OARS

FOR THE ASSABET SUDBURY & CONCORD RIVERS

Water Quality Monitoring Program Final Report: 2020-2021 Field Seasons

April 2022

Acknowledgments

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Cover pictures clockwise from top left: trash collection as part of River Cleanup (courtesy of the Fenn School); collecting bacteria samples in Lowell (Pam Moran); buttonbush (Julia Khorana); collecting water samples in Maynard (Ann Wachur).

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Abstract

This report covers the water quality and streamflow data collected between March 2020 and November 2021, summarizes the findings of trend analysis between 1992 and 2021, presents aquatic plant biomass data collected in 2020 and 2021, and presents bacteria data collected in 2020 and 2021 under our bacteria monitoring program.

Water quality reports for 1999–2019 (OAR, 2000b; OAR, 2001; OAR, 2002; OAR, 2003b; OAR, 2004; OAR, 2005; OAR, 2006b; OAR, 2007; OAR, 2009; OARS, 2011; OARS, 2013; OARS, 2015; OARS, 2016; OARS, 2017; OARS, 2018; OARS, 2020) and 2005 biomass sampling project (OAR, 2006a) are available on OARS' website (http://www.oars3rivers.org/river/waterquality/reports). All data are available upon request.

Introduction

OARS is a 501(c)(3) non-profit organization whose mission is to protect, improve, and preserve the Assabet, Sudbury, and Concord Rivers, their tributaries and watersheds, for public recreation, water supply, and wildlife habitat. Established in 1986 as the Organization for the Assabet River by a group of concerned citizens, OAR added the Sudbury and Concord Rivers to its mission in 2011, becoming OARS. Currently the organization has approximately 750 individual and family memberships, an eleven-member Board of Directors, and three regular staff plus summer staff. Together with our volunteers and partners, OARS has made significant progress over the past 35 years towards achieving our mission.

The combined Assabet, Sudbury, and Concord River watershed comprises about 399 square miles in eastern Massachusetts and is within EPA's Nutrient Ecoregion XIV subregion 59, the Eastern Coastal Plain. The mainstem rivers, particularly the Assabet, have suffered from cultural eutrophication caused by excess nutrients coming from point and non-point sources and from the soft sediments. During the growing season excess nutrients, phosphorus in particular, fuel nuisance algal and macrophytic plant growth that interferes with recreational use of the rivers and causes large daily variations in dissolved oxygen concentrations and pH, making poor habitat for aquatic life. When the algae and plants decay they generate strong sewage-like odors, can dramatically lower dissolved oxygen levels in the water column, and impair aesthetics and use of the rivers.

Under the federal Clean Water Act (Section 305b), states are required to evaluate the condition of the state's surface and ground waters with respect to their ability to support designated uses (such as fishing and swimming) as defined in each of the state's surface water quality standards. In their 2018/2020 assessment (2018/2020 Integrated List of Waters), Massachusetts Department of Environmental Protection lists all sections of the Assabet and Concord Rivers, from the Assabet River Reservoir (A1 Impoundment) in Westborough to the confluence with the Merrimack River in Lowell, on the Impaired Waters List as Category 5 ("Waters Requiring a TMDL") for a variety of impairments (MA DEP, 2021). The Sudbury River upstream of the Fruit Street bridge in Hopkinton/Westborough is listed as Category 2 ("Attaining some uses; other uses not assessed"). All other sections of the Sudbury River from Fruit Street downstream to the confluence with the Assabet in Concord (including the Framingham Reservoirs) are listed as Category 5 for mercury in fish tissue. Many sections in all three rivers are also listed for *E. coli*. Nine of the tributaries in the basin are listed as Category 5 Waters: Beaver Brook (*E. coli*, DO), Coles Brook (*E. coli*, Chloride), Eames Brook (aq. macroinvertebrates, taste/odor, excess algal growth, trash), Elizabeth Brook (*E. coli*), Hop Brook in Sudbury (total phosphorus, dissolved oxygen, noxious aquatic plants, eutrophication), Nashoba Brook (*E. coli*, temperature, dewatering), North Brook (temperature, invasive species), River Meadow Brook (*E. coli*, temperature, trash), Cochituate Brook (*E. coli*, trash, macroinvertebrates).

