nitrogen criteria should be examined more closely to determine if any response variables (chlorophyll, macrophytes, turbidity, macroinvertebrates) indicate that water quality impairments are occurring.

Total Phosphorus

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

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

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

Silica

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

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

Water Temperature

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

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

Dissolved Oxygen

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

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

Alkalinity and pH

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

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

Bacteria

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

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

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

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

Specific Conductance and Dissolved Salts

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

Excess sodium in drinking water may compromise the health of individuals on sodium-restricted diets, such as those with hypertension, and increase the cation-exchange capacity of nearby soils (Kaushal et al., 2017), resulting in the mobilization of base cations (e.g., calcium, potassium, magnesium) to streams thereby altering natural biogeochemical cycles. The EPA established aquatic life criteria for Cl in 1988 at chronic (4-day average) and acute (1-hour average) concentrations of 230 and 830 mg/L, respectively (US EPA, 1988). Neither threshold is to be exceeded more than once every three years. MassDEP has established a linear regression model to derive Cl concentrations from specific conductance values: "Instantaneous exceedances of the acute and chronic Cl criteria are estimated to occur at [specific conductance] readings greater than 3,193 and 904 µS/cm, respectively" (MassDEP-DWM, 2018). MassDEP also established an Office of Research and Standards Guideline (ORSG) of 20 mg/L sodium in drinking water, and a secondary maximum contaminant level (SMCL) for Cl of 250 mg/L (310 CMR 22.07D (2016)). MassDEP does not 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 potential treatment of the algae present in the Reservoir with copper sulfate and adjustments within the treatment system such as increasing the ozone dose (ozone is used as the primary disinfectant at John J. Carroll Water Treatment Plant). The MWRA is responsible for in-reservoir treatment of algae and disinfection of waters prior to delivery to local distributors (Commonwealth of MA, 2004).

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

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

Zooplankton

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

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

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

Secchi Disk Depth/Transparency

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

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Appendix B. Watershed Monitoring Reports

Short Term Forestry Monitoring Reports

Lot S11SQ, Belchertown, MA

MEMORANDUM

To: Yuehlin Lee, Environmental Analyst IV

From: Gary Moulton

Date: April 04, 2021

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

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

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

Forestry Lot PE-20-02 is located on Jucket Hill Road in Belchertown, MA. Two sample locations were determined on the stream where the crossing was located. One sample location was located upstream of the crossing (SC4, Figure 1) and one was located downstream of the crossing (SC4, Figure 1).

Monthly sampling events were conducted through three different phases; prior, during, and following completion of active work. “Prior” sampling events were conducted in three consecutive months prior to the active logging work occurred and served as baseline turbidity data. The post-work sampling was conducted for a 12-month period after the active work ended. The short-term forestry monitoring program at this lot covered in this report occurred from November 2020 to June 2021. Because the SC4 location was dry prior to the start of harvesting, no baseline monitoring data are available for this location.

The results of the turbidity sampling (in NTU) are shown on Table 1 below. The locations of the sample sites are shown on Figure 1.

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

FL S11SQ SC4			
Harvest Status	**Date**	**Upstream Turbidity (NTU)**	**Downstream Turbidity (NTU)**
Baseline	*No samples collected*.		
Active	11/27/2020	0.232	0.243
	12/11/2020	0.216	0.181
	01/15/2021	0.375	0.162
	01/29/2021	0.371	0.228
	02/05/2021	0.203	0.492
Post-Harvest	03/05/2021	0.25	0.238
	04/09/2021	0.179	0.17
	05/07/2021	0.191	0.185
	06/25/2021	0.101	0.102

The minimum turbidity of 0.101 NTU was measured at the downstream location following completion of logging work on June 25, 2021. The greatest turbidity was observed at the downstream, just above the crossing at 0.492 NTU during post-monitoring period on February 5, 2021.

Gates Brook is a tributary to Quabbin Reservoir, downstream of the confluence of the S11SQ SC1 sampling location. For comparison purposes, turbidity at Gates Brook in 2020 ranged from 0.099 to 0.61 NTU. The maximum turbidity recorded in 2020 at Gates Brook was 0.61 NTU which was recorded on September 29, 2020. The minimum turbidity observed in Quabbin Reservoir watershed Core tributary sampling sites (e.g., Boat Cove Brook, Gates Brook, 211, 212, 213, 215, and 216) since 2010 was 0.0.081 NTU at Gates Brook in January 2011 and the greatest turbidity was 9.12 NTU at 211 in July 2013. Variations in turbidity can be affected by many factors such as storm events, beaver dam breaches, construction-related disturbances, etc.

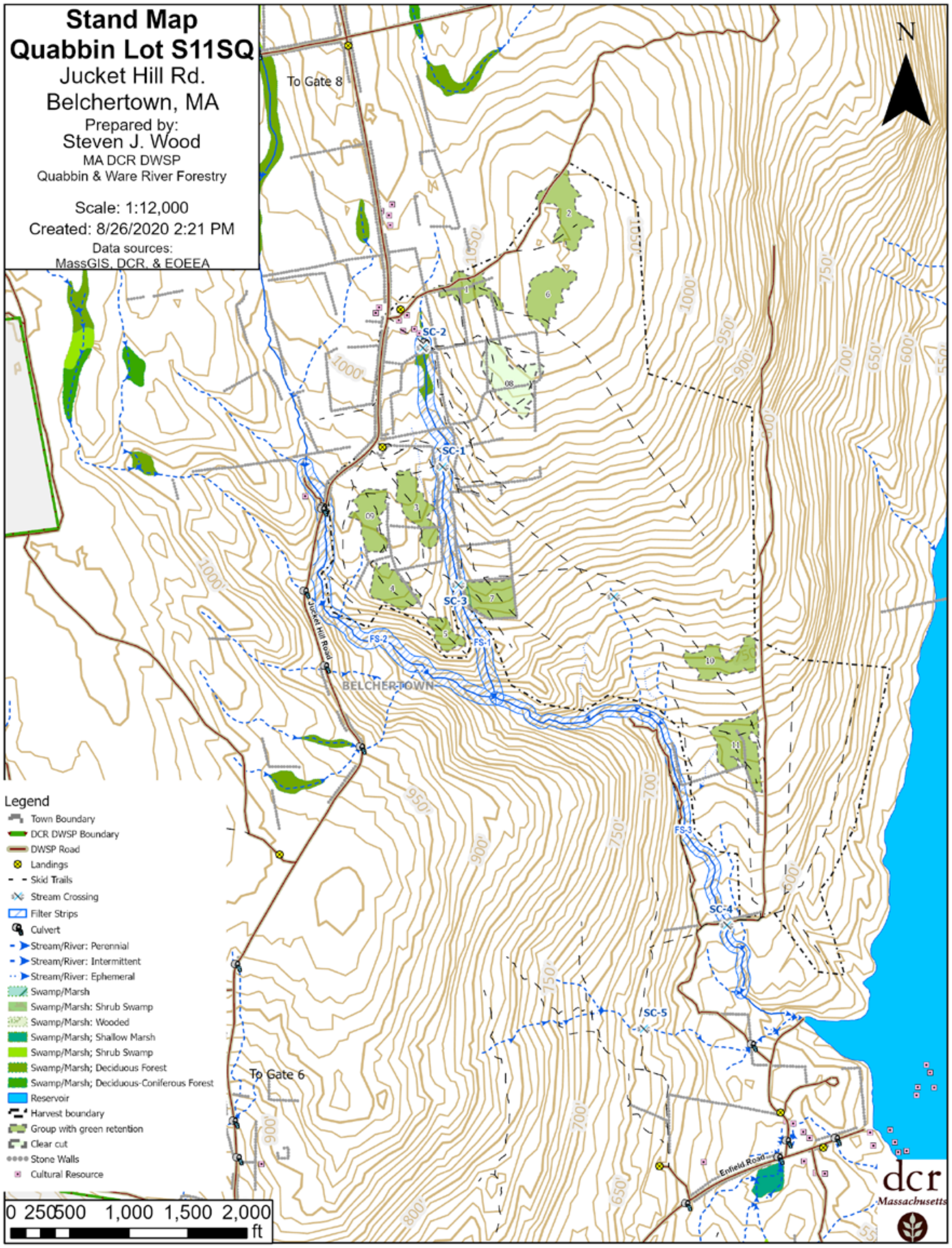

Figure 1. Map showing location of SC4 sampling locations relative to FL S11SQ.

Lot 1056, Hardwick, MA

MEMORANDUM

To: Yuehlin Lee, Environmental Analyst IV

From: Gary Moulton

Date: June 16, 2021

Subject: Monitoring Report for Forestry Lot 1056

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

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

Forestry Lot 1056 is located at the intersection of Dana Road and Route 32A, Petersham and Hardwick, MA (Figure 1). Two sample locations were determined on the stream where the crossing was located. One sample location was located upstream of the crossing and one was located downstream of the crossing (Figure 2, Figure 3).

Monthly sampling events were conducted through three different phases: prior, during, and following completion of active work. "Prior" sampling events were conducted during three consecutive months prior to the active logging work occurred and served as baseline turbidity data. The post-work sampling was conducted for a 12-month period after the active work ended. The short-term forestry monitoring program at this specific lot occurred from March 2019 to June 2021.

The results of the turbidity sampling (in NTU) are shown on Table 1. The locations of the sample sites are shown on Figure 1.

The minimum turbidity of 0.16 NTU was measured at the downstream location during the baseline monitoring period on March 1, 2019. The greatest turbidity was observed at the downstream location at 0.67 NTU during the active harvest monitoring period on April 09, 2021.

Table 1. Turbidity Results (NTU) for SC1 at FL 1056

FL 1056 SC1			
Harvest Status	**Date**	**Upstream Turbidity (NTU)**	**Downstream Turbidity (NTU)**
Baseline	03/01/2019	0.19	0.16
	03/18/2019	0.2	0.19
	04/04/2019	0.2	0.29
	05/20/2019	0.259	0.251
Active	05/12/2020	0.293	0.59
	06/08/2020	0.274	0.322
Post	08/28/2020	0.369	0.448
	10/21/2020	0.292	0.343
	11/06/2020	0.457	0.355
	12/11/2020	0.221	0.266
	01/15/2021	0.397	0.278
	02/05/2021	0.479	0.465
	03/05/2021	0.329	0.327
	04/09/2021	0.397	0.67
	05/07/2021	0.321	0.362

The East Branch Swift River (216) is a tributary to Quabbin Reservoir monitored routinely by DWSP for turbidity. The 1056 lot is in proximity to the East Branch Swift River watershed. For comparison purposes, turbidity at site 216 in March 2019 through December 2020 ranged from 0.39 to 2.0 NTU. The maximum turbidity recorded in 2020 at site 216 was 2.0 NTU which was recorded on August 04, 2020. The minimum turbidity observed in Quabbin Reservoir watershed Core tributary sampling sites (e.g., Boat Cove Brook, Gates Brook, 211, 212, 213, 215, and 216) since 2010 was 0.0.081 NTU at Gates Brook in January 2011 and the greatest turbidity was 9.12 NTU at 211 in July 2013. Variations in turbidity can be affected by many factors such as storm events, beaver dam breaches, construction related disturbances, etc.

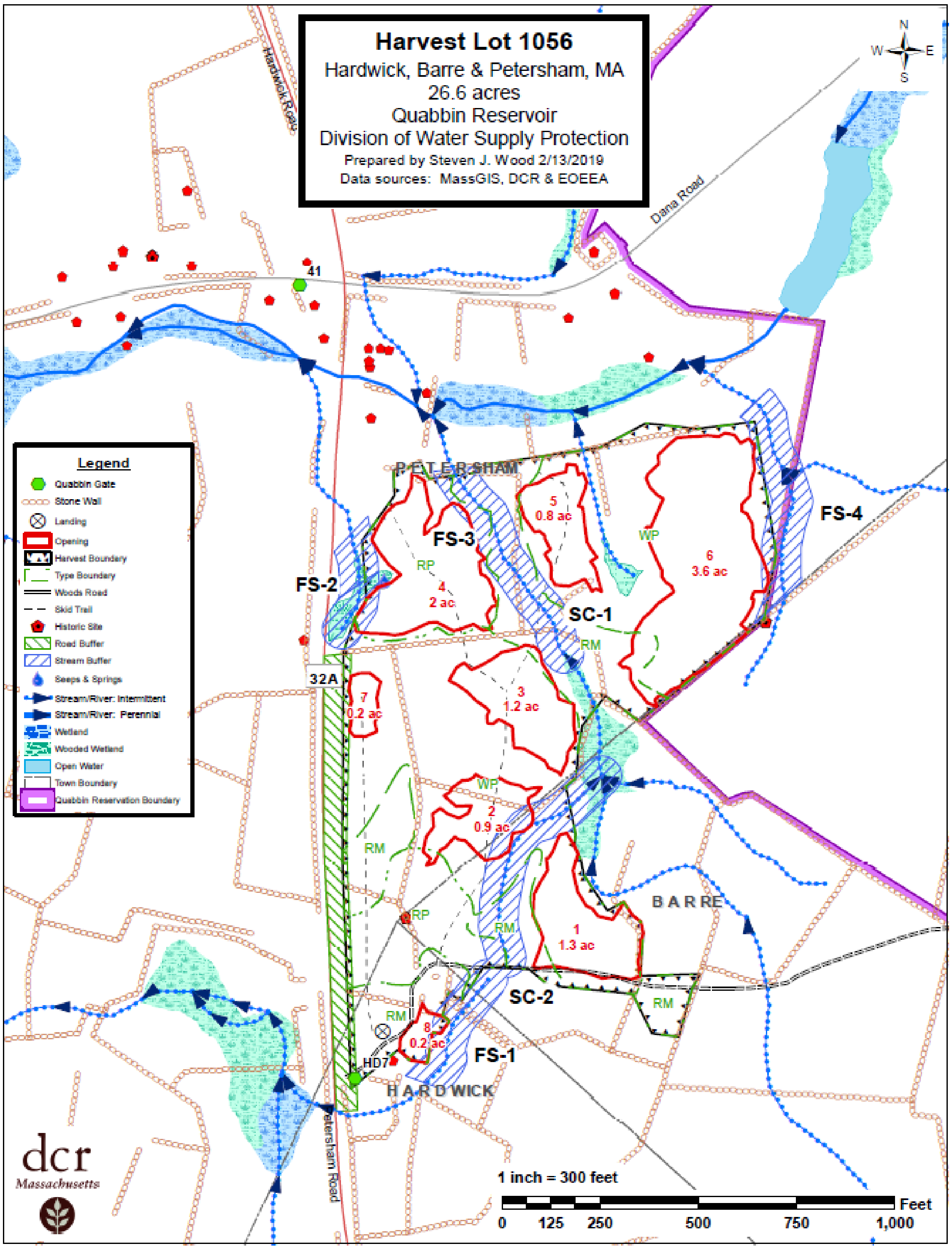

Figure 1. Map showing location of SC1 sampling locations relative to FL 1056.

ATTACHMENTS - Figures

Figure 2. Location of stream crossing 1 (SC1) on 03/18/2019.

Figure 3. Location of SC1 upstream (left) and downstream (right) sample locations on 03/18/2019.

Figure 4. Approximately 10 yards downstream of stream crossing 1 (SC1) on 03/18/2019.

Environmental Quality Assessments

East Branch Swift River Sanitary District

Water quality in surface water in the East Branch Swift River sanitary district in 2020 was generally comparable to that of previous monitoring periods, with some noteworthy exceptions. Samples were collected biweekly from six locations within the East Branch Swift River sanitary district in 2020 (Table 1), and analyzed for a range of constituents (DWSP, 2021) to evaluate potential impacts to water quality in each subdistrict. Concentrations of constituents measured in 2020 were compared to results from prior monitoring periods (2010, 2014, 2015, and 2018) using the non-parametric Kruskal-Wallace (KS) test. If results from the Kruskal–Wallis tests indicated that there were significant differences among years, a post-hoc analysis was performed to determine which years were different. Non-parametric statistical methods were appropriate due to non-normal distributions of the data (Helsel and Hirsch, 2002; Helsel 2012). Lastly, concentration data from 2020 was compared to regulatory thresholds/limits, when applicable.

Table 1. Sample sites within East Branch Swift River Sanitary District monitored in 2016-2020 reporting cycle. Note: Subdistrict designation denotes the subdistrict corresponding to the greatest proportion of upstream contributing area for each site (see Figure 3, main text).

<table>
<tr><th>Subdistrict</th><th>Sub-basin</th><th>Site Type</th><th>Site Description</th><th>DWSP Site No.</th></tr>
<tr><td rowspan="3">East Branch Swift Lower</td><td rowspan="2">East Branch Swift</td><td>Core</td><td>East Branch Swift River at Route 32A</td><td>216</td></tr>
<tr><td rowspan="5">EQA</td><td>Northern Tributary of 216E, at South St</td><td>216E-1</td></tr>
<tr><td>Carter</td><td>Carter Pond, below outlet (at Glen Valley Rd)</td><td>216C</td></tr>
<tr><td>East Petersham</td><td>Rutland</td><td>Connor Pond outlet, at dam (near Pat Connor Rd)</td><td>216D</td></tr>
<tr><td rowspan="2">East Swift Upper</td><td rowspan="2">Brown</td><td>Roaring Brook, Petersham Center</td><td>216G</td></tr>
<tr><td>Moccasin Brook, above Quaker Road</td><td>216I-X</td></tr>
</table>

Most pronounced, annual median specific conductance, total phosphorus, and turbidity were significantly different when compared to 2010 records, during at least one year for the majority of sites in the EBSR sanitary district (Table 2).

Relative to 2010 monitoring, annual median specific conductance increased only at 216, 216C, and 216D (East Branch Swift Lower and East Petersham subdistricts) in 2015. Individual locations exhibited mixed signals (e.g., no change, decrease), in 2015 compared to 2010 results. Elevated specific conductance of select surface waters in during 2015 relative to 2010 likely reflects an increase in the proportion of streamflow originating from contributions from groundwater impacted by legacy road salt runoff, and a lack of dilution from recent precipitation inputs, relative to 2010 monitoring when streamflow was generally within normal to above normal ranges. Specific conductance was not significantly greater during 2020 than in 2010 at any locations, or during any other monitoring periods.

Turbidity decreased at all monitoring sites in the East Branch Swift River Sanitary District between 2010 and 2015. Site 216D in the Rutland Subbasin has exhibited declining annual median turbidity since 2010 monitoring began.

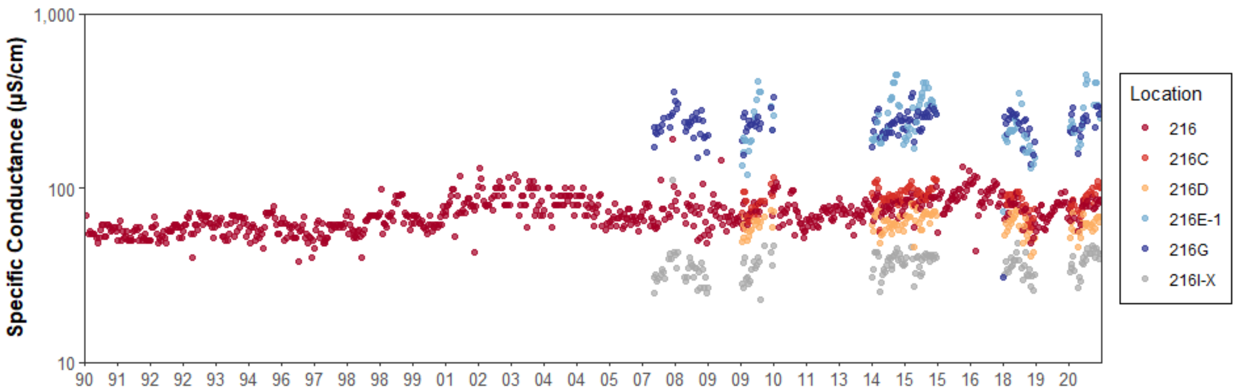

Figure 1. Time series of specific conductance measured in East Branch Swift River tributary monitoring sites.

Table 2. Results (p-values) of non-parametric Kruskal-Wallace test for water quality parameters measured in tributaries in the EBSR sanitary district during 2011, 2015, 2019, and 2020. *Red* text denotes significance at α=0.05.

Parameter	216	216C	216D	216G	216I-X	216E-1
NO_3-N	0.463	0.423	0.473	0.603	*0.001*	*0.000*
NH_3-N	0.705	0.765	0.108	0.178	0.130	0.549
TKN	0.270	0.704	0.066	0.600	0.092	*0.015*
Total Phosphorus	*0.006*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Total Coliform	0.415	0.397	0.136	0.202	0.694	0.871
E. coli	0.595	0.204	*0.006*	0.077	0.934	0.318
Turbidity	*0.015*	*0.023*	*0.001*	0.142	*0.043*	*0.000*
UV_{254}	0.784	*0.002*	0.465	0.313	0.448	0.127
Temperature	0.967	0.997	0.958	0.967	0.999	0.931
Specific Conductance	*0.000*	*0.000*	*0.000*	*0.000*	*0.004*	*0.027*
Dissolved Oxygen	0.220	0.391	0.345	0.193	0.385	0.451

Additionally, annual median concentrations of total phosphorus (TP) observed in all surface water monitoring sites within each sanitary district (aside from 216I-X) were significantly different than those of prior monitoring periods (Table 2). The latter is likely attributable to a change in analytical methods that occurred at the beginning of 2020 (see Tributary Results in main text), rather than an actual disruption of factors controlling the phosphorus cycle within the sanitary district, as no other related parameters exhibited widespread significant changes from prior monitoring periods. No other parameters were affected by the change in analytical methods. TP concentrations in surface water in the East Branch Swift River sanitary district exhibited typical seasonal variations.

Surface water samples collected in 2020 throughout the East Branch Swift River sanitary district ultimately revealed no widespread indicators of impairment/degradation of water quality. Monitoring of EQA sites in the East Branch Swift River sanitary district will resume in 2025.

Table 3. Results (adjusted p-values with Bonferroni correction) of post-hoc Wilcoxon Rank Sum tests between 2010 results and 2014, 2015, 2018, and 2020 results for select water quality parameters measured in Core and EQA sites in the EBSR sanitary district. Statistical analyses were not performed for nutrients measured at site 108, due to quarterly (n=4) monitoring frequencies in place prior to 2020. *Red* text denotes significance at α=0.05.

Comparison Year	Site no.	NO_3-N	TKN	TP	Turbidity	UV_{254}	SC
2014	216	-	-	-	0.805	-	1
	216C	1	1	1	1	0.062	0.119
	216D	1	1	1	*0.024*	1	1
	216G	1	1	1	0.283	1	1
	216I-X	0.137	0.337	1	1	1	1
	216E-1	*0.007*	1	1	0.317	1	1
2015	216	-	-	-	*0.015*	-	*0.004*
	216C	1	1	1	*0.039*	1	*0.003*
	216D	1	1	1	*0.005*	1	*0.021*
	216G	1	1	1	0.973	1	0.241
	216I-X	*0.002*	1	1	1	1	0.188
	216E-1	*0.024*	*0.039*	1	*0.004*	1	0.406
2018	216	-	-	-	1	-	0.241
	216C	1	1	1	1	*0.004*	1
	216D	1	0.28	1	*0.003*	1	1
	216G	1	1	1	1	0.748	1
	216I-X	0.057	0.165	*0.034*	0.215	1	1
	216E-1	1	0.881	1	1	0.494	1
2020	216	-	-	-	0.521	-	1
	216C	1	1	*3.99E-05*	1	0.327	1
	216D	1	0.262	*0.002*	*0.012*	1	1
	216G	1	1	*4.14E-04*	1	1	1
	216I-X	1	1	1	0.079	1	1
	216E-1	1	1	*3.38E-04*	0.632	1	0.768

East Swift Upper Subdistrict

No significant differences in water quality were observed consistently at sites 216G or 216E-1 in the East Swift Upper subdistrict.

East Petersham Subdistrict

Annual median turbidity has been decreasing at 216D (Comet Pond Outlet) in the East Petersham subdistrict since 2010. No other parameters have exhibited persistent, significant changes over the intervals compared.

East Swift Lower Subdistrict

Specific conductance measured at site 216E-1 in the East Swift Upper subdistrict exceeded the MassDEP chronic threshold for aquatic life (904 µS/cm) on September 01, 2020. At the time of measurement, field observations indicated that streamflow was extremely low, coincident with the extended period of drought that impacted Worcester County during 2020 (ranging from D0 through D2 level for six consecutive months). Two weeks prior to this observation (August 18, 2020), no streamflow was present at this location. Thus, it is possible that contributions from upstream stagnant waters may have contributed to the anomaly in specific conductance at 216E-1. No significant changes (aside from TP) in water quality were observed during 2020 when compared to prior monitoring at sites within the East Swift Lower subdistrict.

Pottapaug Subdistrict

Surface water quality was not monitored in Pottapaug Subdistrict in 2020.

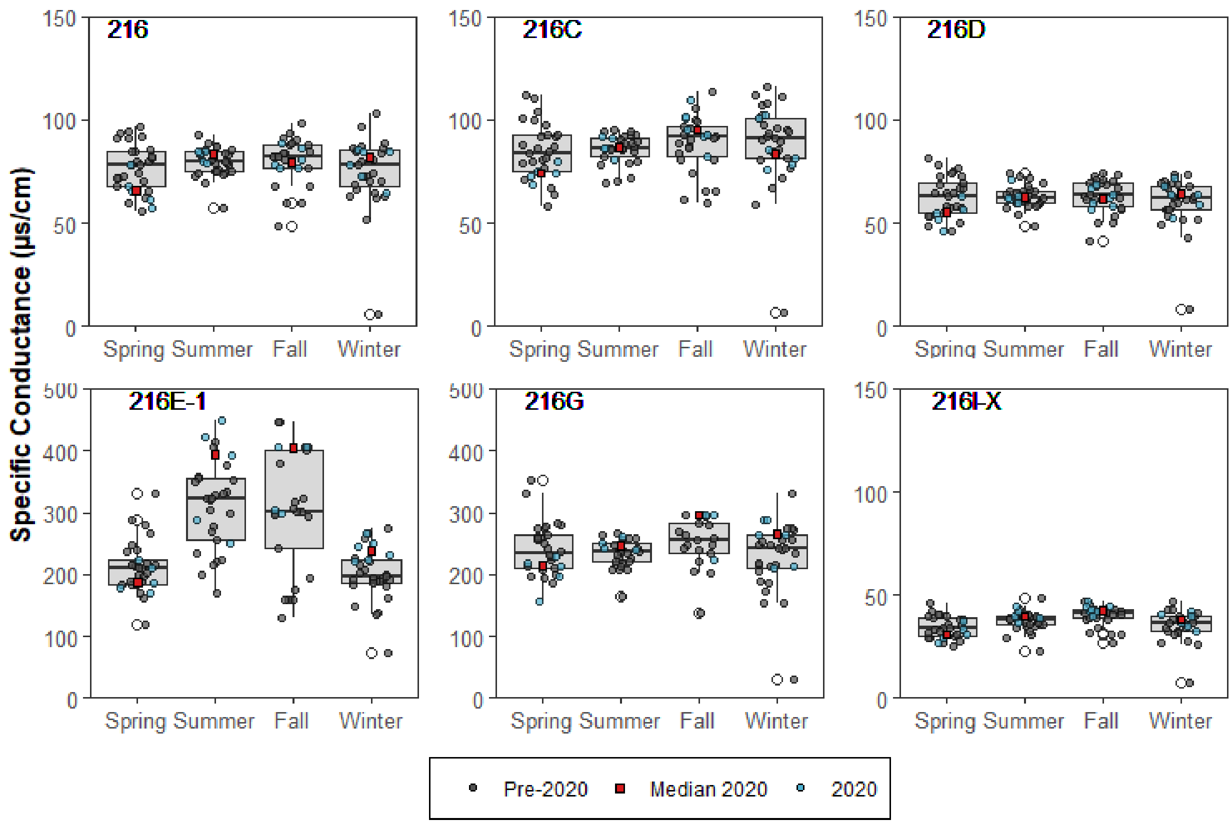

Figure 2. Boxplots depicting the seasonal distributions of specific conductance observed in East Branch Swift River watershed DWSP Core and EQA tributary monitoring sites. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

Table 4. Annual descriptive statistics for specific conductance measured in surface water within the East Branch Swift River Sanitary District. Red text denotes sites with gaps of over two consecutive months of data collection corresponding to moderate to severe drought in Worcester County, MA from August through November 2020. Note: Anomalously low minimum specific conductance during 2018 likely are the result of sensor malfunction at select sites on January 2, 2018.

DWSP Site No.	Year	Count	Minimum	Median	Average	Maximum
216	2010	26	62	74	76	96.8
	2014	26	55.9	78.2	77.5	93.2
	2015	26	59.4	87.05	86.4	103
	2018	24	5.6	73.6	69.9	93
	2020	22	57	78.75	77.2	88.9
216C	2010	26	59	80	81.5	116.3
	2014	26	57.7	88.35	89.6	112.1
	2015	27	80.1	95.3	96.1	113.5
	2018	24	6.3	80.45	77.8	94.9
	2020	23	68.4	86	87.1	110
216E-1	2010	25	120	204.3	237.2	413
	2014	26	179.4	230.3	264.2	447
	2015	26	168.8	297.6	288.5	406.6
	2018	25	73.2	199.2	196.9	353
	2020	21	169.3	251.7	315.5	1,005
216D	2010	26	49	62	61.2	74.5
	2014	26	48.1	61.6	61.9	74.9
	2015	26	46.2	69.7	68.5	81.8
	2018	25	8.5	60	57.3	74.1
	2020	23	46	61.8	61.1	71.7
216G	2010	25	155	234	237.6	331.4
	2014	25	171.4	227.5	226	283.7
	2015	26	184.9	259.15	261.1	353.3
	2018	23	30.6	240.2	220.8	279.8
	2020	18	157.2	240.1	241.8	296
216I-X	2010	26	23	36	35.1	47
	2014	26	25.3	38.55	37.4	45.3
	2015	23	27.2	39.6	38.4	46.2
	2018	24	7.4	34.5	34.1	48.4
	2020	23	26.8	39.7	38.7	46.8

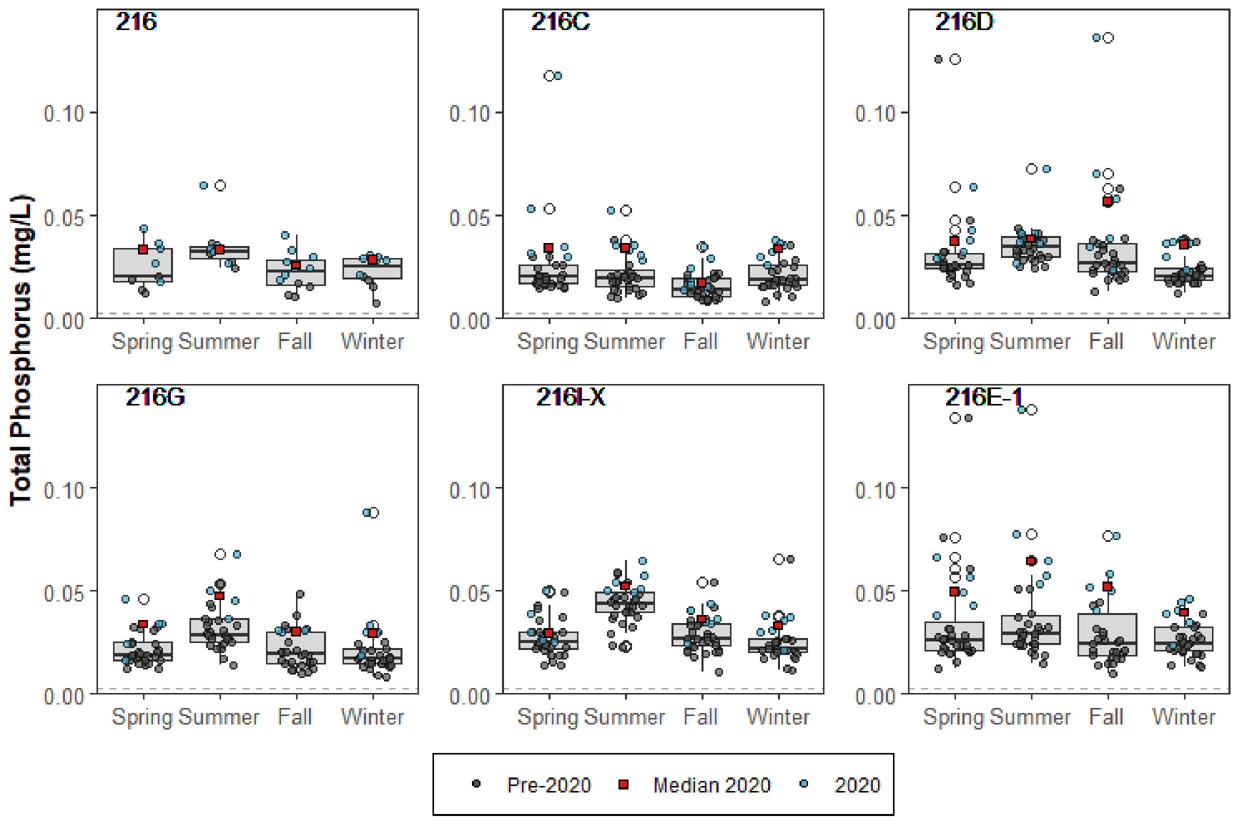

Figure 3. Boxplots depicting the seasonal distributions of total phosphorus observed in East Branch Swift River watershed DWSP Core and EQA tributary monitoring sites. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. The horizontal gray line signifies one-half of the greatest laboratory detection limits (0.0017mg/L).

References

Division of Water Supply Protection. 2020. Water Quality Report: 2019 Quabbin Reservoir Watershed Ware River Watershed. Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management.

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East Branch Ware River Sanitary District

Water quality in surface water in the East Branch Ware River sanitary district in 2020 was generally comparable to that of previous monitoring periods, with several noteworthy exceptions. Samples were collected biweekly from six locations within the East Branch Ware River sanitary district in 2020 (Table 1), and analyzed for a range of constituents (DWSP, 2021) to evaluate potential impacts to water quality in each subdistrict. Concentrations of constituents measured in 2020 were compared to results from prior monitoring periods (2010, 2015, and 2019) using the non-parametric Kruskal-Wallace (KS) test. If results from the Kruskal–Wallis tests indicated that there were significant differences among years, a post-hoc analysis was performed to determine which years were different. Non-parametric statistical methods were appropriate due to non-normal distributions of the data (Helsel and Hirsch, 2002; Helsel 2012). Lastly, concentration data from 2020 was compared to regulatory thresholds/limits, when applicable.

Table 1. Sample sites within East Branch Ware River Sanitary District monitored in 2016-2020 reporting cycle. Note: Subdistrict designation denotes the subdistrict corresponding to the greatest proportion of upstream contributing area for each site (see Figure 3, main text).

Subdistrict	Core	Site Description	DWSP Site No.
Pommogusset	Core	East Branch Ware River, at Intervale Road	108
East Branch Ware	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

Most pronounced, annual median specific conductance was significantly greater in 2020 than 2011 at all surface water quality monitoring locations in the East Branch Ware River sanitary district (Table 2). Relative to 2015 monitoring, annual median specific conductance increased only at 108C and 116 (East Branch Ware Headwaters and Asnacomet subdistrict, respectively). Specific conductance was significantly greater in 2020 relative to 2019 at 116 (Asnacomet) only. All other locations exhibited mixed signals (e.g., no change, significant decrease), compared to 2015 or 2019 results. Elevated specific conductance of surface waters in during 2020 relative to 2019 likely reflects an increase in the proportion of streamflow originating from contributions from groundwater impacted by legacy road salt runoff, and a lack of dilution from recent precipitation inputs, relative to 2019 monitoring when streamflow was generally within normal to above normal ranges. Notably, Worcester County experienced abnormally dry, moderate, to severe drought for six consecutive months in 2020 (see Precipitation results in Main text), and daily streamflow in the Ware River fell below 25th percentile lows for several months during the summer of 2020. Elevated specific conductance of surface waters in 2020 relative to 2015 or 2011 may reflect the interaction of watershed-wide response to severe drought coupled with the long-term impacts of deicing salt application to impervious surfaces across the sanitary district.

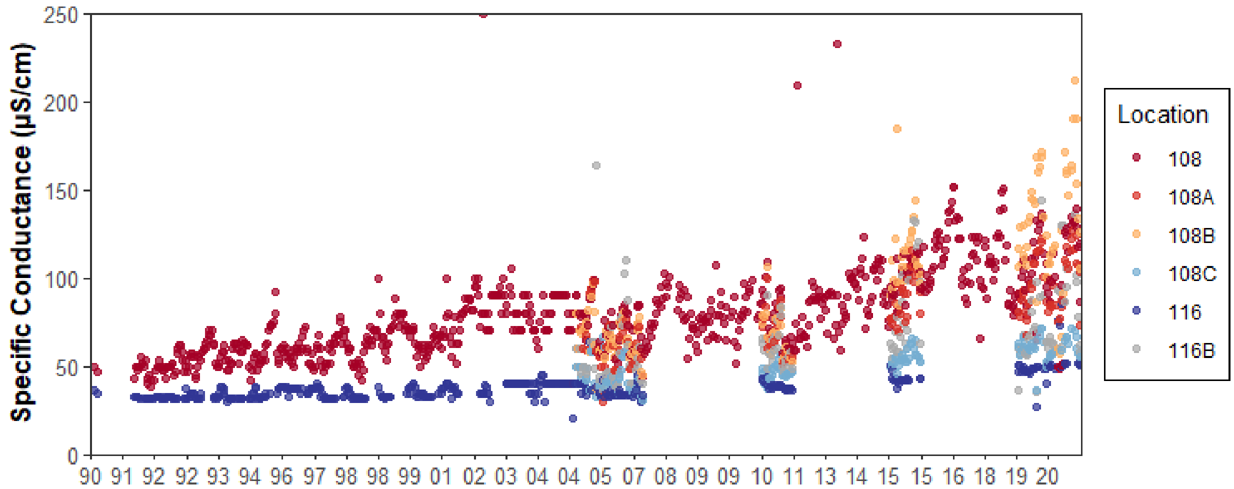

Figure 2. Time series of specific conductance measured in East Branch Ware River tributary monitoring sites.

Table 2. Results (p-values) of non-parametric Kruskal-Wallace test for water quality parameters measured in tributaries in the EBSR sanitary district during 2011, 2015, 2019, and 2020. Red text denotes significance at α=0.05.

Parameter	108	108A	108B	108C	116	116B
NO_3N	0.486	0.234	*0.000*	0.175	0.059	0.113
NH_3N	0.342	0.175	*0.006*	0.677	0.295	*0.000*
TKN	0.938	0.722	*0.000*	*0.000*	0.211	0.226
Total Phosphorus	*0.037*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Total Coliform	0.809	0.509	0.848	0.978	0.084	0.771
E. coli	0.714	0.953	0.162	0.752	0.928	0.307
Turbidity	0.951	0.950	*0.002*	0.893	*0.043*	0.425
UV_{254}	0.771	0.526	*0.000*	*0.027*	*0.000*	0.681
Temperature	0.895	0.935	0.953	0.911	0.664	0.636
Specific Conductance	*1.10E-06*	*9.60E-09*	*9.70E-12*	*1.23E-12*	*2.18E-12*	*3.28E-04*
Dissolved Oxygen	0.867	0.938	0.747	0.724	0.715	0.569

Additionally, annual median concentrations of total phosphorus (TP) observed in all surface water monitoring sites within each sanitary district were significantly different than those of prior monitoring periods (Table 2). The latter is likely attributed to a change in analytical methods that occurred at the beginning of 2020 (see Tributary Results in main text), rather than an actual disruption of factors controlling the phosphorus cycle within the sanitary district, as no other related parameters exhibited widespread significant changes from prior monitoring periods. No other parameters were affected by the change in analytical methods. TP concentrations in surface water in the East Branch Ware River sanitary district exhibited typical seasonal variations.

Surface water samples collected in 2020 throughout the East Branch Ware River sanitary district ultimately reveled no widespread indicators of impairment/degradation of water quality, aside from increasing conductivity at select locations from 2011 measures. Monitoring of EQA sites in the East Branch Ware River sanitary district will resume in 2025.

Table 3. Results (adjusted p-values with Bonferroni correction) of post-hoc Wilcoxon Rank Sum tests between 2011 results and 2015, 2019, and 2020 results for select water quality parameters measured in Core and EQA sites in the EBWR sanitary district. Statistical analyses were not performed for nutrients measured at site 108, due to quarterly (n=4) monitoring frequencies in place prior to 2020. Red text denotes significance at α=0.05.

Comparison Year	Site no.	NO_3-N	TKN	TP	Turbidity	UV_{254}	SC
2015	108	-	-	-	1	1.00	4.87E-06
	108A	1.00	1	0.522	1	1	1.12E-05
	108B	0.05	0.088	1	1	9.42E-05	1.54E-08
	108C	1.00	0.015	0.003	1	0.075	9.42E-07
	116	1.00	0.942	0.099	0.672	0.376	1.76E-04
	116B	1.00	1	1	1	1	0.006
2019	108	-	-	-	1	1.00	1.35E-05
	108A	1.00	1	1	1	1	3.73E-06
	108B	0.83	2.03E-04	2.49E-05	0.004	4.94E-06	8.28E-09
	108C	1.00	0.001	1	1	0.786	2.63E-07
	116	0.23	1	1	1	0.003	1.42E-06
	116B	0.97	0.505	0.72	1	1	0.196
2020	108	-	-	-	1	1.00	0.003
	108A	0.33	1	0.002	1	1	1.49E-06
	108B	0.00	6.84E-07	1	0.81	7.92E-07	5.24E-06
	108C	0.18	6.66E-07	1.75E-07	1	0.074	5.48E-08
	116	1.00	0.224	0.006	1	1	1.58E-06
	116B	1.00	1	0.016	1	1	0.001

Asnacomet Subdistrict

Site 116 in the Asnacomet subdistrict demonstrated significantly greater annual median specific conductance in 2020 relative to all prior monitoring periods. This result is complicated by gaps ins sample collection during 2020 that may have biased the annual dataset towards seasons that typically have greater specific conductance (e.g. summer and winter), and was further complicated by the extended period of drought that impacted Worcester County during 2020 (ranging from D0 through D2 level for six consecutive months), which may have resulted in a relative increase in the proportion of streamflow originating from groundwater contributions. Thus, caution should be exercised when interpreting the apparent upward trend in specific conductance for site 116. Site 116B in the Asnacomet subdistrict demonstrated significantly greater annual median specific conductance in 2020 than in 2011 only.

East Branch Ware Headwaters Subdistrict

Specific conductance (annual median) at site 108C (East Branch Ware Headwaters) was not significantly greater during 2020 than in 2019, despite an annual maximum specific conductance of 332 µS/cm (site maximum for the period of record) at this location in June 2020 (Table 3).

East Branch Ware Subdistrict

Annual median specific conductance in 2020 was significantly greater than that of 2011 at sites 108A and 108B in the East Branch Ware subdistrict (Table 2). Annual median specific conductance for 2020 increased at 108A and decreased at 108B from 2019, although not significantly.

Pommogusset Subdistrict

Annual median specific conductance at sites 108 in the Pommogusset subdistrict was significantly greater in 2020 than 2011 (Table 2).

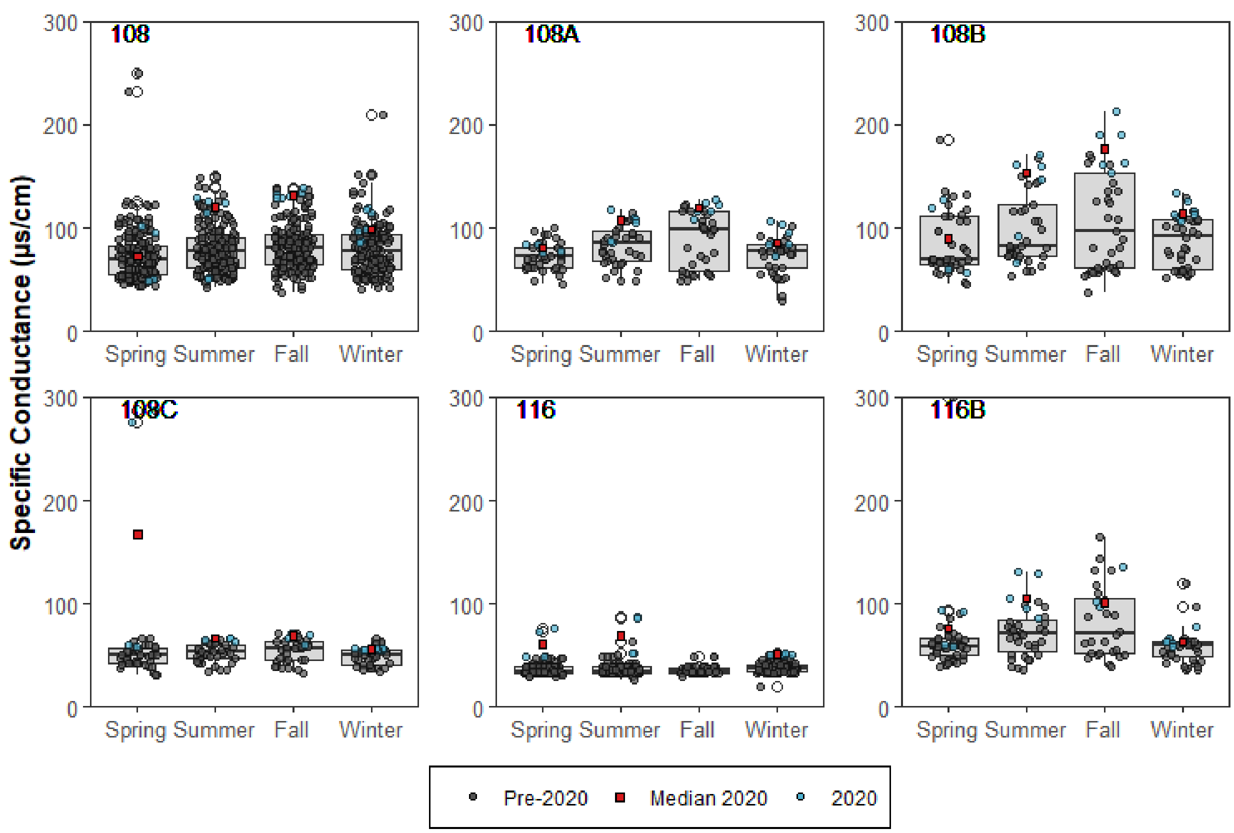

Figure 2. Boxplots depicting the seasonal distributions of specific conductance observed in East Branch Ware River watershed DWSP Core and EQA tributary monitoring sites. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

Table 4. Annual descriptive statistics for specific conductance measured in surface water within the East Branch Ware River Sanitary District. Red text denotes sites with gaps of over two consecutive months of data collection corresponding to moderate to severe drought in Worcester County, MA from August through November 2020.