Nutrient limits were first set for the Assabet River wastewater treatment plants (WWTPs) in 1993, seven years after OAR was established. The EPA and MA DEP set summer discharge concentration limits of 1.0 mg/L for all four plants, and by 2000 all plants reported average summer concentrations below 1.0 mg/L achieved through waste treatment with ferrous sulfate, ferrous chloride, ferric chloride, and/or alum. The *Assabet River Total Maximum Daily Load for Total Phosphorus* study (MA DEP, 2004) was completed in 2004, and confirmed that the majority of the nutrients entering the Assabet were coming from the wastewater treatment plants that discharge treated effluent to the river. In particular, treatment plants were the major source of ortho phosphorus (the bioavailable form of phosphorus). While non-point sources (e.g., stormwater) contributed nutrients, they contributed significantly less than the point sources. The 2004 study concluded that reductions in nutrient loads from both point and non-point sources would be required to restore the Assabet River to Class B conditions. MA DEP and EPA adopted a two-phased adaptive management plan to reduce phosphorus loads in the Assabet. In Phase 1, lower summertime total phosphorus discharge limits of 0.1 mg/L were required at the four major WWTPs. Also, as a part of Phase 1, ways of limiting nutrient flux from the nutrient-rich sediments which accumulate in the slower moving and impounded river sections were studied. The *Assabet River, Massachusetts, Sediment and Dam Removal Study* (ACOE, 2010) examined sediment dredging, dam removal, and lower winter phosphorus discharge limits as ways of controlling the annual phosphorus loading from the sediments. The study concluded that: (1) dredging would achieve, at best, short-term improvements; (2) phosphorus discharge from the WWTPs in the winter contributes to the annual phosphorus budget for the Assabet and, therefore, decreased winter phosphorus discharge limits would be another way to control phosphorus loading to the system; and (3) dam removal plus the Phase 1 WWTPs' phosphorus discharge reductions would almost meet the goal of reducing the sediment phosphorus contribution by 90% (MA DEP, 2004), achieving an estimated 80% overall reduction. Upgrades to the four municipal wastewater treatment plants that discharge to the Assabet River were completed as of the spring of 2012: Hudson in September 2009, Maynard in spring 2011, Marlborough Westerly and Westborough in the spring of 2012. The Marlborough Easterly plant, discharging to Hop Brook (tributary to the Sudbury River), finished required upgrades by spring 2015. With the upgrades complete, all the treatment plants currently meet a summer total phosphorus discharge limit of 0.1 mg/L and a winter limit of 1.0 mg/L. In Phase 2, MA DEP and EPA were tasked with jointly deciding what additional phosphorus treatment would be needed for the Assabet to meet water quality standards. As of 2022, they have taken the next step of reducing the winter phosphorus discharge limit to 0.2 mg/L, and a new NPDES winter phosphorus limit has been set for all plants (Marlborough Westerly's limit is set at 4.8 lb/day, which corresponds to 0.2 mg/L at design flow). Westborough and Marlborough Westerly have until 2023 to achieve the lower winter limit.

For the nutrient load reductions proposed in the state's TMDL to be effective in restoring water quality in the mainstem, the existing baseflow in the Assabet and its tributaries must be preserved and augmented if possible. Baseflow, the flow of groundwater into the streams, is particularly critical during the summer and is essential to diluting the effluent discharged to the rivers. The water resources of the area are under the strain of an increasing demand for water supply and centralized wastewater treatment, which results in the net loss of water from many sub-basins and reduced baseflow in the mainstem and tributaries. A natural streamflow regime (i.e., range, duration, and timing of streamflow) throughout the year is critical to supporting fish and other aquatic life.

Invasive aquatic plants are also a problem throughout the watershed. The Sudbury River has a long history of invasive water chestnut (*Trapa natans*), and efforts to remediate those problems have been underway for many years. Significant water chestnut infestations are also common on the Concord River, particularly in the Billerica impoundment, and in sections of the Assabet River downstream of Hudson. Other invasive aquatic plants include Eurasian milfoil, fanwort, and curly leaf pondweed.