Subdistrict	DWSP Site No.	Year	Specific Conductance (µS/cm)				
			Count	Minimum	Median	Average	Maximum
Pommogusset	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
		2020	23	49.2	115.2	104.8	139.4
East Branch Ware	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
		2020	23	73.2	103.8	99.2	126.7
	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
		2020	23	57	127.1	132.5	212.3
East Branch Ware Headwaters	108C	2011	26	37	46.6	46.8	56.5
		2015	26	46.3	54.2	55.2	65.4
		2019	26	36	61	60.3	71.7
		2020	21	55.2	62.7	107.8	332.2
Asnacomet	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
		2020	15	49	51.3	59.2	87.1
	116B	2011	26	47.1	58.8	60.9	90.4
		2015	22	54.4	70	81.2	132.5
		2019	24	35.3	64.6	69.8	144.5
		2020	19	57.9	86.1	86.4	136.3

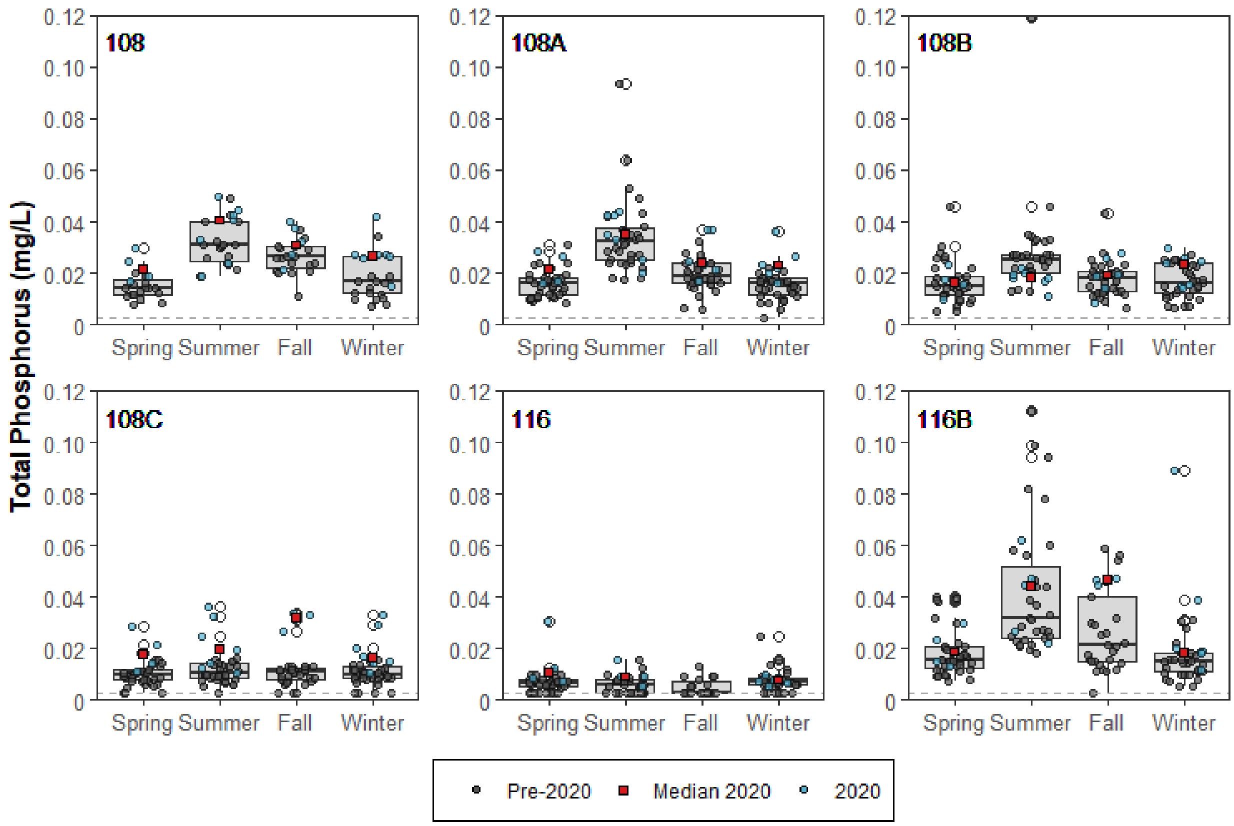

Figure 3. Boxplots depicting the seasonal distributions of total phosphorus observed in East Branch Ware River watershed DWSP Core and EQA tributary monitoring sites. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. The horizontal gray line signifies one-half of the greatest laboratory detection limits (0.0017mg/L).

References

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Helsel, D.R., 2012. Statistics for censored environmental data using Minitab and R, 2nd edition. John Wiley and Sons, New York. 344 p.

Appendix C. Figures and Tables

Tributary Monitoring: Temperature and Dissolved Oxygen

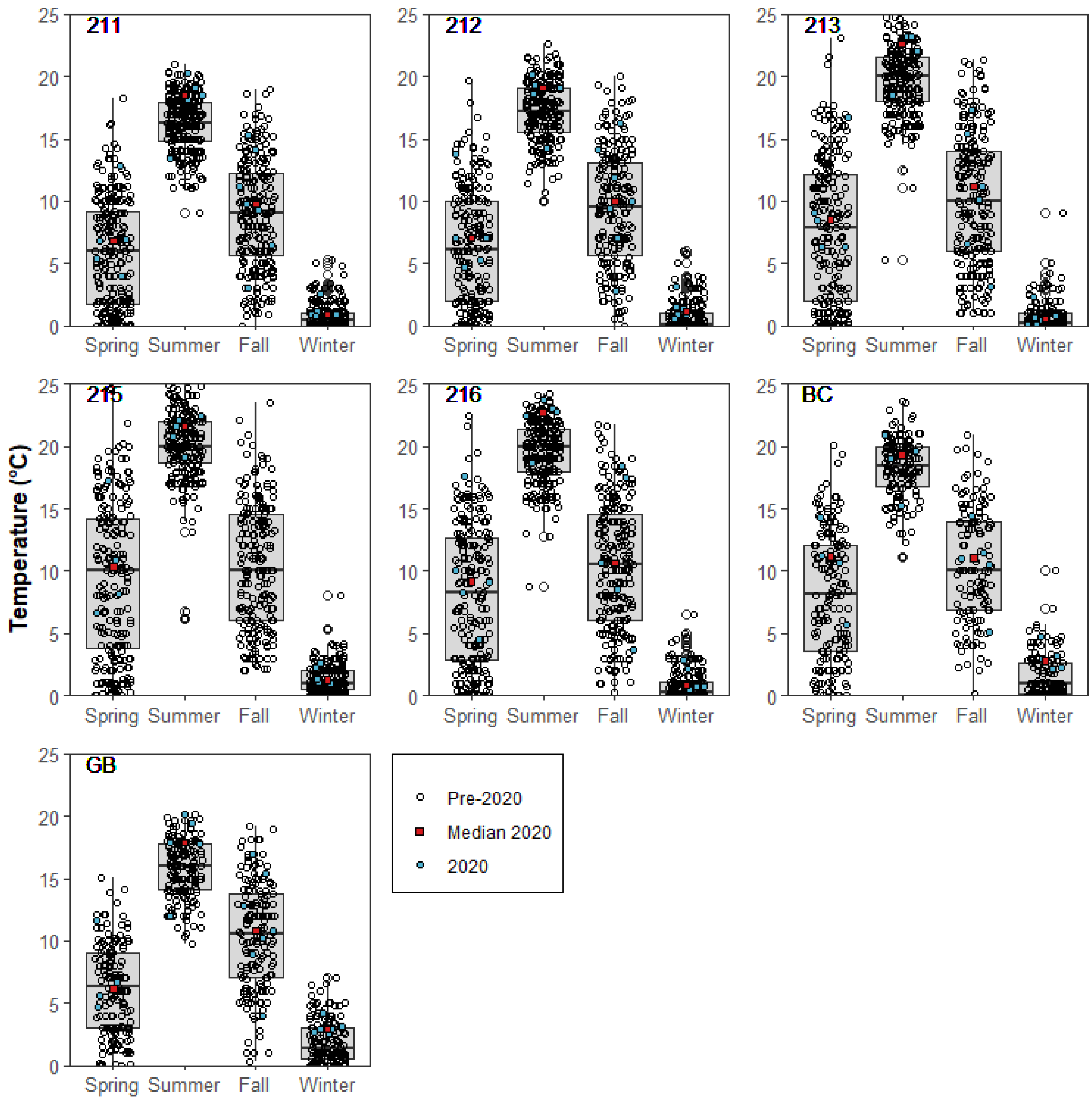

Figure C1. Boxplots depicting seasonal distributions of temperature observed in Quabbin Reservoir watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

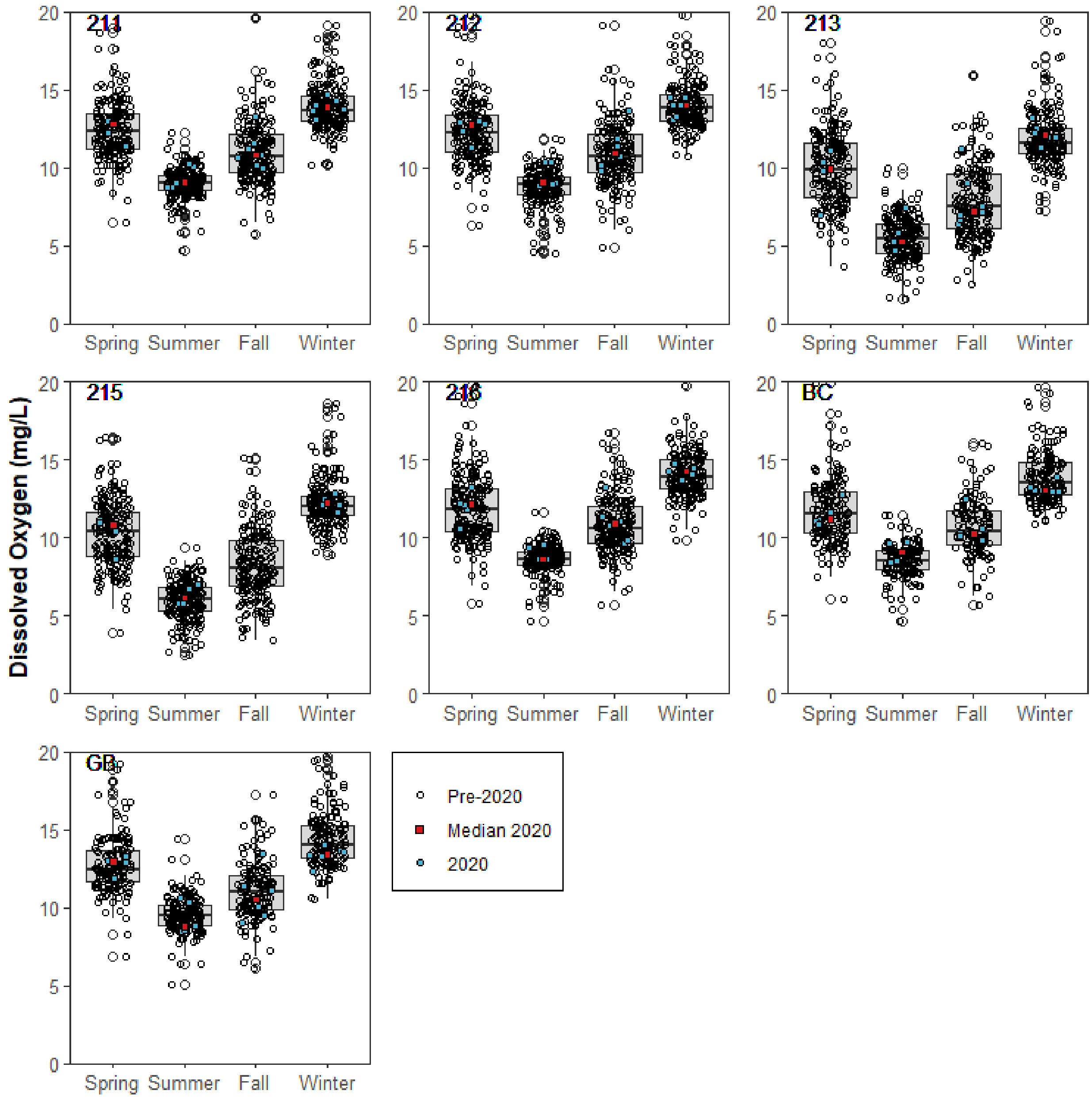

Figure C2. Boxplots depicting seasonal distributions of dissolved oxygen observed In Quabbin Reservoir watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. Dissolved oxygen concentrations >20 mg/L were considered suspect and excluded for visualization purposes. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

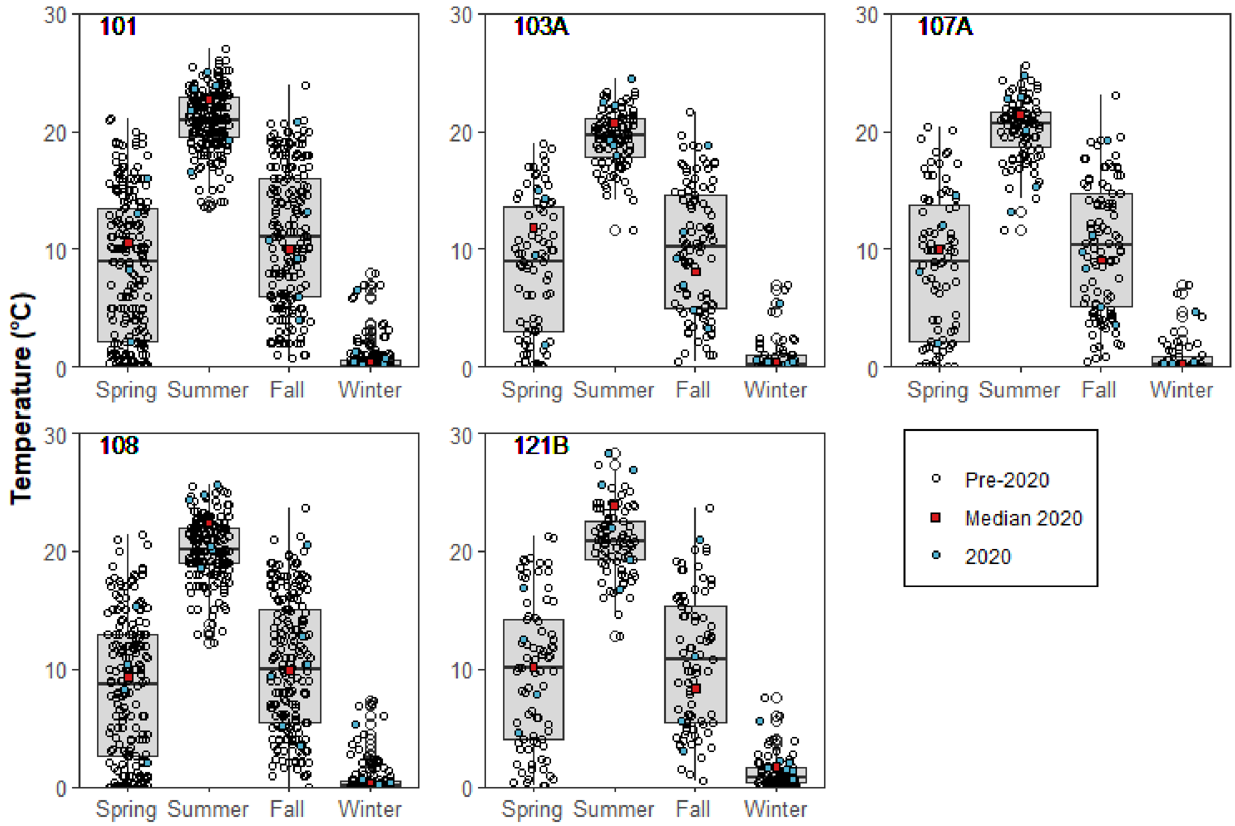

Figure C3. Boxplots depicting seasonal distributions of temperature observed In Ware River watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

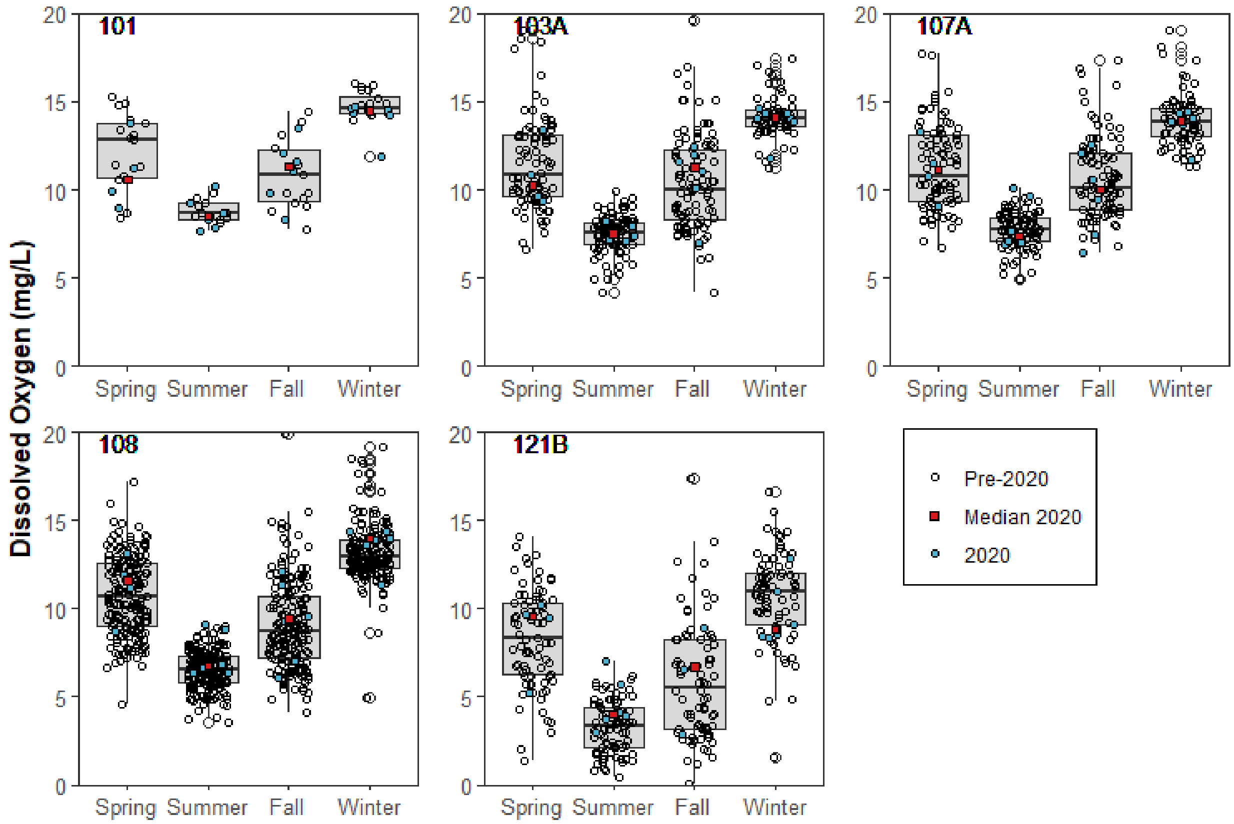

Figure C4. Boxplots depicting seasonal distributions of dissolved oxygen observed In Ware River watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. Dissolved oxygen concentrations >20 mg/L were considered suspect and excluded for visualization purposes. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

Table C1. Descriptive statistics (minimum, median, average, and maximum) for temperature and dissolved oxygen in Core tributaries in the Quabbin Reservoir watershed during 2020.

Site	Season	Water Temperature (°C)					Dissolved Oxygen (mg/L)				
		Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max
211	Spring	5	3.98	6.80	7.19	12.8	5	11.4	12.8	12.5	13.0
	Summer	5	13.4	18.5	17.9	20.2	5	8.73	9.07	9.36	10.2
	Fall	7	3.03	9.76	9.86	15.2	7	9.95	10.8	11.1	13.3
	Winter	6	0.76	0.90	1.19	2.53	6	13.0	13.9	13.9	14.7
212	Spring	5	4.69	7.05	7.56	13.7	5	11.3	12.8	12.4	13.0
	Summer	5	14.2	19.1	18.3	20.1	5	8.79	9.06	9.50	10.4
	Fall	7	2.79	9.97	10.2	16.3	7	9.74	10.9	11.2	13.7
	Winter	6	0.55	1.14	1.37	3.08	6	13.1	14.0	13.9	14.5
213	Spring	5	6.37	8.49	9.39	16.7	5	6.93	9.92	9.62	11.1
	Summer	5	18.5	22.6	21.9	23.3	5	4.69	5.26	5.65	7.43
	Fall	7	3.14	11.2	11.6	17.4	7	6.42	7.18	7.85	11.2
	Winter	6	0.07	0.53	0.71	2.26	6	11.3	12.1	12.2	13.2
215	Spring	5	6.67	10.3	10.7	17.2	5	8.57	10.9	10.4	11.1
	Summer	5	19.2	21.6	21.2	22.5	5	5.77	6.16	6.28	7.01
	Fall	0	-	-	-	-	0	-	-	-	-
	Winter	6	1.01	1.22	1.55	2.56	6	11.6	12.2	12.3	12.8
216	Spring	5	4.46	9.13	9.88	17.6	5	10.5	12.1	12.0	13.2
	Summer	5	18.7	22.8	22.1	23.7	5	8.59	8.61	8.95	9.57
	Fall	6	3.71	10.6	11.6	18.5	6	9.65	10.9	11.0	13.2
	Winter	6	0.48	0.85	1.29	2.80	6	137	14.3	14.2	14.8
BC	Spring	5	5.72	11.2	10.6	14.3	5	10.9	11.2	11.5	12.8
	Summer	4	15.2	19.4	18.7	21.0	4	8.40	9.08	9.08	9.76
	Fall	5	5.05	11.0	10.5	14.4	5	9.85	10.3	10.65	12.45
	Winter	6	2.11	2.79	2.98	4.71	6	13.0	13.0	13.18	13.86
GB	Spring	4	4.63	6.19	7.16	11.6	4	11.9	12.9	12.75	13.27
	Summer	5	12.0	17.9	17.5	20.1	5	8.51	8.81	9.36	10.63
	Fall	7	3.92	10.8	11.3	16.9	7	9.02	10.6	10.74	13.45
	Winter	6	2.61	2.89	3.06	4.15	6	12.3	13.4	13.37	14.08

Table C2. Descriptive statistics (minimum, median, average, and maximum) for temperature and dissolved oxygen in Core tributaries in the Ware River watershed during 2020.

Site	Season	Water Temperature (°C)					Dissolved Oxygen (mg/L)				
		Count	Min	Med	Avg	Max	Count	Min	Med	Avg	Max
101	Spring	4	2.21	10.6	9.86	16.0	4	9.00	10.6	11.0	13.8
	Summer	6	16.6	22.7	21.7	25.1	6	7.62	8.51	8.66	10.2
	Fall	6	3.96	10.0	10.7	20.8	6	8.30	11.3	11.0	13.5
	Winter	7	-0.08	0.47	1.34	6.55	7	11.9	14.5	14.1	14.7
103A	Spring	4	1.86	11.9	10.1	15.0	4	9.31	10.2	10.8	13.4
	Summer	6	18.0	20.7	20.9	24.5	6	7.05	7.5	7.56	8.18
	Fall	6	3.24	8.08	9.08	18.8	6	7	11.3	10.7	12.5
	Winter	7	0.15	0.49	1.16	5.43	7	11.8	14.1	13.9	14.6
107A	Spring	4	2.02	10.01	9.15	14.6	4	9.09	11.1	11.2	13.3
	Summer	6	13.2	21.4	19.8	24.7	6	6.88	7.36	8.05	10.1
	Fall	6	3.51	9.06	9.52	19.2	6	6.47	10.0	9.77	12.5
	Winter	7	-0.01	0.27	0.86	4.76	7	11.7	13.9	13.7	14.4
108	Spring	4	2.11	9.33	9.03	15.4	4	8.71	11.6	11.2	13.1
	Summer	6	18.6	22.4	22.3	25.6	6	6.35	6.73	7.35	9.10
	Fall	6	3.46	9.94	10.3	20.6	6	6.12	9.43	9.24	12.1
	Winter	7	-0.08	0.35	0.99	5.33	7	11.4	14.0	13.7	14.4
121B	Spring	4	4.67	10.2	10.5	16.9	4	5.21	9.57	8.65	10.2
	Summer	6	16.7	23.9	23.2	28.3	6	2.99	4.03	4.58	7.01
	Fall	4	3.01	8.36	10.2	21.0	4	2.89	6.67	6.28	8.88
	Winter	7	0.61	1.67	2.15	5.56	7	8.31	8.81	9.56	12.9

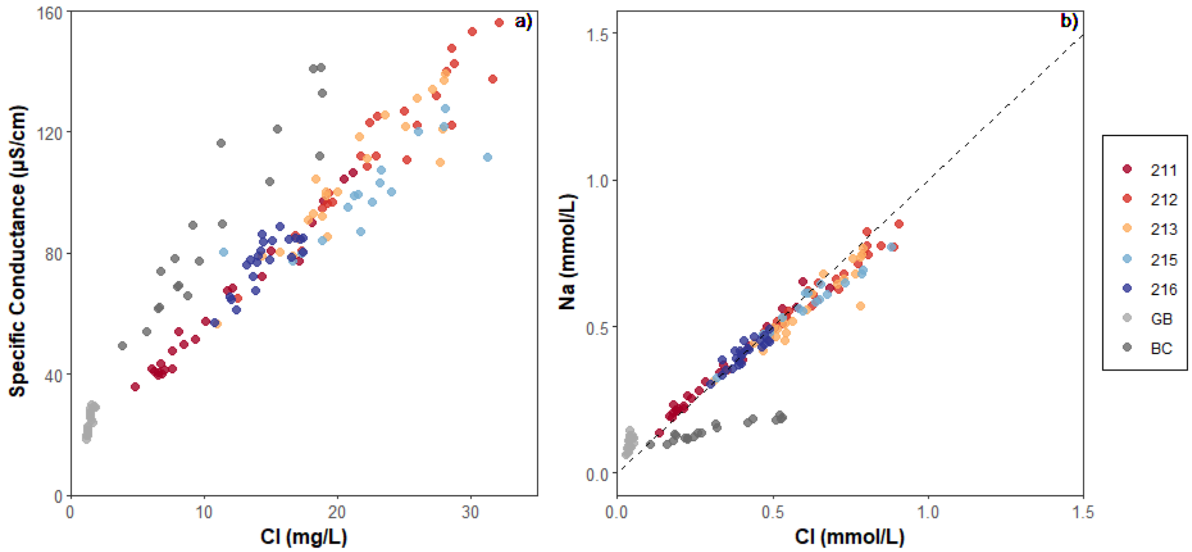

Figure C5. a) Specific conductance and concentrations of chloride and b) molar ratios of sodium and chloride in in Core tributaries in the Quabbin Reservoir watershed in 2020. The dashed line denotes a 1:1 molar ratio of sodium to chloride. The clustering of results around the 1:1 line suggests that concentrations of sodium and chloride in most tributaries to the Quabbin Reservoir likely originate from halite sources (e.g. road salt). The linear relationship among variables reveals that specific conductance in most Core tributaries is predominantly controlled by concentrations of dissolved chloride.