Because of these issues, OARS conducts water quality, streamflow, and aquatic plant biomass monitoring on the mainstems and large tributaries of the Assabet, Sudbury, and Concord Rivers. Without the support and work of its volunteers, OARS would not be able to conduct such an extensive monitoring program. The summer of 2021 was OARS' 30^{th} consecutive year collecting data at mainstem Assabet River sites, its 20^{th} year collecting data at tributary sites, its 18^{th} year collecting data at mainstem Concord River sites, its 12^{th} year collecting Sudbury River data, its 17^{th} year assessing aquatic plant biomass in the large impoundments of the Assabet River, its 4^{th} year collecting chloride data, and its 3^{rd} year collecting fecal indicator bacteria data. Water quality data, collected under OARS' *Quality Assurance Project Plan for OARS' Water Quality and Quantity Monitoring Program* (OARS, 2018b), and bacteria data, collected under OARS' *Quality Assurance Project Plan for OARS' Bacteria Monitoring Program* (OARS, 2019), may be used by EPA and DEP in making regulatory decisions. The goals of OARS' monitoring program remain: to understand long-term trends in the condition of the rivers and their tributaries, to provide sound scientific information to evaluate and support regulatory decisions that affect the rivers, and to promote stewardship of the rivers through volunteer participation in the project.

Figure 1: Water Quality Monitoring Sites 2020-2021

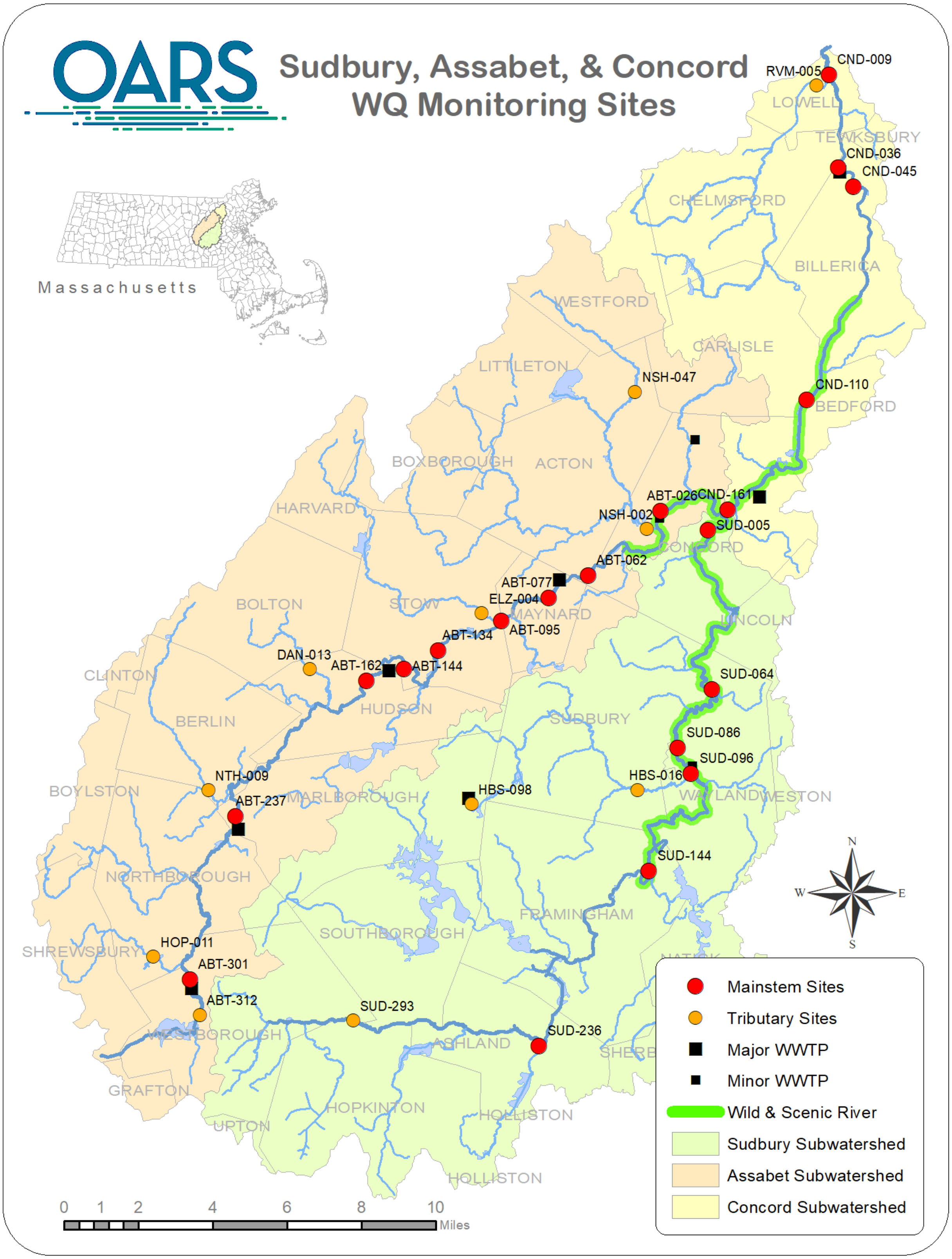


Table 1: Water Quality Monitoring Sites 2020-2021

OARS Site #	Waterbody	Site Description	Municipality	SARIS #	Lat/Lon	Sampling Dates			Gage reading /streamflow*
						June/Jul/ Aug	May/ Sept	Nov/ March	
CND-009	Concord River	Rogers Street	Lowell	46500	42° 38' 09"/ -71° 18' 05"	√	√	√	(USGS Gage)
CND-036	Concord River	Bristol & Amherst Streets	Billerica	46500	42° 35' 59"/ -71° 17' 49"	√			
CND-045	Concord River	Lowell Street	Billerica	46500	42° 35' 30"/ -71° 17' 18"	√			
CND-110	Concord River	Route 225	Bedford	46500	42° 30' 33"/ -71° 18' 51"	√			
CND-161	Concord River	Lowell Rd. Bridge	Concord	46500	42° 27' 59"/ -71° 21' 21"	√	√	√	
ABT-026	Assabet River	Route 2	Concord	46775	42° 27' 57"/ -71° 23' 28"	√	√	√	
ABT-062	Assabet River	Route 62 (Canoe access)	Acton	46775	42° 26' 27"/ -71° 25' 46"	√			
ABT-077	Assabet River	USGS Maynard Gage	Maynard	46775	42° 25' 55"/ -71° 26' 59"	√	√	√	(USGS Gage)
ABT-095	Assabet Impound	White Pond Road	Stow/Maynard	46775	42° 25' 24"/ -71° 28' 29"	√*	√*		
ABT-134	Assabet Impound	Sudbury Road	Stow	46775	42° 24' 41"/ -71° 30' 30"	√*	√*		
ABT-144	Assabet River	Route 62 (Gleasondale)	Stow	46775	42° 24' 16"/ -71° 31' 35"	√			
ABT-162	Assabet Impound	Cox Street	Hudson	46775	42° 23' 59"/ -71° 32' 46"	√*	√*		
ABT-237	Assabet River	Robin Hill Road	Marlborough	46775	42° 20' 48"/ -71° 36' 53"	√			
ABT-301	Assabet River	Route 9	Westborough	46775	42° 16' 59"/ -71° 38' 19"	√	√	√	