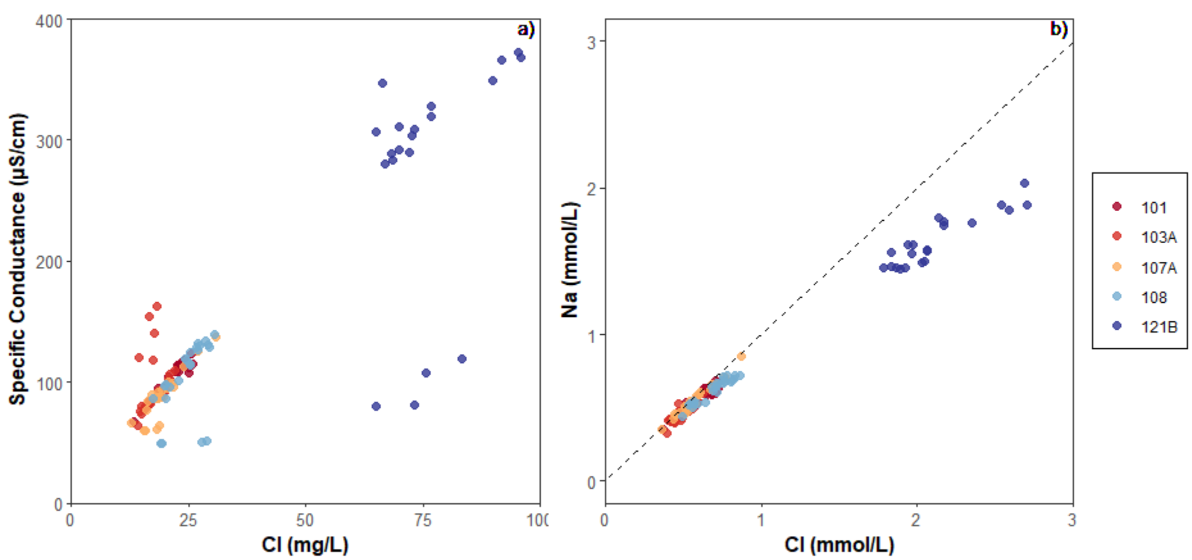

Figure C6. a) Specific conductance and concentrations of chloride and b) molar ratios of sodium and chloride in in Core tributaries in the Ware River watershed in 2020. The dashed line denotes a 1:1 molar ratio of sodium to chloride. The clustering of results around the 1:1 line suggests that concentrations of sodium and chloride in most tributaries to the Ware River likely originate from halite sources (e.g. road salt). The linear relationship among variables reveals that specific conductance in most Core tributaries is predominantly controlled by concentrations of dissolved chloride.

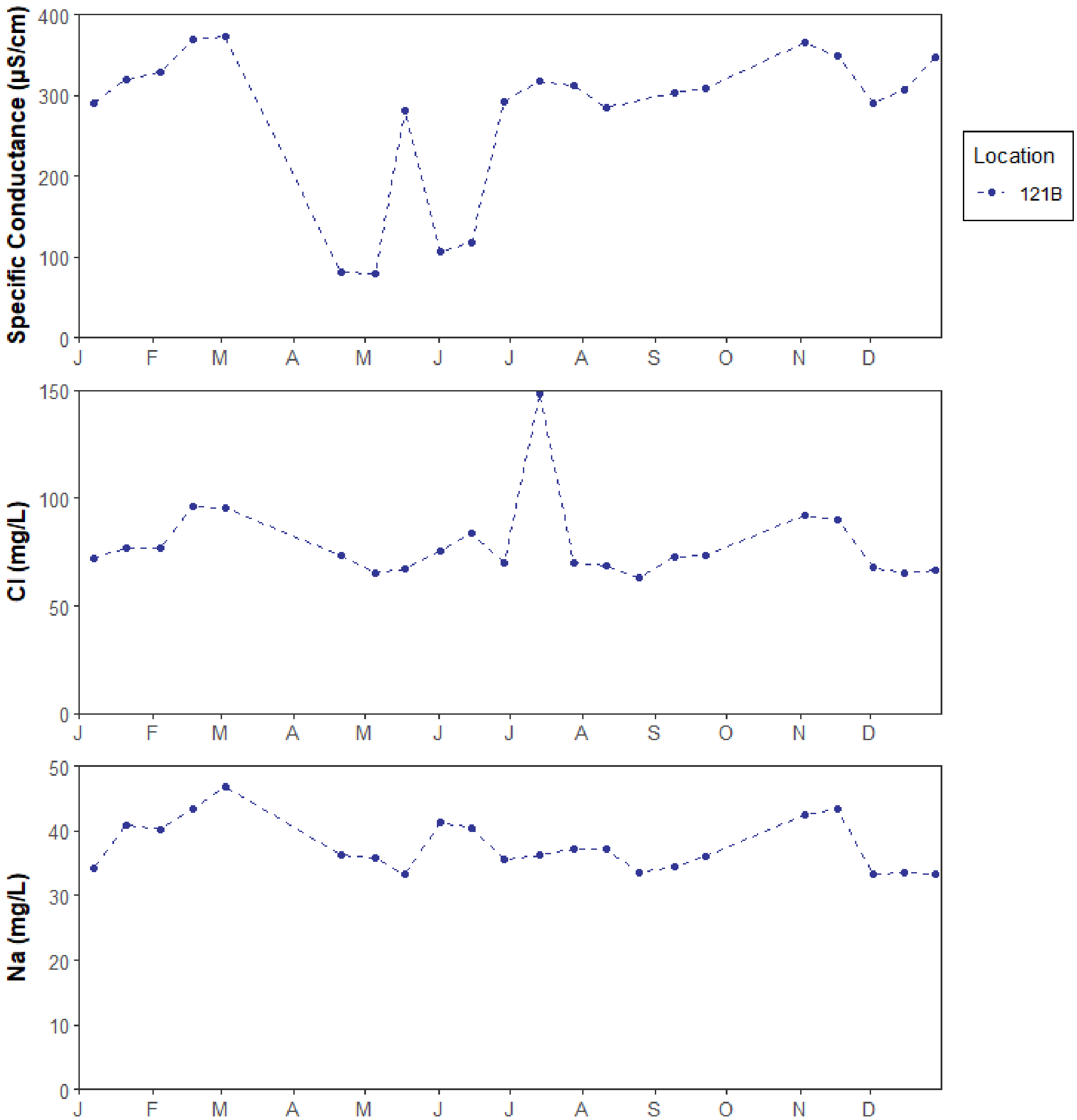

Figure C7. Time series of specific conductance, Cl, and Na measured at site 121B in the Ware River watershed in 2020.

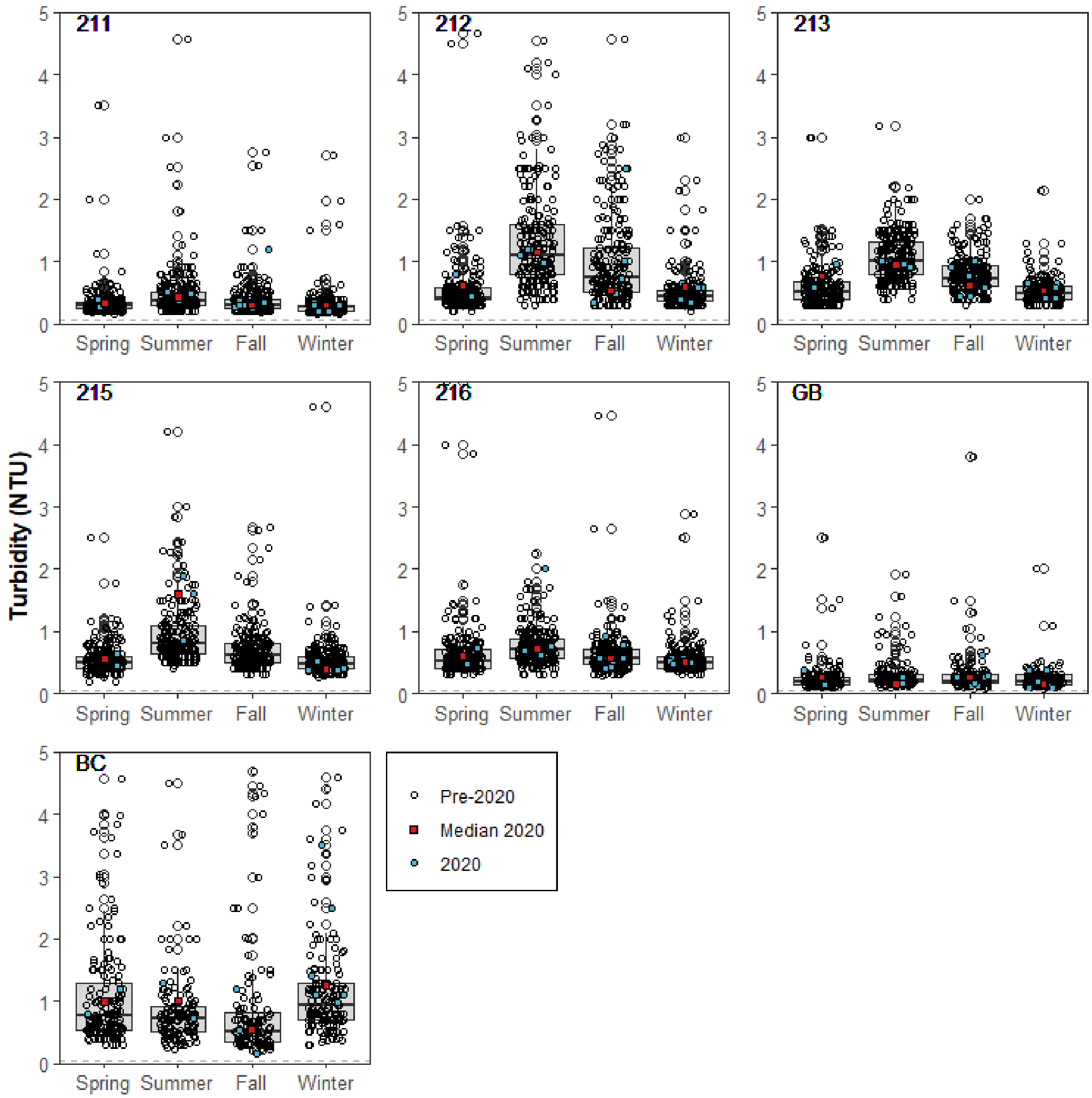

Figure C8. Boxplots depicting seasonal distributions of turbidity observed In Quabbin Reservoir watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

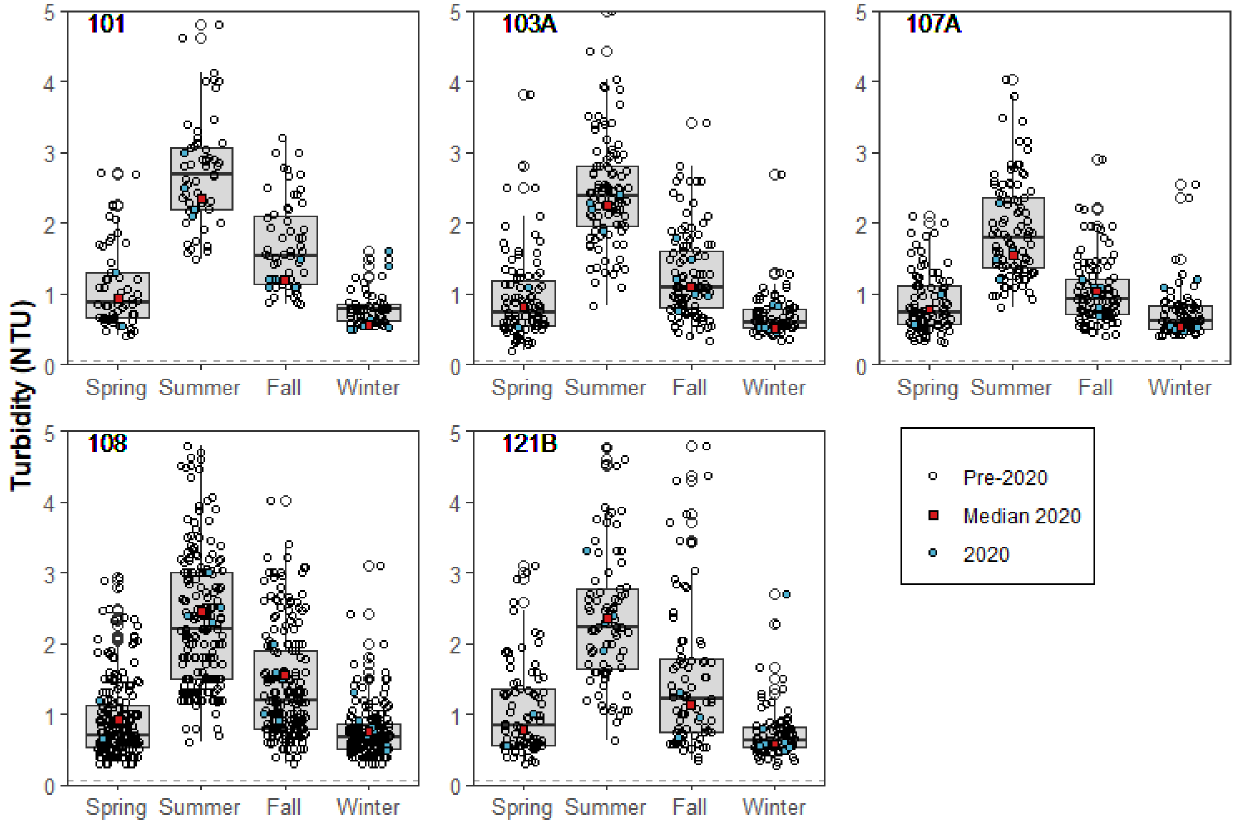

Figure C9. Boxplots depicting seasonal distributions of turbidity observed In Ware River watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

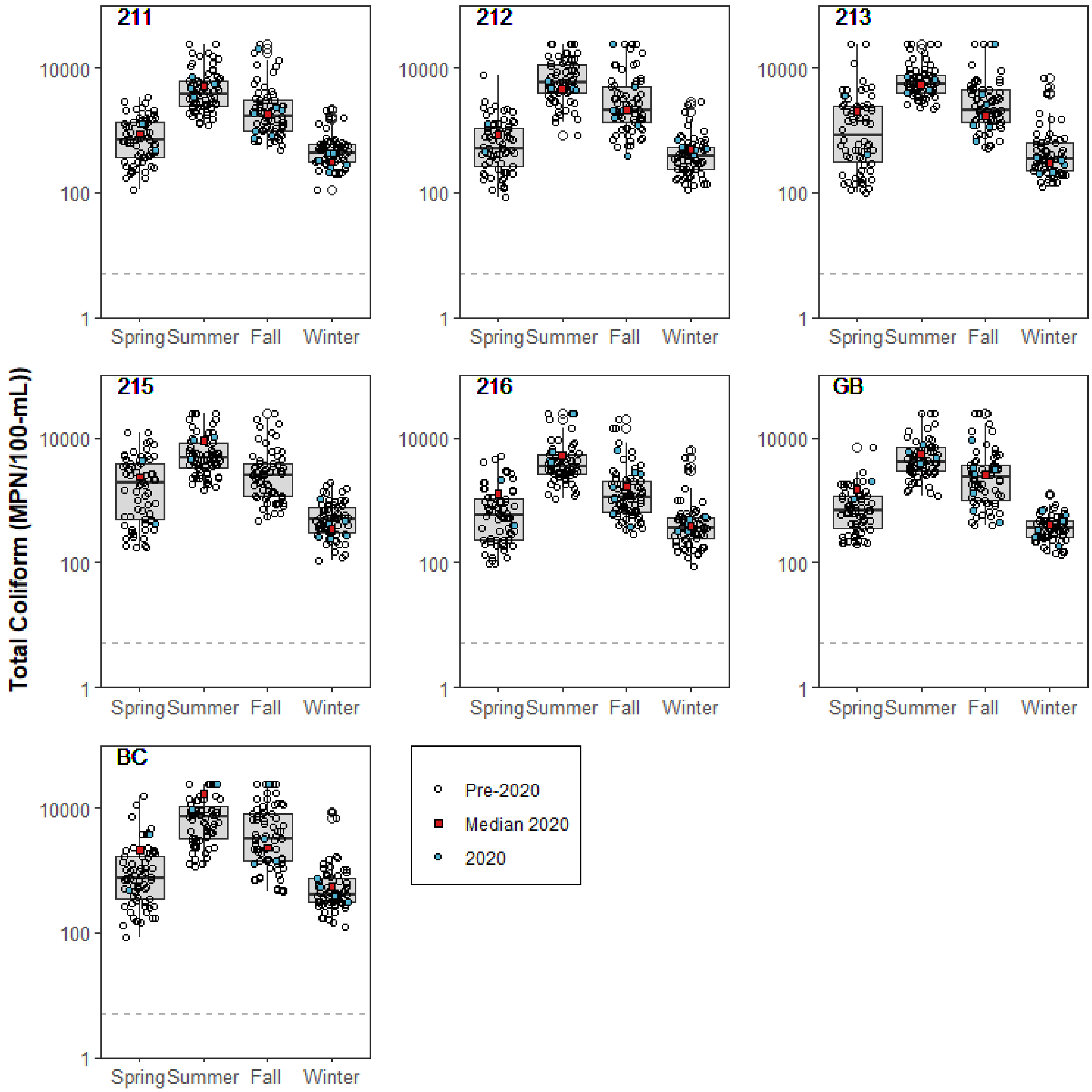

Figure C10. Boxplots depicting seasonal distributions of total coliform observed In Quabbin Reservoir watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively. The dashed horizontal line represents one-half of the greatest laboratory detection limit (5 MPN/100-mL).

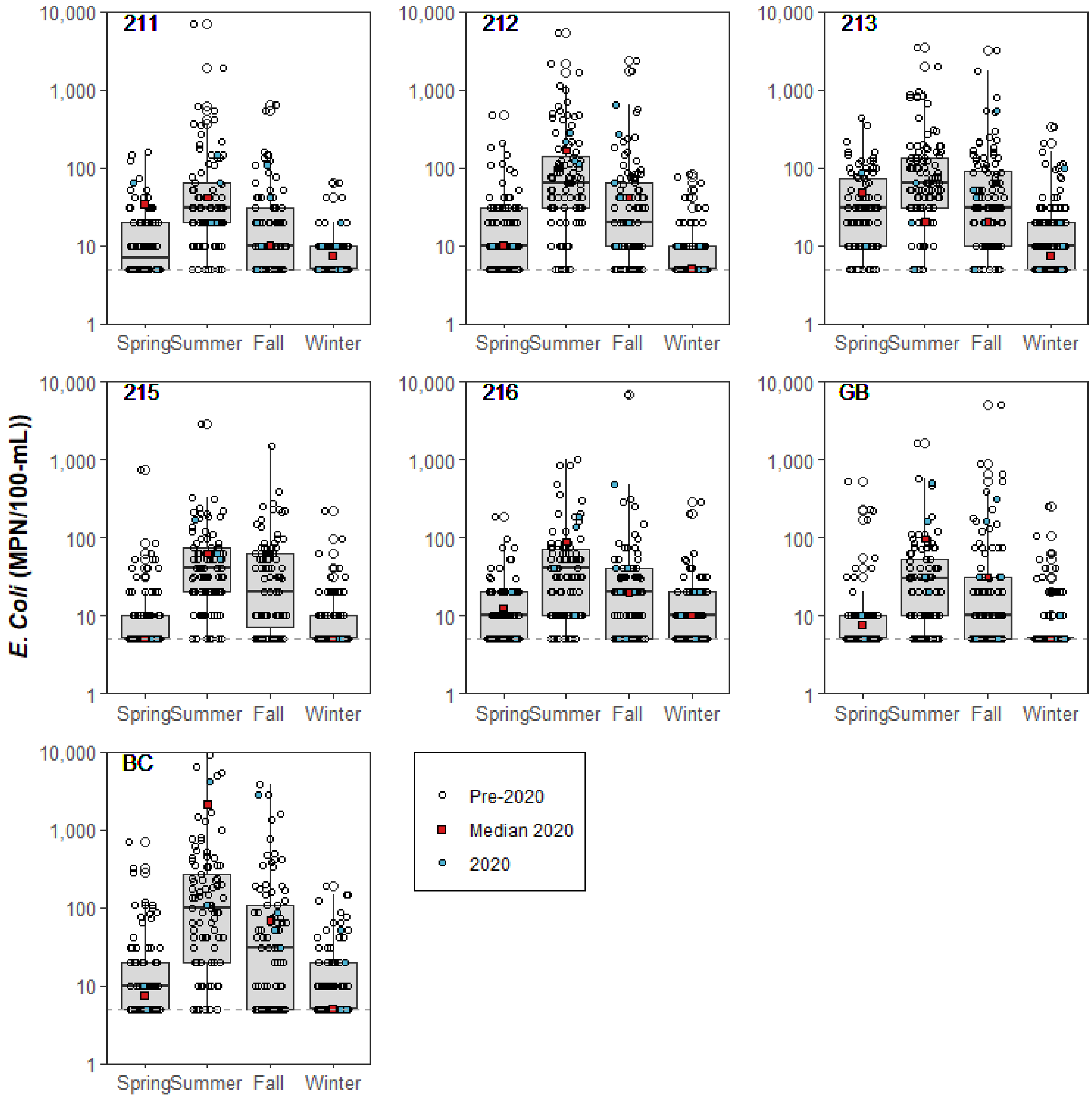

Figure C11. Boxplots depicting seasonal distributions of *E. coli* observed In Quabbin Reservoir watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively. The dashed horizontal line represents one-half of the greatest laboratory detection limit (5 MPN/100-mL).

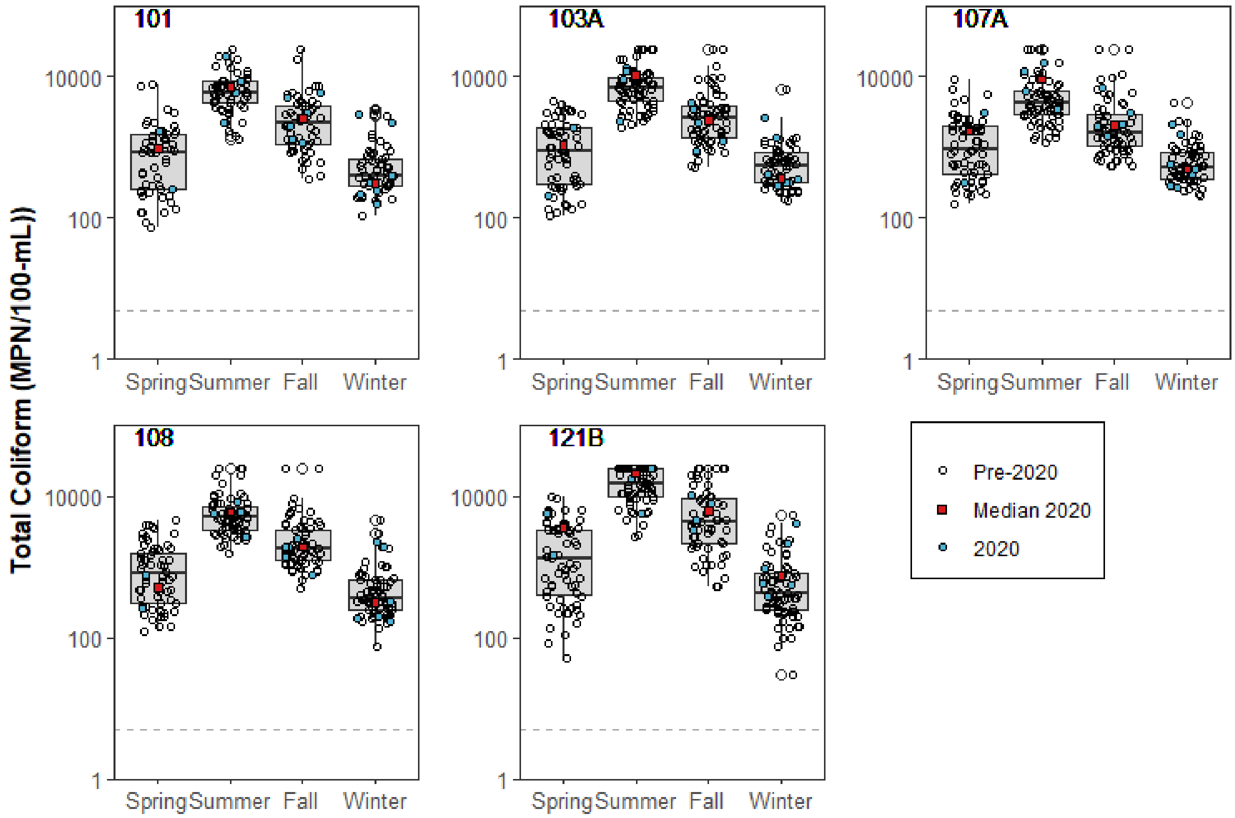

Figure C12. Boxplots depicting seasonal distributions of total coliform observed In Ware River watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively. The dashed horizontal line represents one-half of the greatest laboratory detection limit (5 MPN/100-mL).

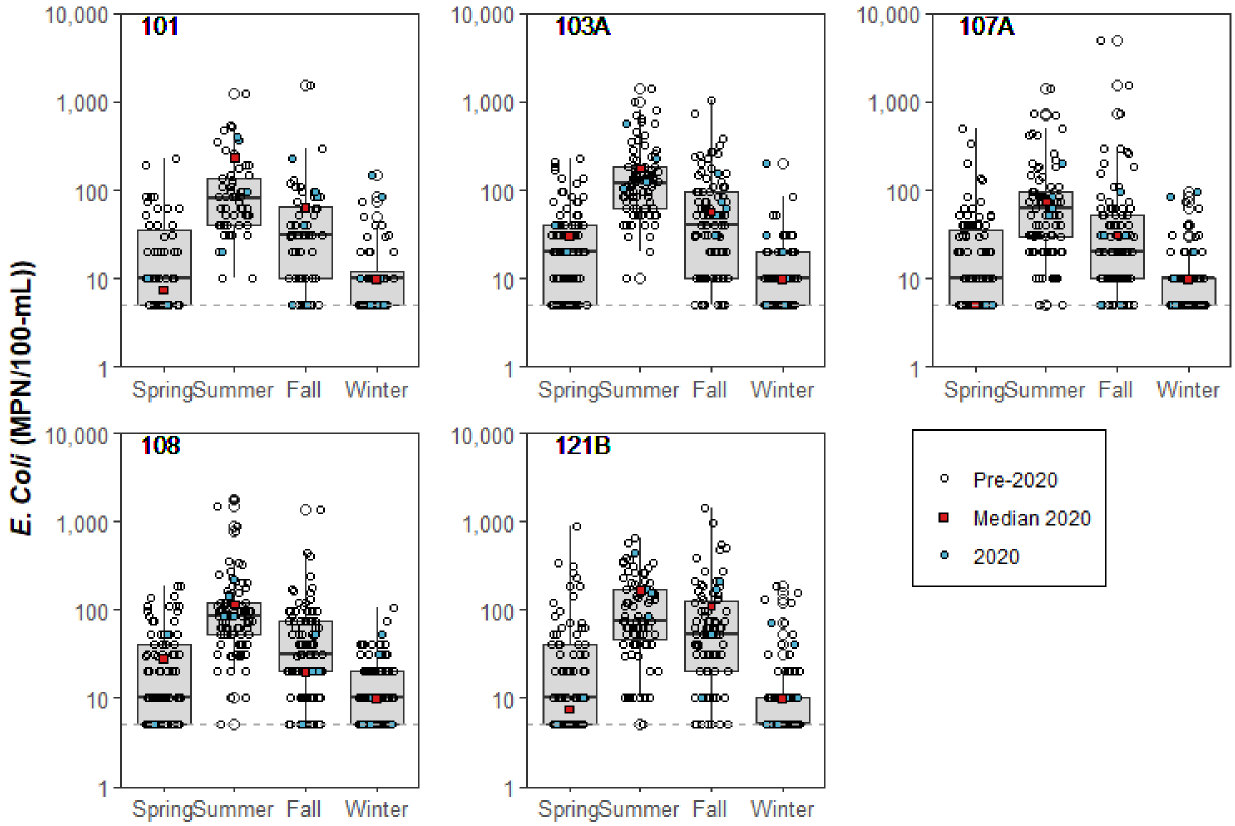

Figure C13. Boxplots depicting seasonal distributions of *E. coli* observed In Ware River watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively. The dashed horizontal line represents one-half of the greatest laboratory detection limit (5 MPN/100-mL).

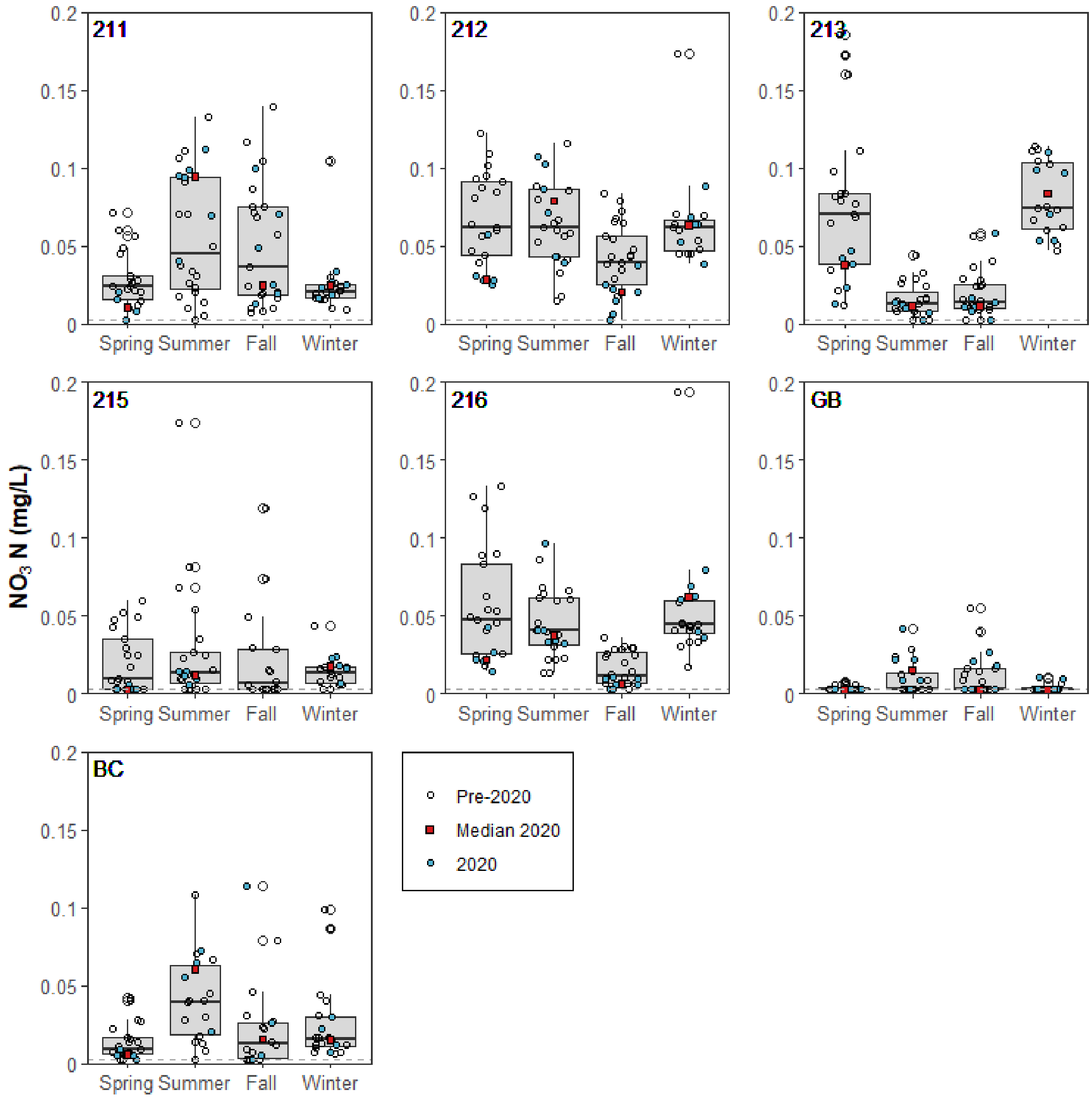

Figure C14. Boxplots depicting seasonal distributions of NO_3-N observed In Quabbin Reservoir watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively. The dashed horizontal line represents one-half of the greatest laboratory detection limit (0.0025 mg/L).

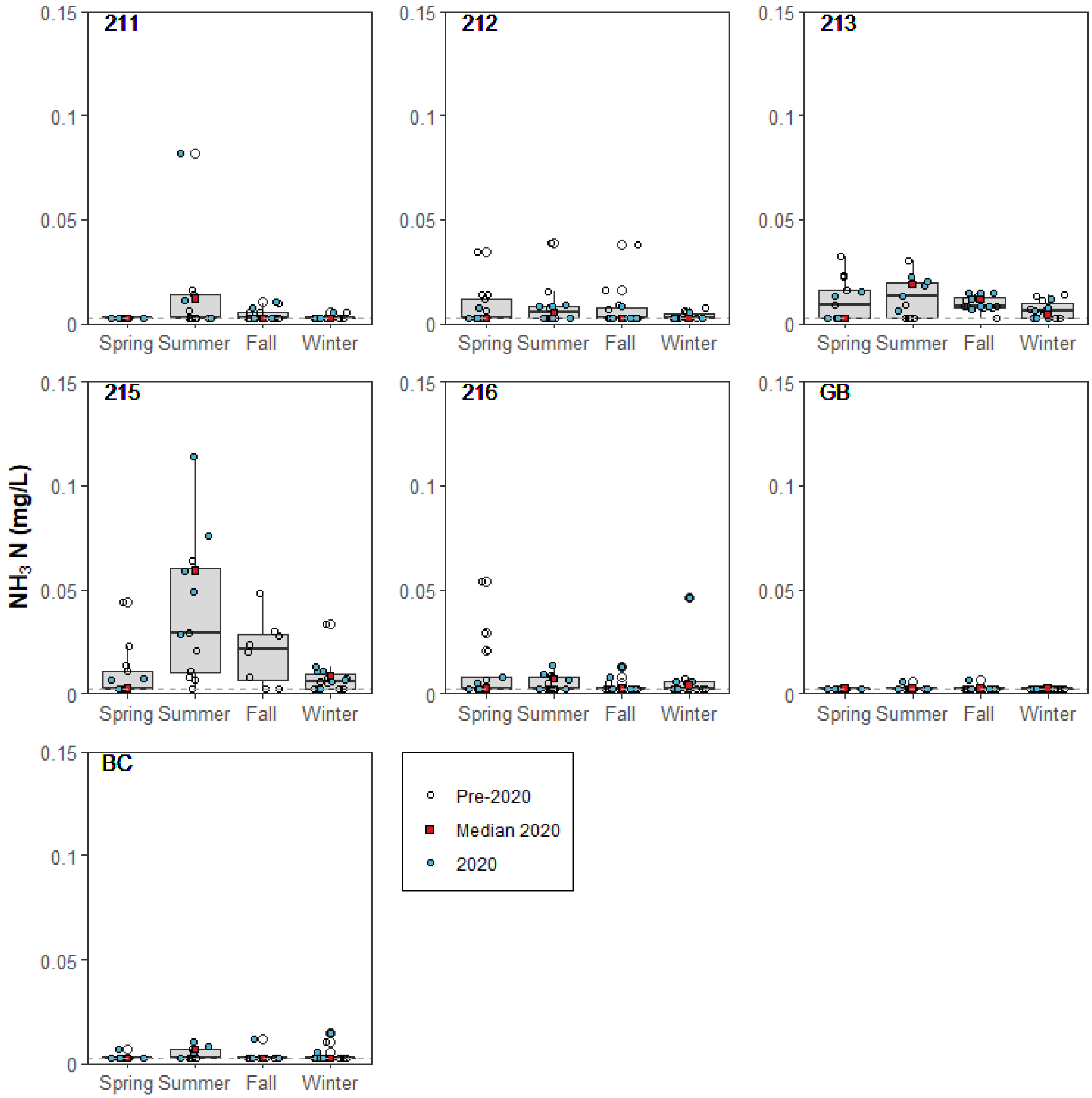

Figure C15. Boxplots depicting seasonal distributions of NH_3-N observed In Quabbin Reservoir watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively. The dashed horizontal line represents one-half of the greatest laboratory detection limit (0.0025 mg/L).

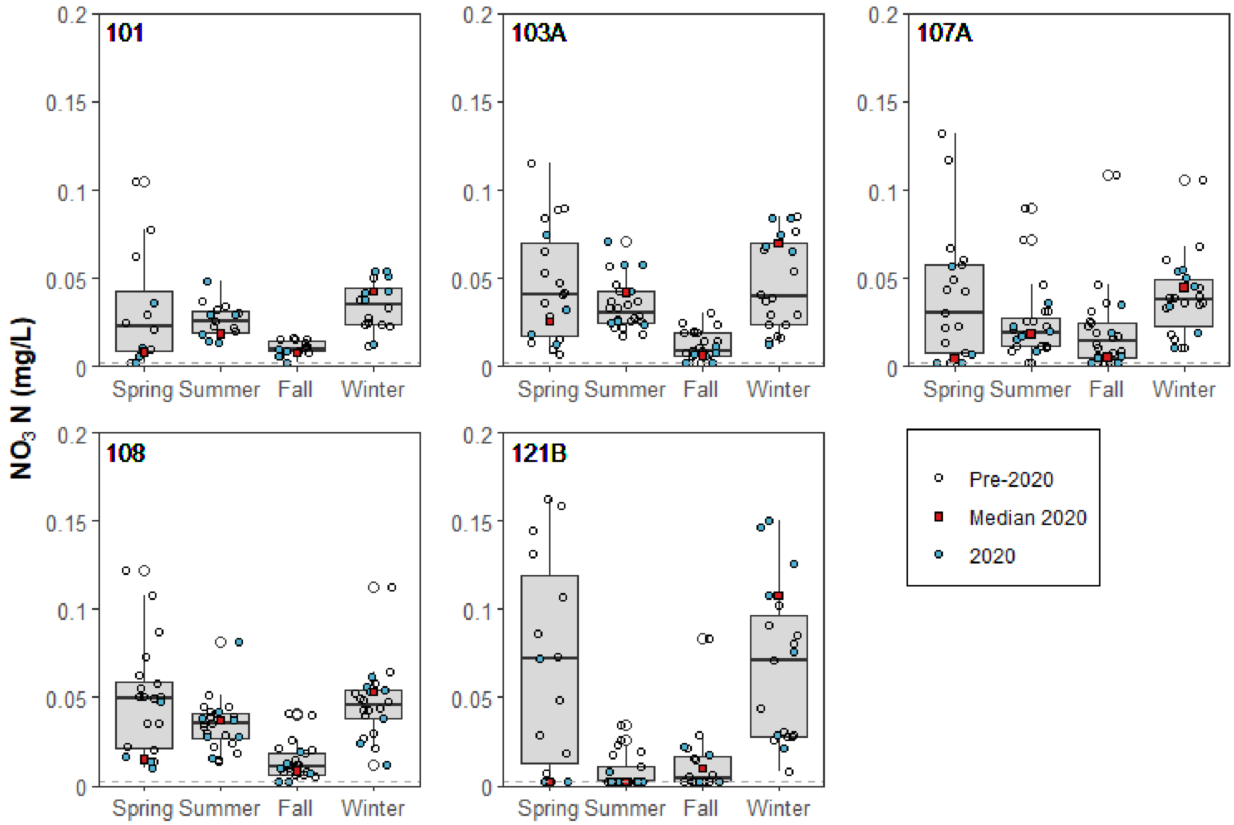

Figure C16. Boxplots depicting seasonal distributions of NO_3-N observed In Ware River watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively. The dashed horizontal line represents one-half of the greatest laboratory detection limit (0.0025 mg/L).

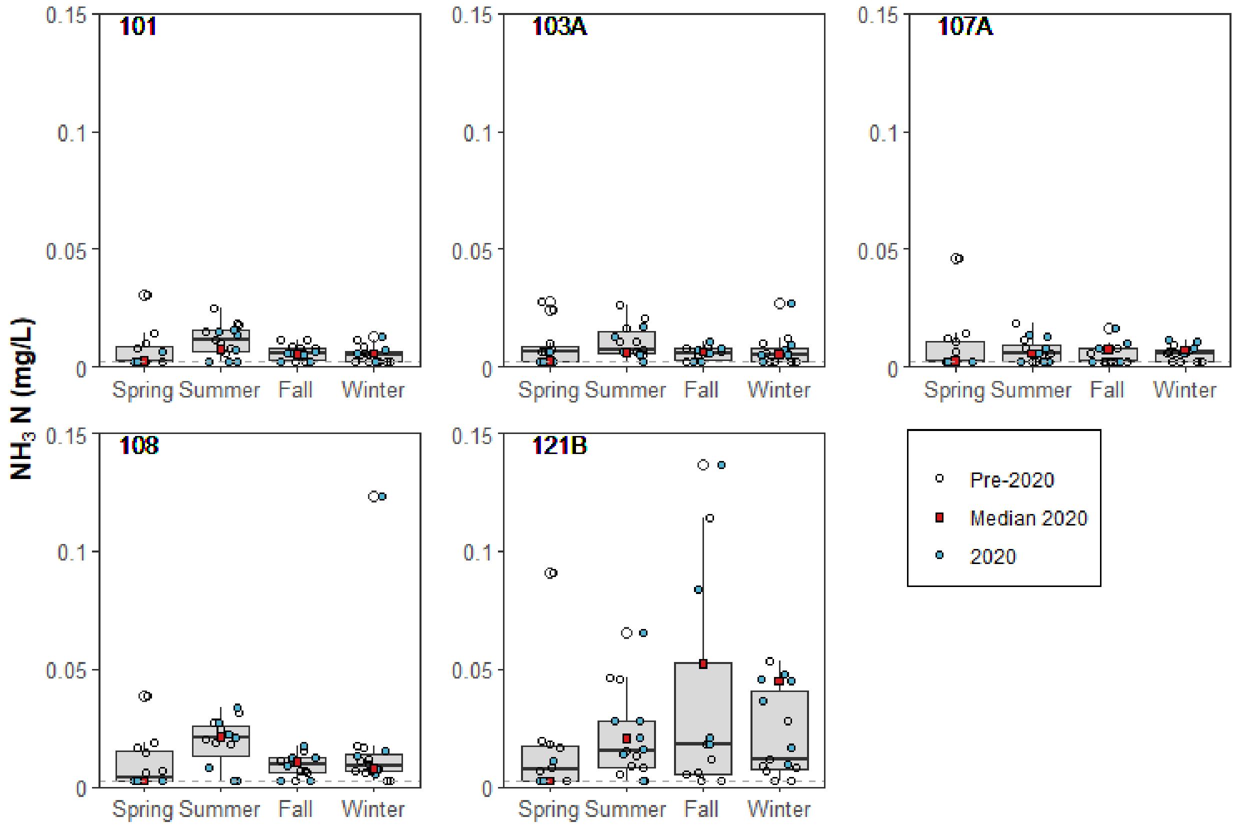

Figure C17. Boxplots depicting seasonal distributions of NH_3-N observed In Ware River watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively. The dashed horizontal line represents one-half of the greatest laboratory detection limit (0.0025 mg/L).