ABT-312	Assabet River	Mill Road	Westborough	46775	42° 16' 10"/ -71° 37' 60"	√	√	√	OARS Gage
SUD-005	Sudbury River	Route 62 (Boat House)	Concord	47650	42° 27' 30"/ -71° 21' 59"	√	√	√	
SUD-064	Sudbury River	Sherman Bridge Road	Wayland	47650	42° 23' 47"/ -71° 21' 52"	√	√		
SUD-086	Sudbury River	River Road	Wayland	47650	42° 22' 26"/ -71° 22' 54"	√	√		
SUD-096	Sudbury River	Route 20	Wayland	47650	42° 21' 49"/ -71° 22' 31"	√	√		
SUD-144	Sudbury River	Sudbury Landing	Framingham	47650	42° 19' 32"/ -71° 23' 51"	√	√	√	(USGS Gage)
SUD-236	Sudbury River	Chestnut Street	Ashland	47650	42° 15' 27"/ -71° 27' 18"	√			
SUD-293	Sudbury River	Fruit Street	Southborough	47650	42° 16' 03"/ -71° 33' 09"	√	√	√	OARS Gage
DAN-013	Danforth Brook	Route 85	Hudson	47275	42° 24' 14"/ -71° 34' 29"	√	√	√	OARS Gage
ELZ-004	Elizabeth Brook	White Pond Road	Stow	47125	42° 25' 36"/ -71° 29' 07"	√	√	√	
HOP-011	Hop Brook N'boro	Otis Street	Northborough	47600	42° 21' 26"/ -71° 37' 46"	√	√	√	OARS Gage
HBS-016	Hop Brook Sudbury	Landham Road	Sudbury	47825	42° 21' 26"/ -71° 24' 11"	√	√	√	
HBS-098	Hop Brook Sudbury	Route 20 Above Hager Pond	Marlborough	47825	42° 21' 03"/ -71° 29' 26"	√			
NSH-002	Nashoba Brook	Commonwealth Ave.	Concord	unnamed	42° 27' 32"/ -71° 23' 50"	√	√	√	OARS Gage
NSH-047	Nashoba Brook	Wheeler Lane	Acton	46875	42° 30' 43"/ -71° 24' 17"	√	√	√	(USGS Gage)
NTH-009	North Brook	Pleasant St.	Berlin	47375	42° 21' 26"/ -71° 37' 46"	√	√	√	OARS Gage
RVM-005	River Meadow	Thorndike Street	Lowell	46525	42° 37' 55"/ -71° 18' 32"	√	√	√	