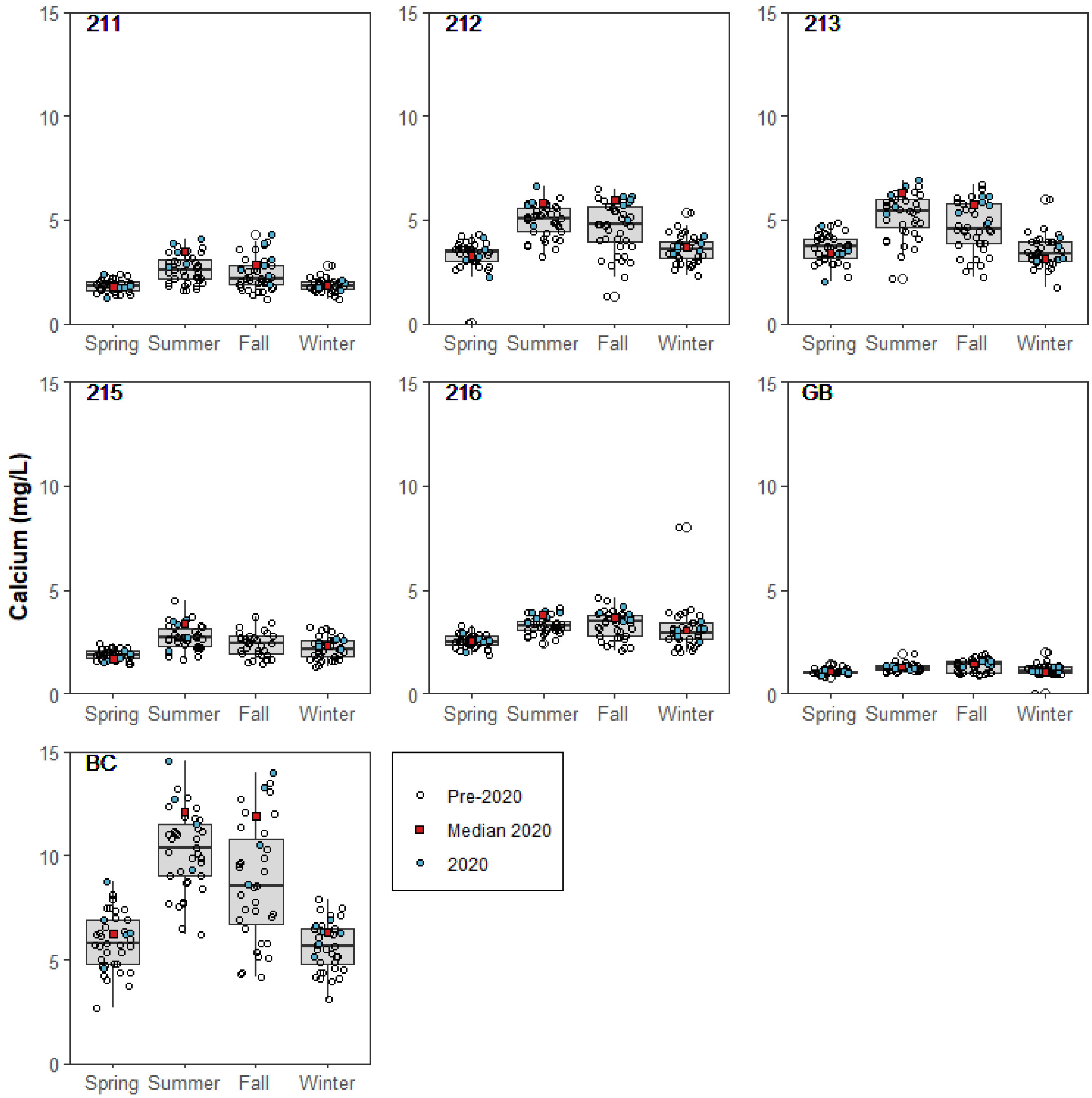

Figure C18. Boxplots depicting seasonal distributions of Ca observed In Quabbin Reservoir watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

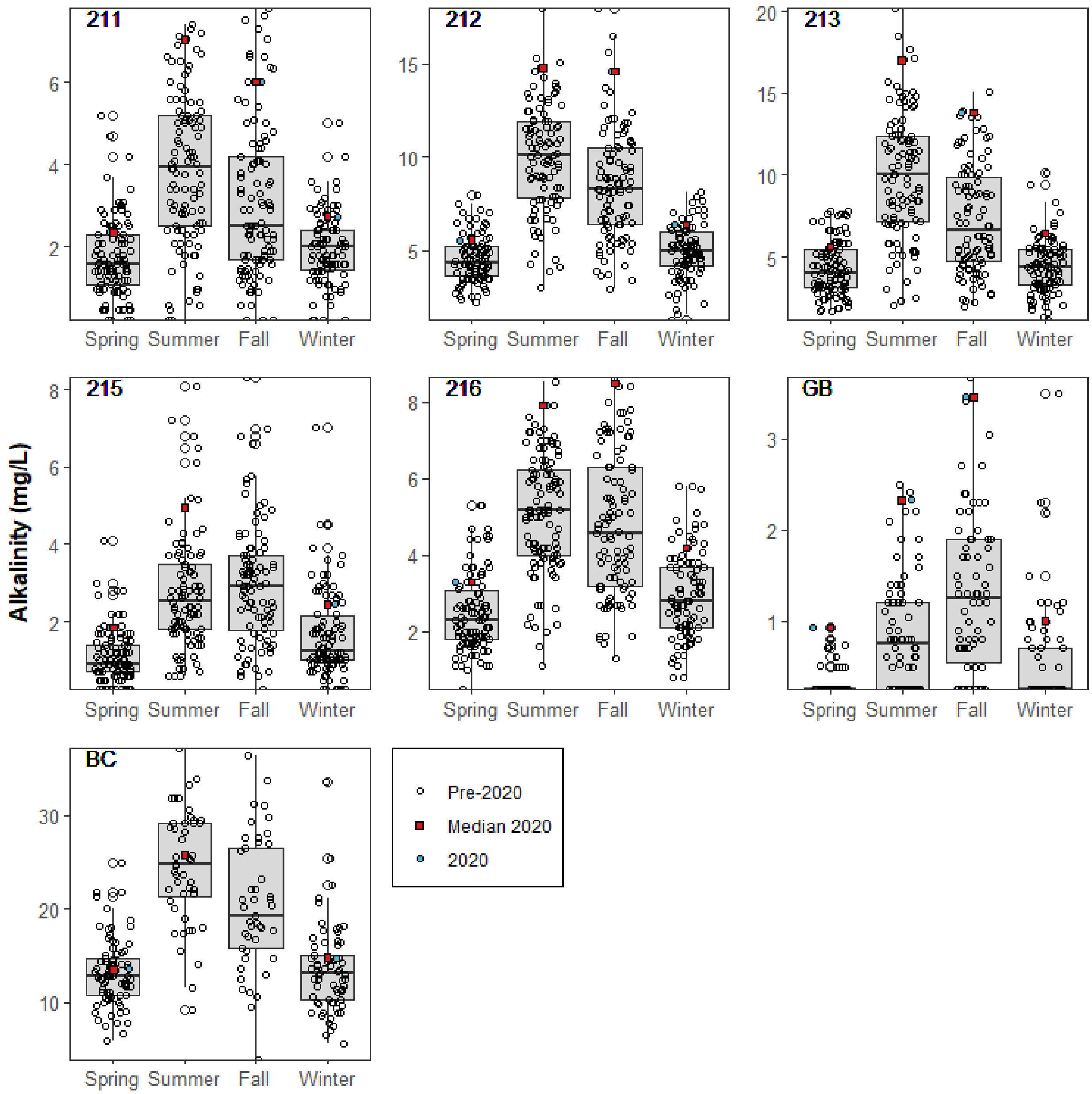

Figure C19. Boxplots depicting seasonal distributions of alkalinity observed In Quabbin Reservoir watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

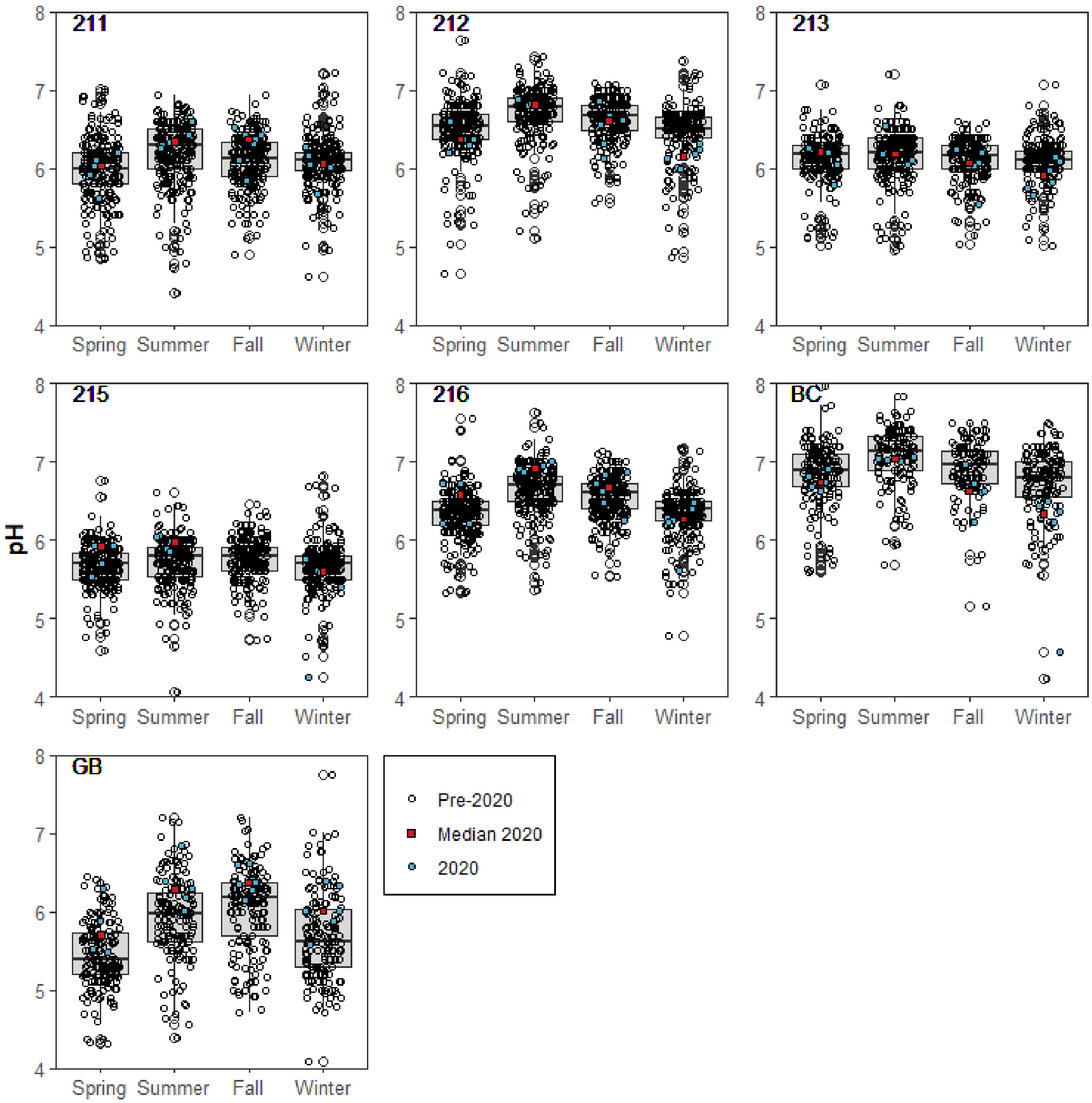

Figure C20. Boxplots depicting seasonal distributions of pH observed In Quabbin Reservoir watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

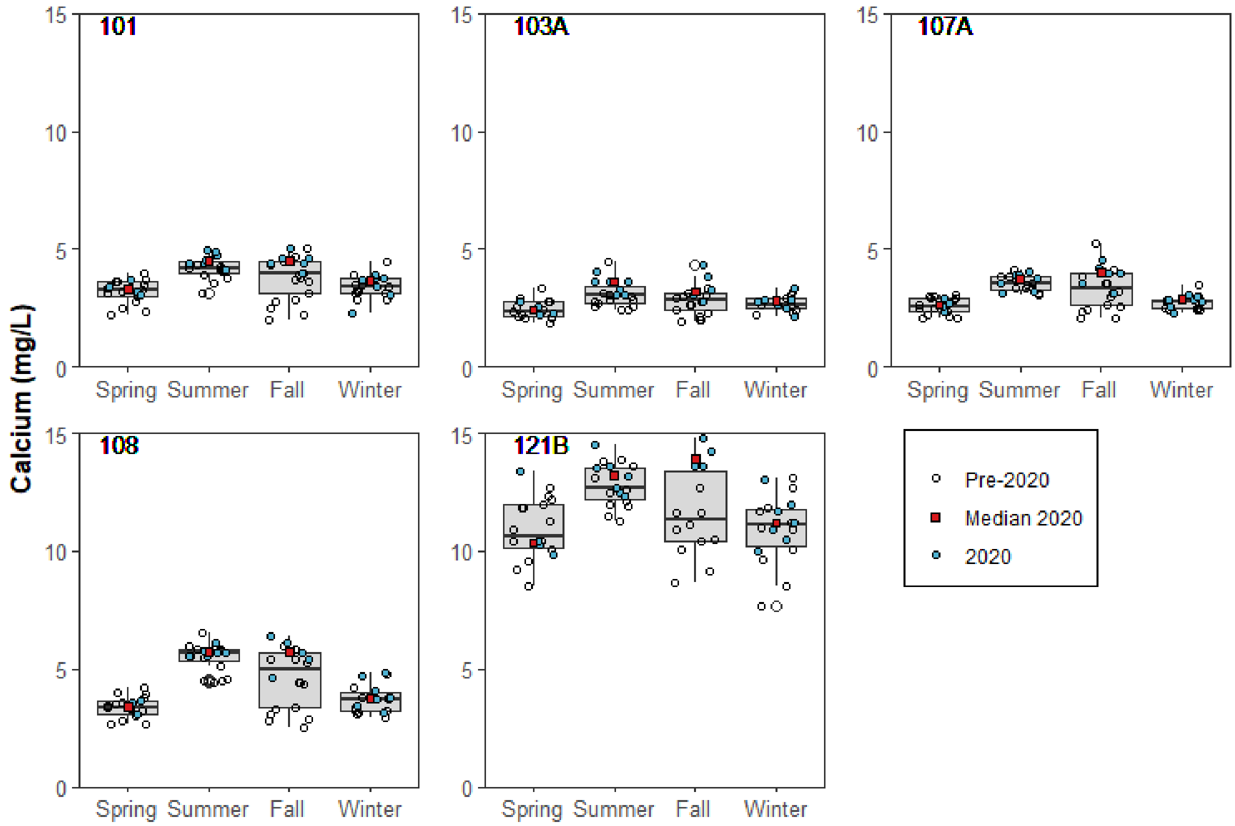

Figure C21. Boxplots depicting seasonal distributions of Ca observed in Ware River watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

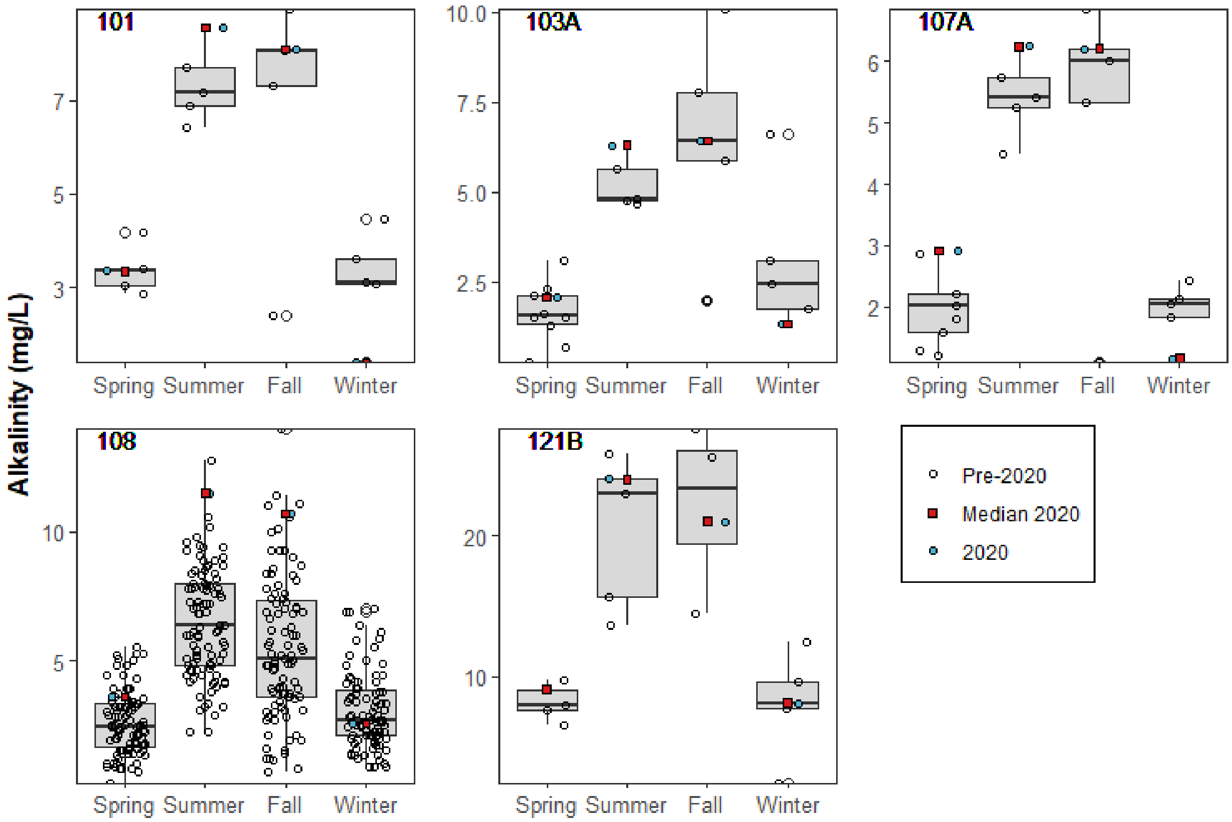

Figure C22. Boxplots depicting seasonal distributions of alkalinity observed in Ware River watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

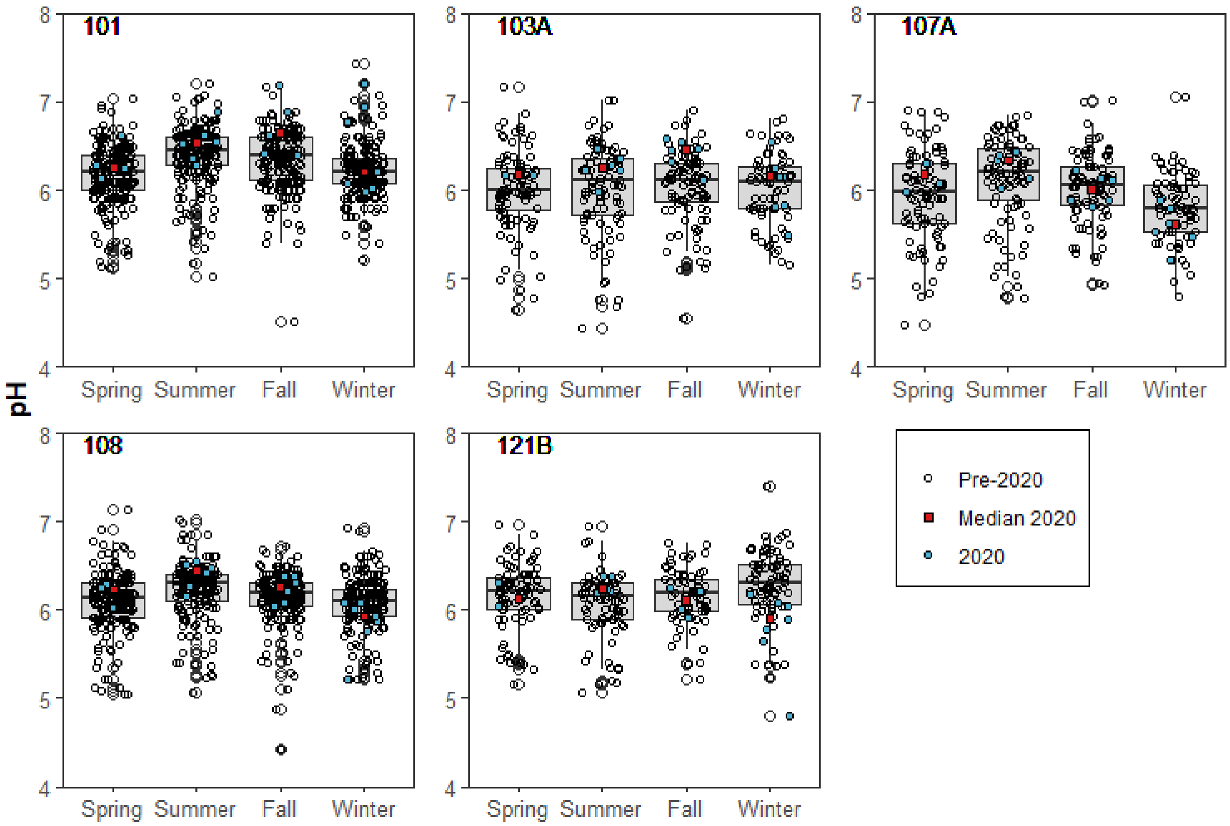

Figure C23. Boxplots depicting seasonal distributions of pH observed in Ware River watershed Core tributary sites. Results corresponding to 2020 are signified by the blue points. The solid black line represents the historical median, and outliers for the period of record are represented by open circles. The whiskers and box represent 1.5 times the interquartile range and the 25th and 75th percentiles of all data, respectively.

Table C3. Descriptive statistics (minimum, median, average, and maximum) for Ca, alkalinity, and pH in Core tributaries in the Quabbin Reservoir watershed during 2020.

Site	Season	Calcium (mg/L)					Alkalinity (mg/L)		pH				
		Count	Min	Med	Avg	Max	Count	Result	Count	Min	Med	Avg	Max
211	Spring	5	1.23	1.76	1.78	2.36	1	2.36	5	5.61	6.03	5.97	6.20
	Summer	6	2.71	3.49	3.42	4.05	1	7.03	5	6.25	6.34	6.38	6.59
	Fall	7	1.89	2.82	2.98	4.26	1	6.01	7	5.84	6.37	6.28	6.52
	Winter	6	1.60	1.84	1.86	2.12	1	2.74	6	5.68	6.07	6.04	6.27
212	Spring	5	2.25	3.26	3.27	4.18	1	5.55	5	6.21	6.37	6.37	6.59
	Summer	6	4.75	5.82	5.76	6.65	1	14.8	5	6.78	6.82	6.84	6.92
	Fall	7	5.00	5.95	5.81	6.12	1	14.6	7	6.13	6.61	6.55	6.86
	Winter	6	3.40	3.67	3.73	4.23	1	6.40	6	5.99	6.16	6.15	6.32
213	Spring	5	2.05	3.40	3.41	4.75	1	5.63	5	5.78	6.21	6.11	6.25
	Summer	6	5.25	6.31	6.17	6.90	1	17.0	5	6.05	6.18	6.22	6.54
	Fall	7	4.76	5.73	5.53	6.12	1	13.8	7	5.54	6.07	6.05	6.24
	Winter	6	3.05	3.12	3.37	4.15	1	6.46	6	5.66	5.91	5.91	6.15
215	Spring	5	1.48	1.69	1.74	2.06	1	1.85	5	5.53	5.92	5.8	5.93
	Summer	5	2.04	3.36	3.02	3.53	1	4.94	5	5.85	5.98	5.97	6.07
	Fall	0	-	-	-	-	0	-	0	-	-	-	-
	Winter	6	2.15	2.31	2.36	2.65	1	2.45	6	4.25	5.6	5.37	5.76
216	Spring	5	2.02	2.54	2.51	2.92	1	3.30	5	6.22	6.58	6.49	6.72
	Summer	6	3.39	3.8	3.75	3.98	1	7.90	5	6.88	6.92	6.93	7.01
	Fall	7	3.47	3.66	3.75	4.18	1	8.48	6	6.25	6.68	6.63	6.87
	Winter	6	2.47	3.06	3.00	3.51	1	4.18	6	5.61	6.27	6.21	6.48
GB	Spring	5	0.84	1.06	1.03	1.17	1	0.93	5	6.62	6.74	6.76	6.92
	Summer	6	1.13	1.28	1.27	1.38	1	2.33	4	7.01	7.04	7.04	7.06
	Fall	7	1.27	1.42	1.45	1.62	1	3.46	5	6.24	6.63	6.63	6.97
	Winter	6	1.04	1.06	1.12	1.28	1	1.00	6	4.57	6.33	6.07	6.50
BC	Spring	5	4.57	6.25	6.54	8.77	1	13.5	4	5.48	5.71	5.80	6.29
	Summer	4	9.29	12.1	12.0	14.6	1	25.8	5	6.01	6.29	6.34	6.84
	Fall	4	8.58	11.9	11.6	14.0	0	-	7	6.15	6.37	6.40	6.61
	Winter	6	5.14	6.3	6.17	6.90	1	14.7	6	5.58	6.02	6.04	6.39

Table C4. Descriptive statistics (minimum, median, average, and maximum) for Ca, alkalinity, and pH in Core tributaries in the Ware River watershed during 2020.

Site	Season	Calcium (mg/L)					Alkalinity (mg/L)		pH				
		Count	Min	Med	Avg	Max	Count	Result	Count	Min	Med	Avg	Max
101	Spring	4	3.03	3.30	3.33	3.69	1	3.35	4	6.14	6.26	6.32	6.63
	Summer	7	4.10	4.52	4.57	4.94	1	8.55	6	6.29	6.54	6.54	6.88
	Fall	6	4.01	4.50	4.50	5.00	1	8.09	6	6.40	6.65	6.70	7.18
	Winter	7	2.28	3.66	3.40	3.89	1	1.39	7	5.99	6.21	6.46	7.21
103A	Spring	4	2.23	2.44	2.48	2.80	1	2.08	4	6.16	6.18	6.18	6.19
	Summer	7	3.07	3.61	3.47	4.02	1	6.3	6	5.98	6.26	6.26	6.48
	Fall	6	2.80	3.21	3.41	4.31	1	6.43	6	6.11	6.47	6.42	6.59
	Winter	7	2.14	2.80	2.73	3.36	1	1.33	7	5.49	6.16	6.03	6.54
107A	Spring	4	2.37	2.65	2.65	2.93	1	2.92	4	5.98	6.19	6.17	6.31
	Summer	7	3.14	3.73	3.63	4.1	1	6.25	6	6.02	6.34	6.28	6.43
	Fall	6	3.10	4.00	3.90	4.54	1	6.21	6	5.81	6.01	6.01	6.23
	Winter	7	2.29	2.86	2.77	3.05	1	1.16	7	5.22	5.62	5.64	5.91
108	Spring	4	3.11	3.41	3.40	3.66	1	3.6	4	6.03	6.24	6.20	6.29
	Summer	7	5.54	5.71	5.71	6.13	1	11.5	6	6.15	6.45	6.40	6.56
	Fall	6	4.65	5.72	5.67	6.38	1	10.7	6	6.05	6.26	6.24	6.38
	Winter	7	3.17	3.75	3.94	4.81	1	2.55	7	5.21	5.93	5.85	6.08
121B	Spring	4	9.85	10.4	11.0	13.4	1	9.03	4	6.04	6.13	6.15	6.31
	Summer	7	12.3	13.2	13.2	14.5	1	24	6	6.20	6.25	6.28	6.39
	Fall	4	13.6	13.9	14.05	14.8	1	21	4	5.92	6.12	6.10	6.25
	Winter	7	9.97	11.2	11.3	13.0	1	8.09	7	4.80	5.9	5.78	6.18

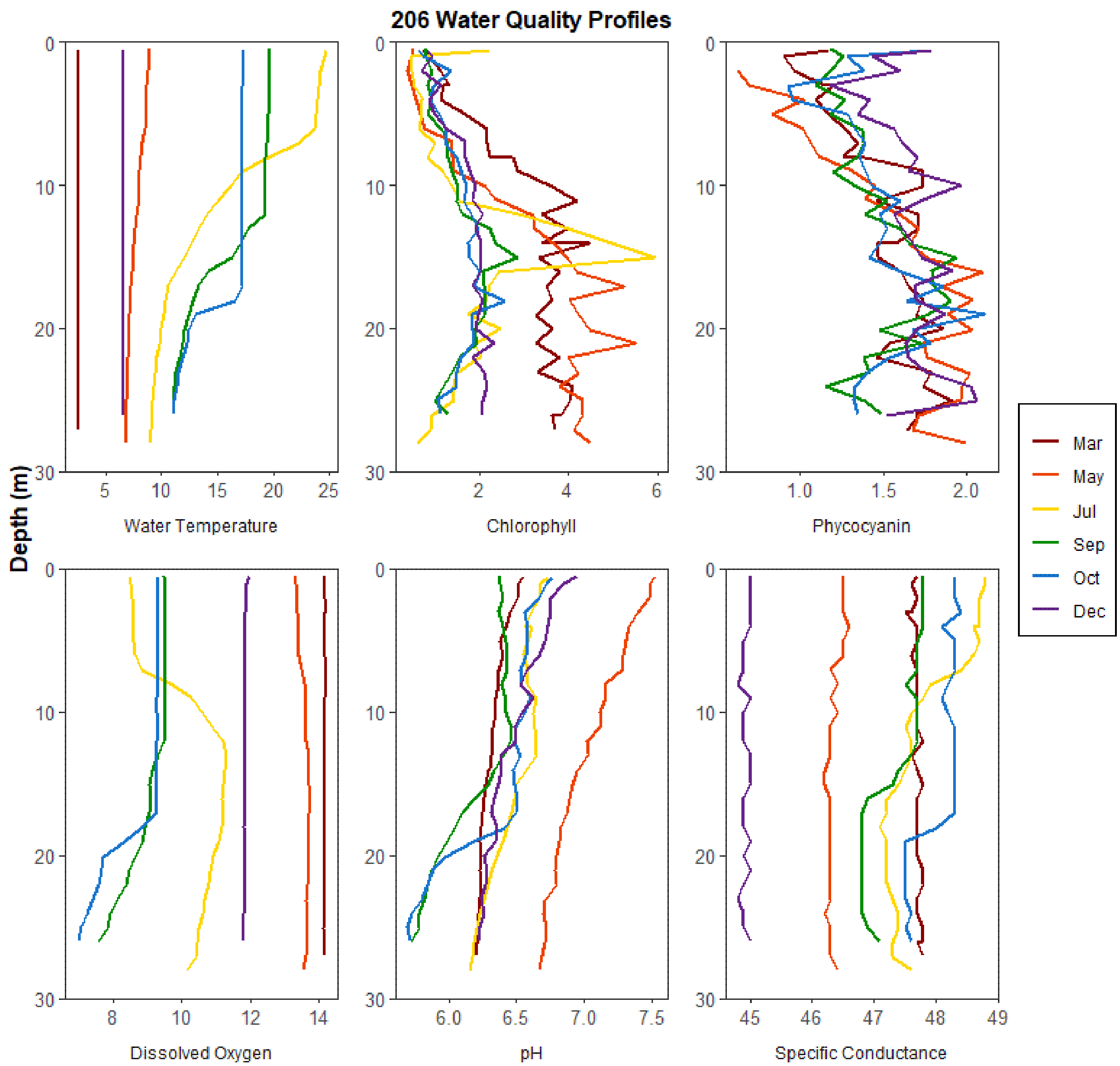

Figure C24. Select depth profiles of temperature **(°C)**, chlorophyll *a* **(µg/L)**, phycocyanin **(µg/L)**, dissolved oxygen **(mg/L),** pH, and specific conductance **(µS/cm)** Select depth profiles of temperature, chlorophyll *a*, phycocyanin, dissolved oxygen pH, and specific conductance collected by DWSP at Quabbin Reservoir monitoring site 206 in 2020. The March 2020 profile corresponds to spring isothermy, which existed from March through April. Note the high chlorophyll *a* levels in March, driven by a spring proliferation of Dinobryon. The May profile corresponds to the beginning of stratification of Quabbin Reservoir and continued elevated chlorophyll *a* level in association with the persisting Dinobryon growth. The July profile signifies full thermal stratification, and lower chlorophyll *a* concentrations, with the exception of an aggregation in the metalimnion. The September profile shows continued stratification through the fall months despite cooling surface water temperatures, and the November profile signifies the beginning of fall turnover. The December profile indicates a return to isothermy.

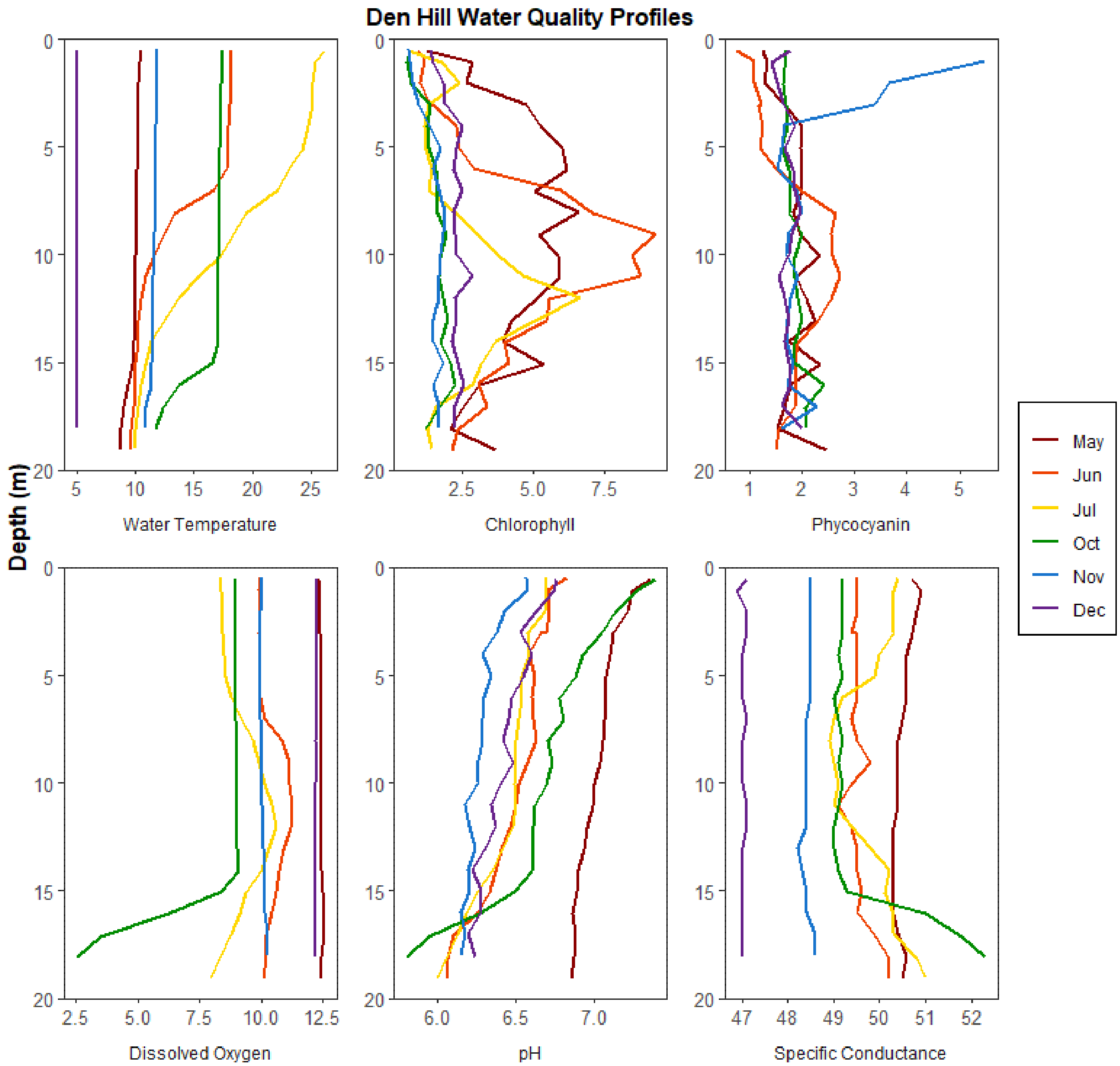

Figure C25. Select depth profiles of temperature, chlorophyll a, phycocyanin, dissolved oxygen pH, and specific conductance collected by DWSP at Quabbin Reservoir monitoring site Den Hill in 2020. May 2020 profile signifies spring isothermy. June profile corresponds with full stratification, and heightened chlorophyll *a* concentrations. July signifies a relative decrease in phytoplankton. The water column began to mix in October. Full fall turnover was almost completely achieved by the November sampling date. The December profile indicates a return to isothermy.

Table C5. Descriptive statistics (minimum, median, average, and maximum) for physical water quality parameters monitored in Quabbin Reservoir during 2020 at DWSP monitoring site 206. Statistics provided include measurements conducted in conjunction with monthly Quabbin Reservoir water quality monitoring and routine phytoplankton sampling (January through December 2020). Phycocyanin was not recorded from July 6 to September 3, 2020. Negative phycocyanin concentrations (n=2) were excluded from calculations for descriptive statistics, as they likely represent sensor interference. Erroneous optical datapoints collected 1-m above the reservoir bottom on July 15, August 7, and September 4, 2020 were also excluded from calculations, as these measurements likely reflect artificial introduction of turbidity during instrument deployment, and thus do not accurately reflect undisturbed water column conditions.

Analyte	Season	Count	Min	Med	Avg	Max
Water Temperature (°C)	Winter	88	1.75	2.92	3.66	6.62
	Spring	90	2.49	7.23	6.11	9.18
	Summer	141	8.17	13.3	15.5	25.4
	Fall	137	10.1	13.5	15.5	23.1
Chlorophyll *a* (µg/L)	Winter	88	0.71	2.35	2.34	6.08
	Spring	90	0.40	3.33	2.94	8.19
	Summer	141	0.45	1.50	1.82	6.08
	Fall	137	0.59	1.54	1.56	3.52
Phycocyanin (µg/L)	Winter	88	0.12	1.57	1.58	4.46
	Spring	88	0.63	1.56	1.51	2.39
	Summer	28	0.97	1.42	1.48	2.12
	Fall	137	0.56	1.48	1.61	9.74
Dissolved Oxygen (mg/L)	Winter	88	11.8	13.4	13.2	14.2
	Spring	90	13.0	13.6	13.7	14.2
	Summer	141	8.31	10.1	10.0	12.1
	Fall	137	6.67	9.28	9.26	10.9
Oxygen Saturation (% Sat.)	Winter	88	97.5	102	101	104
	Spring	90	105	116	112	118
	Summer	141	83.8	104	101	111
	Fall	137	60.4	97.1	94.8	110
pH	Winter	88	6.22	6.37	6.42	6.94
	Spring	90	6.21	6.76	6.70	7.52
	Summer	141	5.96	6.47	6.43	6.82
	Fall	137	5.70	6.33	6.34	7.47
Specific Conductance (µS/cm)	Winter	88	44.8	47.7	46.9	47.9
	Spring	90	46.2	46.7	46.9	47.8
	Summer	141	46.6	47.4	47.7	48.9
	Fall	137	46.8	47.5	47.6	48.4

Table C6. Descriptive statistics (minimum, median, average, and maximum) for physical water quality parameters monitored in Quabbin Reservoir during 2020 at DWSP monitoring site Den Hill. Statistics provided include measurements conducted in conjunction with monthly Quabbin Reservoir water quality monitoring and routine phytoplankton sampling (January through December 2020). Phycocyanin was not recorded from July 6 until September 3, 2020. Negative phycocyanin concentrations (n=3) were excluded from calculations for descriptive statistics, as they likely represent sensor interference.

Analyte	Season	Count	Min	Med	Avg	Max
Water Temperature (°C)	Winter	19	4.96	4.97	4.98	5.02
	Spring	20	8.71	10.1	9.88	10.5
	Summer	121	9.54	17.9	18.2	26.2
	Fall	57	10.8	17.0	15.6	21.3
Chlorophyll *a* (µg/L)	Winter	19	1.38	2.27	2.21	2.85
	Spring	20	1.29	4.89	4.40	6.58
	Summer	121	0.65	1.77	2.33	9.27
	Fall	57	0.58	1.69	1.75	4.65
Phycocyanin (µg/L)	Winter	19	1.43	1.76	1.73	2.01
	Spring	20	1.24	1.93	1.87	2.46
	Summer	61	0.77	1.63	1.73	2.73
	Fall	55	1.48	1.79	2.03	5.48
Dissolved Oxygen (mg/L)	Winter	19	12.2	12.2	12.2	12.3
	Spring	20	12.3	12.4	12.4	12.6
	Summer	121	3.67	8.23	8.38	11.3
	Fall	57	2.51	8.96	8.65	10.3
Oxygen Saturation (% Sat.)	Winter	19	96.6	97.0	97.0	97.4
	Spring	20	109	113	113	113
	Summer	121	33.2	100	90.9	108
	Fall	57	23.8	94.6	88.7	99.4
pH	Winter	19	6.20	6.42	6.44	6.76
	Spring	20	6.85	7.02	7.02	7.36
	Summer	121	5.43	6.40	6.30	6.95
	Fall	57	5.73	6.55	6.49	7.38
Specific Conductance (µS/cm)	Winter	19	46.9	47.0	47.0	47.1
	Spring	20	50.3	50.5	50.5	50.9
	Summer	121	48.9	49.9	50.0	53.0
	Fall	57	48.2	49.0	49.1	52.3

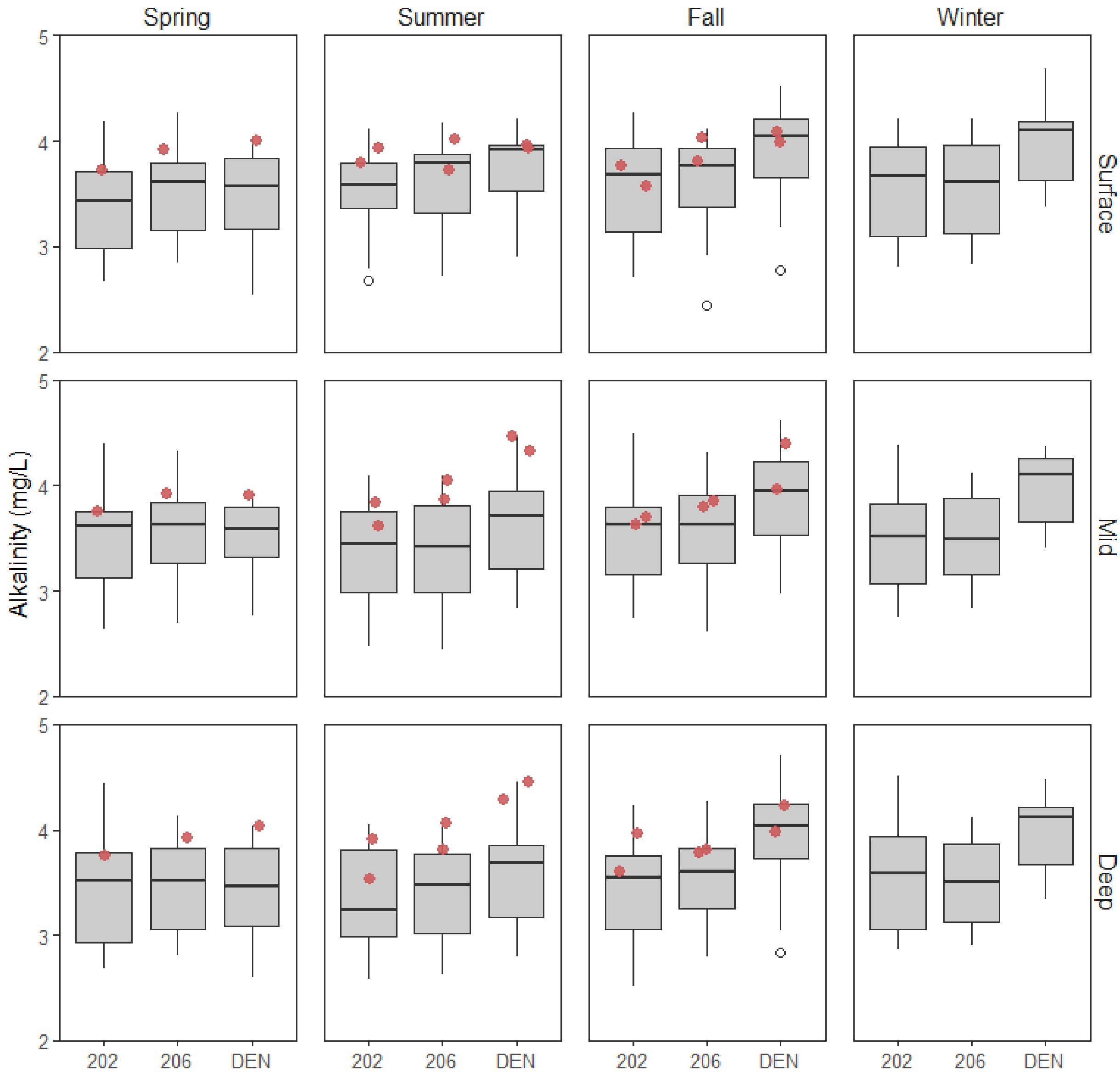

Figure C26. Boxplots depicting the seasonal and vertical distributions of alkalinity observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected in 2020 are signified by the red points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. The scale has been adjusted to best display 2020 variation, and thus excludes the following outliers: 7.5 mg/L at Den Hill deep from 2015, 5.51 mg/L at 206 deep from 2018, and 5.1 mg/L from Den Hill surface in 2018.

Reservoir Monitoring: Cl, Na, and Turbidity

Table C7. Descriptive statistics (minimum, median, average, and maximum) for sodium and chloride monitored in Quabbin Reservoir, DWSP monitoring sites 206 and Den Hill, for 2020 monitoring period.

Site	Analyte	Season	Count	Min	Med	Avg	Max
206	Na (mg/L)	Surface	5	5.73	5.79	5.85	6.15
		Mid	5	5.33	5.40	5.60	6.11
		Deep	5	5.44	5.65	5.69	6.08
	Cl (mg/L)	Surface	5	7.79	8.05	8.12	8.42
		Mid	5	7.78	8.04	8.04	8.32
		Deep	5	7.75	7.89	7.91	8.13
Den Hill	Na (mg/L)	Surface	5	5.70	6.04	5.93	6.16
		Mid	5	5.58	5.90	5.82	6.00
		Deep	5	5.65	6.04	5.99	6.15
	Cl (mg/L)	Surface	5	8.17	8.44	8.49	9.04
		Mid	5	8.17	8.45	8.44	8.90
		Deep	5	8.15	8.47	8.46	8.86

Table C8. Descriptive statistics (minimum, median, average, and maximum) for turbidity monitored in Quabbin Reservoir, DWSP monitoring sites 206 and Den Hill, for 2020 monitoring period.

Turbidity (NTU)						
Site	**Depth**	**Count**	**Min**	**Med**	**Avg**	**Max**
206	Surface	8	0.22	0.26	0.29	0.43
	Mid	8	0.23	0.26	0.28	0.39
	Deep	8	0.27	0.30	0.32	0.51
Den Hill	Surface	8	0.29	0.35	0.40	0.61
	Mid	8	0.33	0.44	0.45	0.59
	Deep	8	0.39	0.49	0.49	0.64

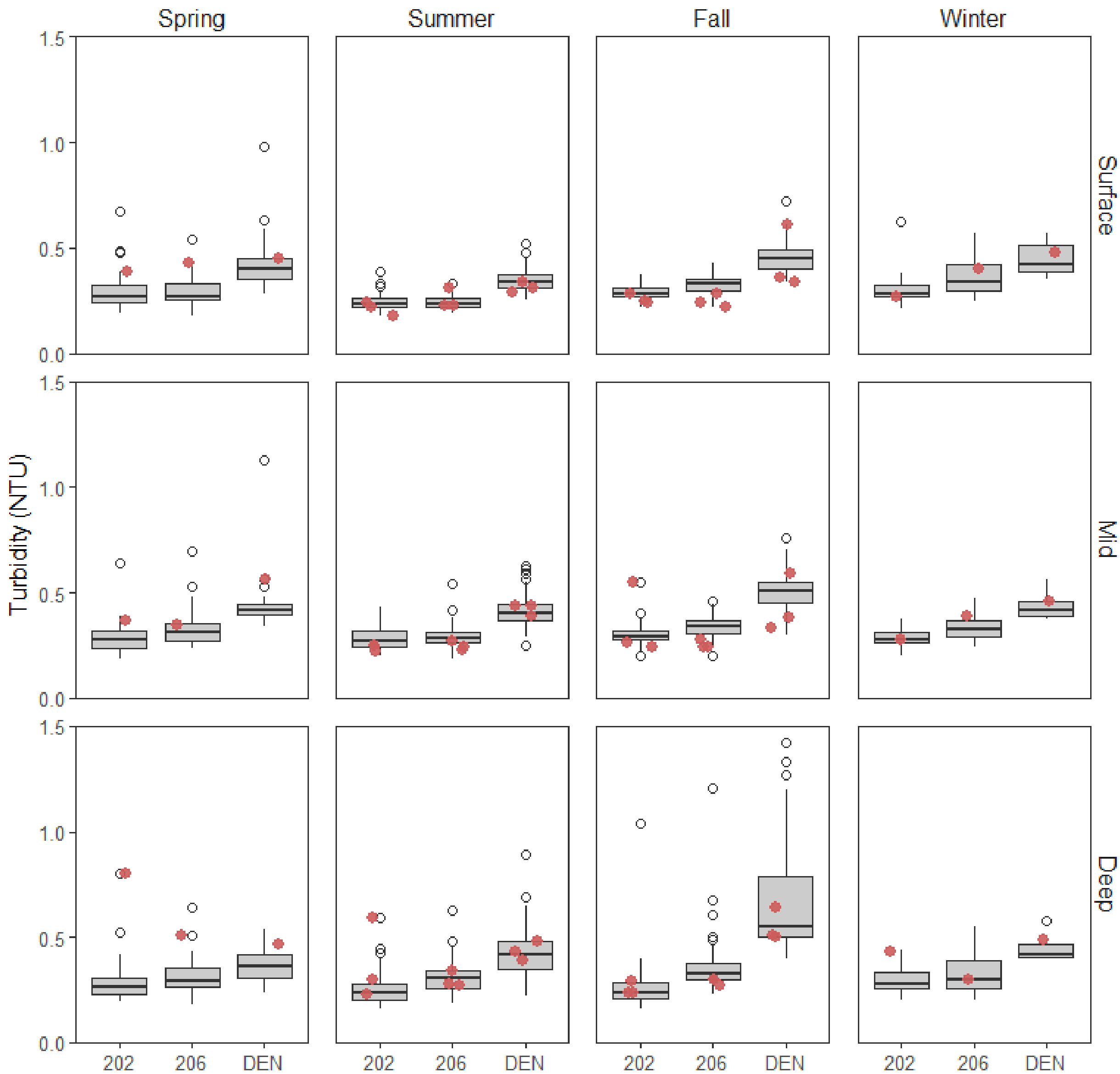

Figure C27. Boxplots depicting the seasonal and vertical distributions of turbidity observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected in 2020 are signified by the red points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. The scale has been adjusted to best display 2020 variation, and thus excludes the following outliers: 2.460 NTU at Den Hill deep from 2007, 2.020 NTU at Den Hill deep from 2009, and 1.680 NUT at Den Hill deep from 2016.

Reservoir Monitoring: Nutrients

Table C9. 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 206, for 2020 monitoring period. Detection limits were <0.005 mg/L for NO_3-N and NH_3-N. TP was measured via Valderrama (1981) with a detection limit of 0.0034 mg/L, a different method from previous years. TKN concentrations for 2020 were calculated by subtracting half the detection limit of NO_2-N (0.0025 mg/L) plus the reported NO_3-N concentration from measured concentrations of TN (detection limit 0.0226 mg/L). NO_2-N were analyzed previously in Quabbin Reservoir (DWSP, 2011) and were below laboratory detection limits in all samples. 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	8	<0.005	<0.005	0.003	0.006
	Mid	8	<0.005	<0.005	0.003	0.006
	Deep	8	<0.005	0.004	0.004	0.007
NH_3-N (mg/L)	Surface	8	<0.005	<0.005	0.003	0.005
	Mid	8	<0.005	<0.005	0.003	0.005
	Deep	8	<0.005	<0.005	0.003	0.007
TKN (mg/L)	Surface	9	0.106	0.135	0.130	0.149
	Mid	9	0.096	0.132	0.133	0.177
	Deep	9	0.106	0.126	0.128	0.148
TP (mg/L)	Surface	9	<0.0034	0.010	0.008	0.013
	Mid	9	<0.0034	0.009	0.007	0.013
	Deep	9	<0.0034	0.010	0.008	0.018
Ca (mg/L)	Surface	3	2.10	2.17	2.20	2.32
	Mid	5	1.85	2.10	2.06	2.24
	Deep	3	2.05	2.19	2.18	2.29
Si (mg/L)	Surface	8	1.62	1.80	1.82	1.97
	Mid	8	1.55	1.66	1.68	1.92
	Deep	8	1.62	1.94	1.91	2.08

Table C10. 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 Den Hill, for 2020 monitoring period. Detection limits were <0.005 mg/L for NO_3-N and NH_3-N. TP was measured via Valderrama (1981) with a detection limit of 0.0034 mg/L, a different method from previous years. TKN concentrations for 2020 were calculated by subtracting half the detection limit of NO_2-N (0.0025 mg/L) plus the reported NO_3-N concentration from measured concentrations of TN (detection limit 0.0226 mg/L). NO_2-N were analyzed previously in Quabbin Reservoir (DWSP, 2011) and were below laboratory detection limits in all samples. 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	8	<0.005	<0.005	0.004	0.013
	Mid	8	<0.005	<0.005	0.005	0.012
	Deep	8	<0.005	0.004	0.006	0.013
NH_3-N (mg/L)	Surface	8	<0.005	<0.005	0.004	0.012
	Mid	8	<0.005	<0.005	0.007	0.020
	Deep	8	<0.005	0.007	0.007	0.013
TKN (mg/L)	Surface	9	0.121	0.158	0.154	0.183
	Mid	9	0.125	0.152	0.152	0.173
	Deep	9	0.114	0.159	0.159	0.226
TP (mg/L)	Surface	9	<0.0034	0.0088	0.0101	0.0208
	Mid	9	<0.0034	0.0097	0.0097	0.0222
	Deep	9	<0.0034	0.0095	0.0114	0.0270
Ca (mg/L)	Surface	3	1.97	2.05	2.11	2.32
	Mid	5	1.99	2.13	2.12	2.25
	Deep	3	2.11	2.17	2.19	2.29
Si (mg/L)	Surface	8	1.49	1.62	1.83	2.78
	Mid	8	1.51	1.76	1.94	2.57
	Deep	8	1.55	2.05	2.16	2.79

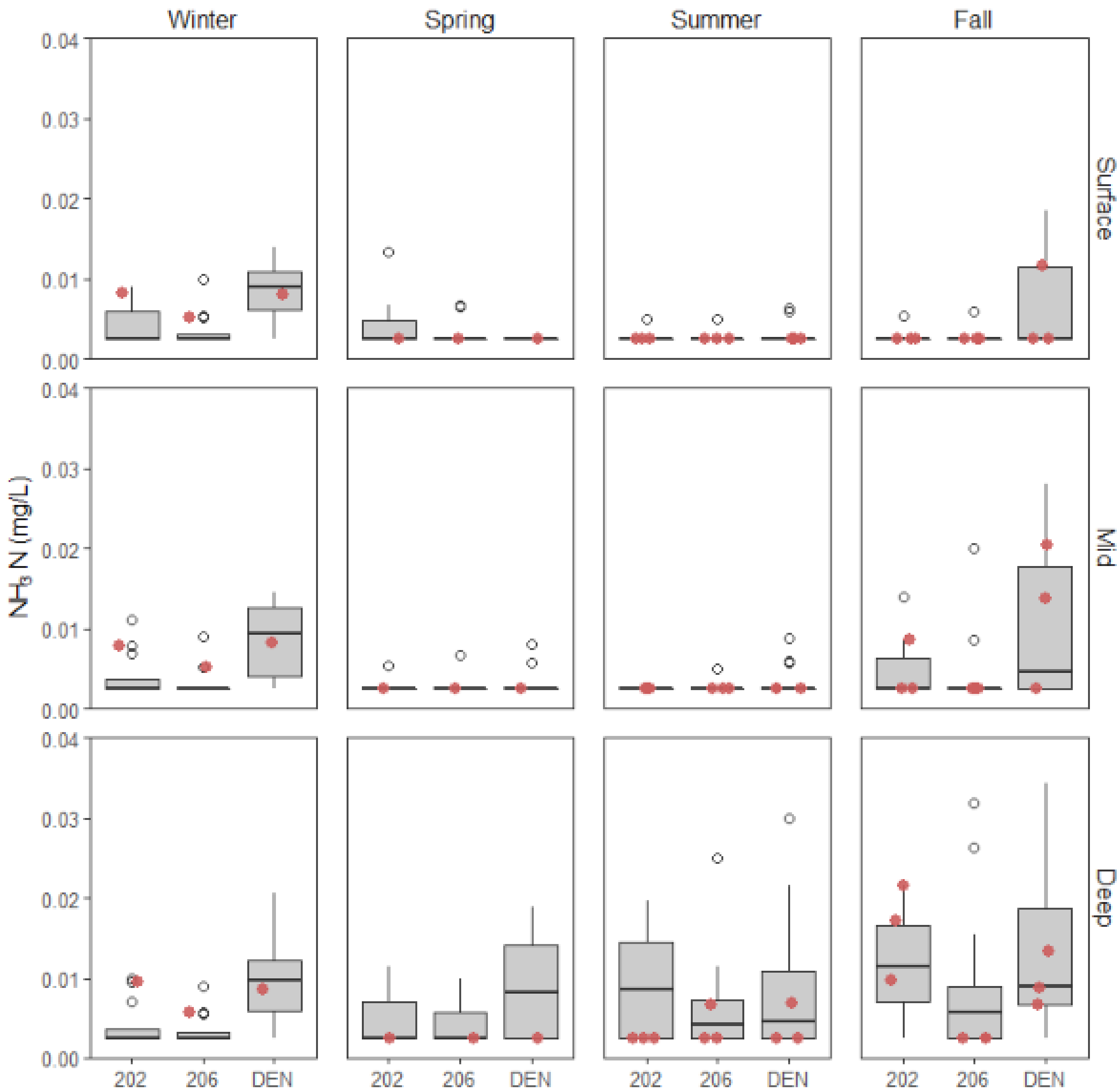

Figure C28. Boxplots depicting the seasonal and vertical distributions of NH_3-N observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected quarterly in 2020 are signified by the red points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

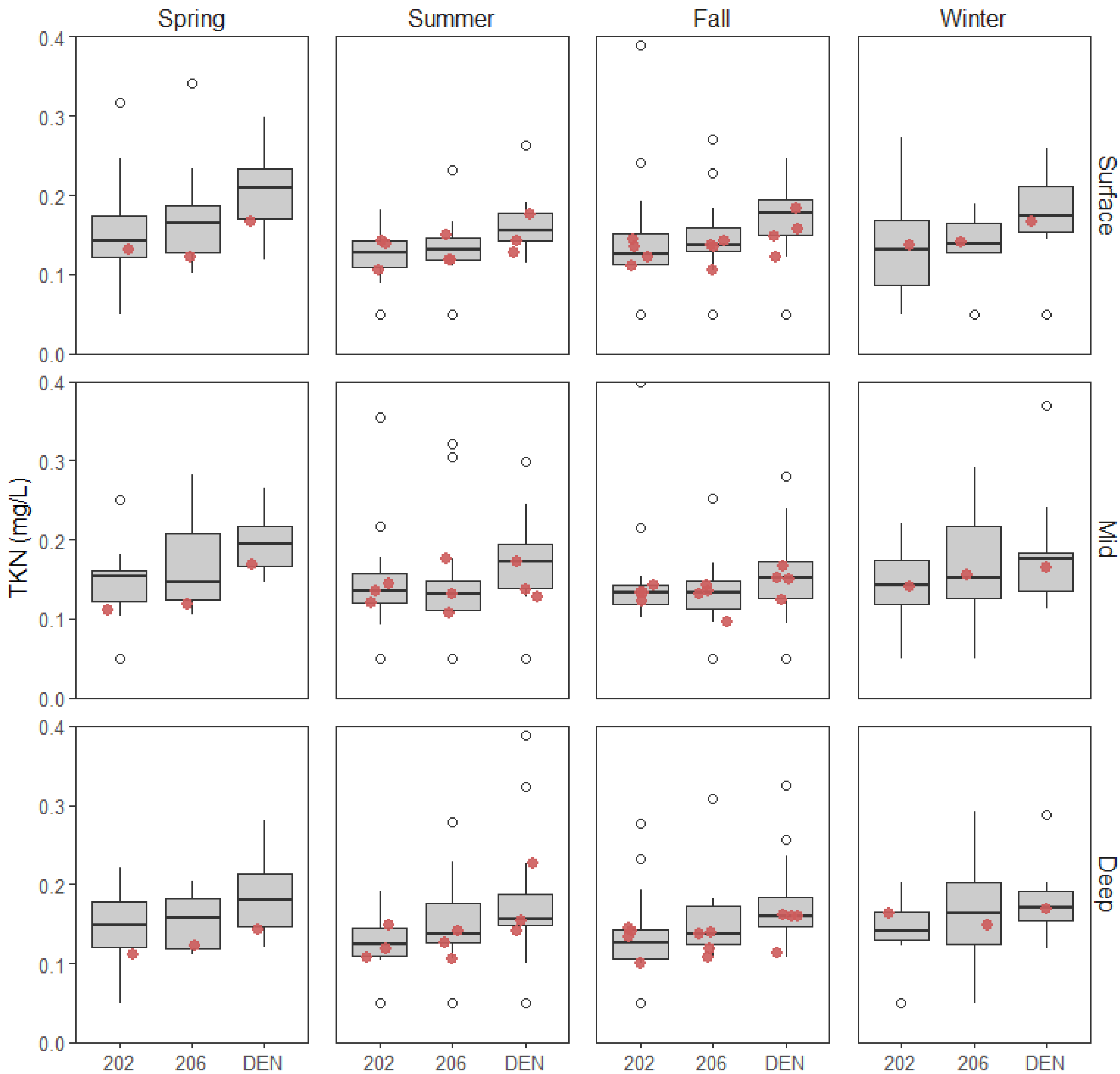

Figure C29. Boxplots depicting the seasonal and vertical distributions of TKN observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. TKN was calculated from TN (detection limit 0.0226 mg/L) by subtracting half the detection limit for NO_2-N (0.0025) plus the NO_3-N value from the TN value. Results corresponding to samples collected in 2020 are signified by the red points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively. The scale has been adjusted to best display 2020 variation, and thus excludes the following outliers: 0.560 mg/L at 202 surface from 2016, 0.4570 mg/L at Den Hill surface from 2013, 0.4490 mg/L at Den Hill middle from 2018, and 0.4120 from Den Hill middle from 2016.

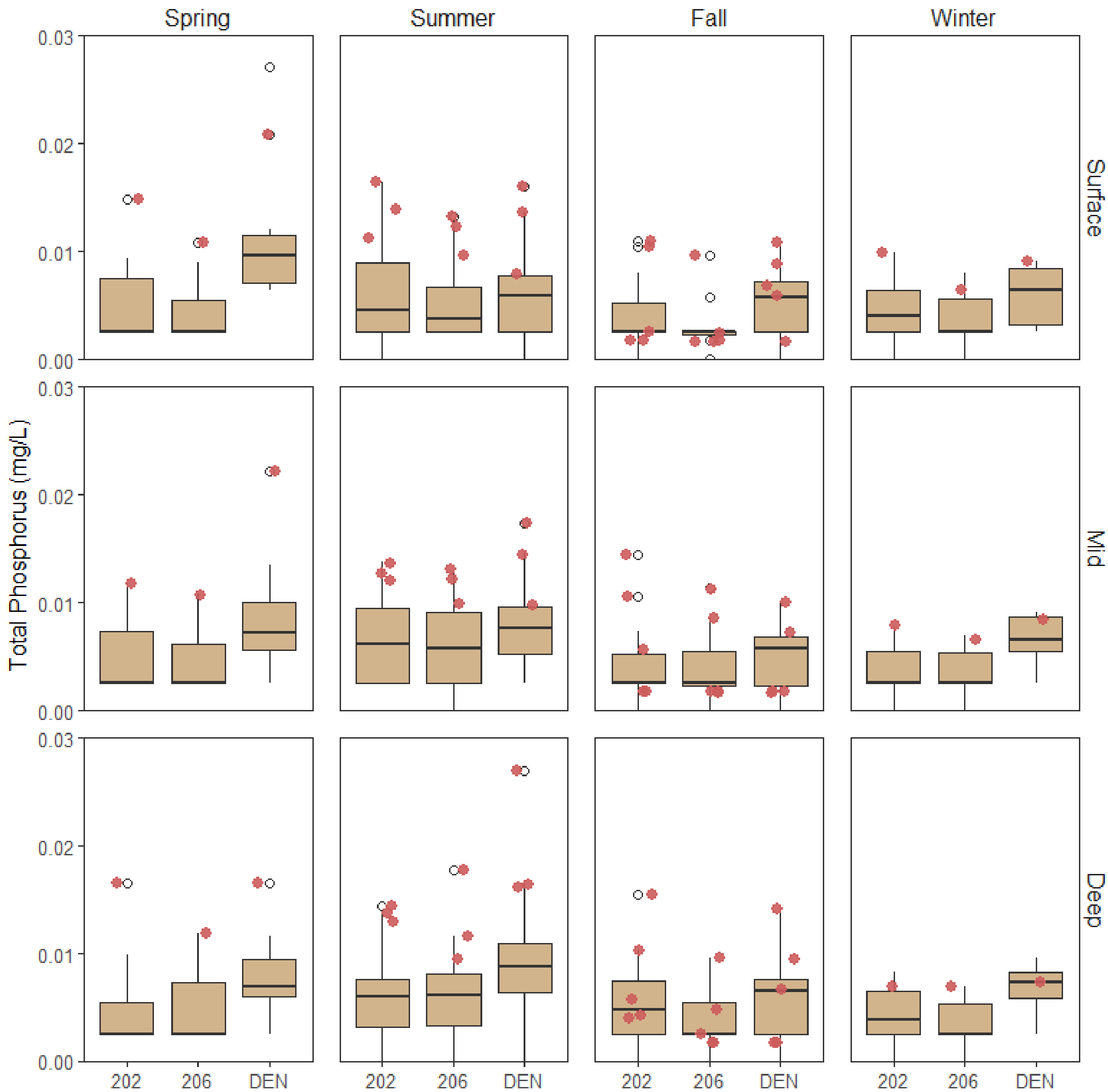

Figure C30. Boxplots depicting the seasonal and vertical distributions of TP observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected quarterly in 2020 are signified by the red points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

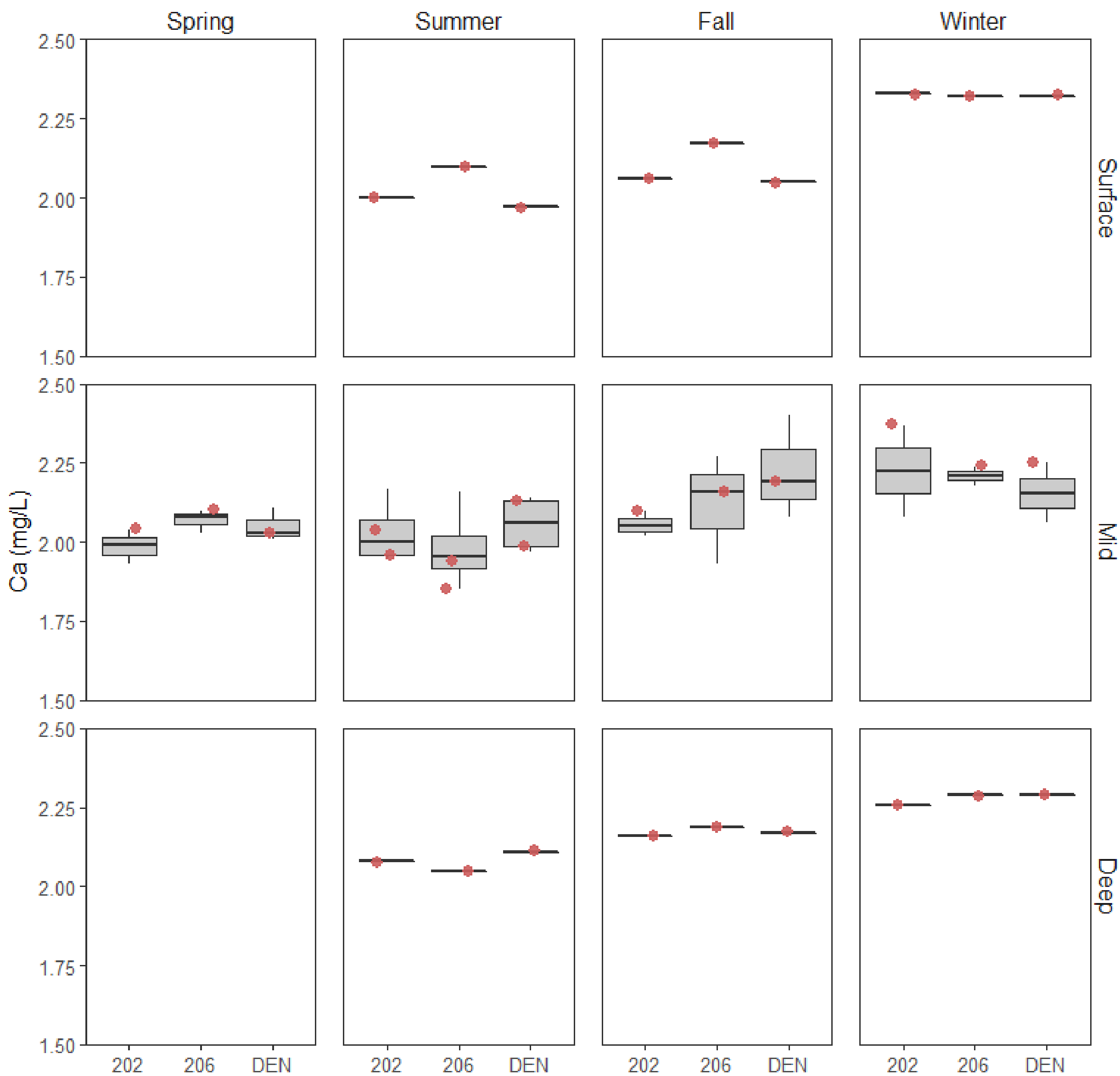

Figure C31. Boxplots depicting the seasonal distributions of Ca observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected in 2020 are signified by the red points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respectively.

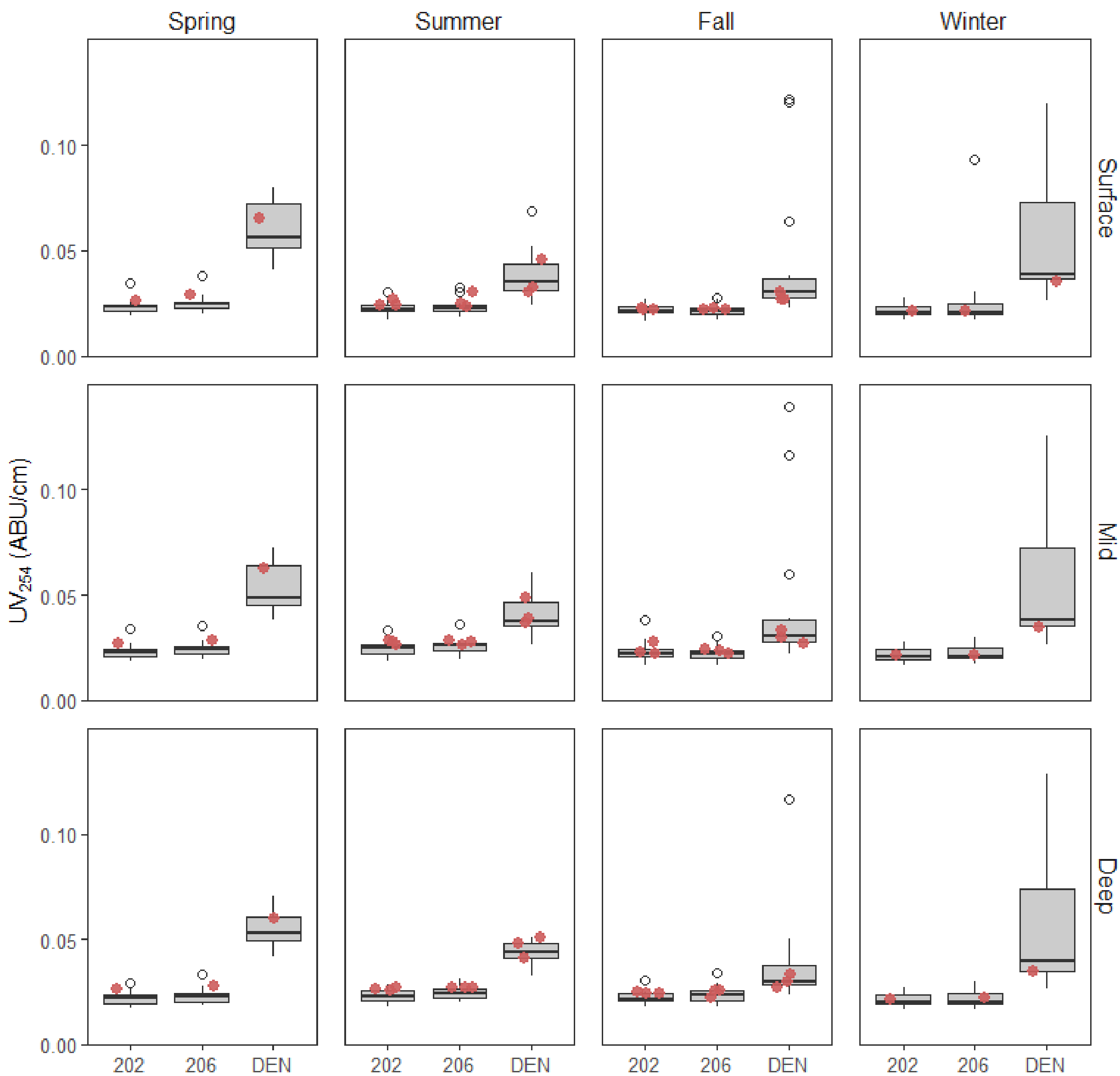

Figure C32. Boxplots depicting the seasonal and vertical distributions of UV_{254} observed In Quabbin Reservoir DWSP monitoring sites (202, 206, Den Hill), with depth. Results corresponding to samples collected in 2020 are signified by the red points. The solid black line represents the historical median, outliers for the period of record are represented by open circles, and the whiskers and box represent 1.5 times the interquartile range, and the 25th and 75th percentiles of all data, respect. The scale has been adjusted to best display 2020 variation, and thus excludes the following outlier: 0.1710 ABU/cm at Den Hill deep from 2005.

Table C11. Descriptive statistics (minimum, median, average, and maximum) for UV_{254} monitored in Quabbin Reservoir, DWSP monitoring sites 206 and Den Hill, for 2020 monitoring period.

UV_{254} (ABU/cm)						
Site	**Depth**	**Count**	**Min**	**Med**	**Avg**	**Max**
206	Surface	8	0.0214	0.0231	0.0244	0.0305
	Mid	8	0.0212	0.0253	0.0252	0.0282
	Deep	8	0.0221	0.0263	0.0256	0.028
Den Hill	Surface	8	0.0268	0.0317	0.0366	0.0655
	Mid	8	0.0268	0.0359	0.0390	0.0626
	Deep	8	0.0271	0.0380	0.0407	0.0599