* USGS Gage indicates that data is collected from USGS real-time gaging stations via the USGS NWS website. OARS Gages are maintained and read manually by OARS volunteers and staff.
** USGS Gage at Mill Road, Westborough, is no longer available on the real-time USGS NWS website; gage is maintained and read by OARS.
√* indicates that site is only monitored for in-situ measurements – no water sample.

Figure 2: Bacteria Sampling Sites 2020-2021

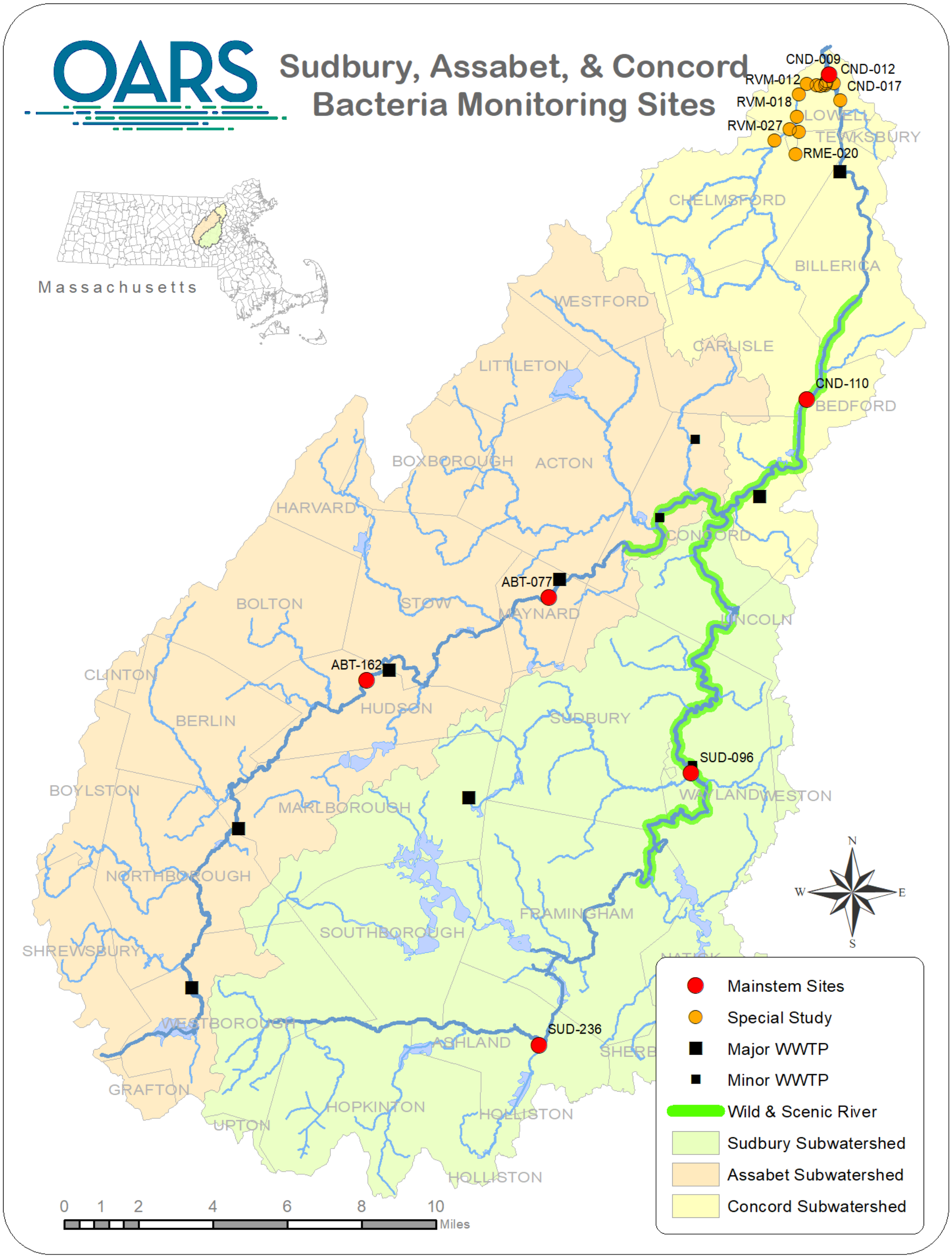


Table 2: Bacteria Sampling Sites 2020-2021

OARS Site #	Waterbody	Description	Municipality	SARIS #	Lat/Lon
ABT-077	Lower Assabet River	USGS Maynard Gage	Maynard	46775	42° 25' 55"/ -71° 26' 59"
ABT-162	Upper Assabet River	Cox Street	Hudson	46775	42° 23' 59"/ -71° 32' 46"
CND-009	Lower Concord River	Rogers Street	Lowell	46500	42° 38' 09"/ -71° 18' 05"
CND-110	Upper Concord River	Route 225	Bedford	46500	42° 30' 33"/ -71° 18' 51"
SUD-096	Lower Sudbury River	Route 20	Wayland	47650	42° 21' 49"/ -71° 22' 31"
SUD-236	Upper Sudbury River	Chestnut Street	Ashland	47650	42° 15' 27"/ -71° 27' 18"

Table 3: Bacteria Special Study Sites 2020-2021

OARS Site #	Waterbody	Description	Municipality	SARIS #	Lat/Lon
CND-012	Concord River	Centennial Island East	Lowell	46500	42° 37' 58"/ -71° 17' 59"
CND-017	Concord River	Muldoon Park	Lowell	46500	42° 37' 33"/ -71° 17' 45"
RME-003	River Meadow East	Industrial Ave. East	Chelmsford	46525	42° 36' 49"/ -71° 19' 04"
RME-020	River Meadow East	Riverneck Rd.	Chelmsford	46525	42° 36' 19"/ -71° 19' 11"
RVM-001	River Meadow	649 Lawrence St.	Lowell	46525	42° 37' 60"/ -71° 18' 11"
RVM-0015	River Meadow	UMACO	Lowell	46525	42° 37' 58"/ -71° 18' 13"
RVM-002	River Meadow	Industrial Tool	Lowell	46525	42° 37' 55"/ -71° 18' 14"
RVM-004	River Meadow	Newhall St.	Lowell	46525	42° 37' 53"/ -71° 18' 22"
RVM-005	River Meadow	Gorham and Chambers St.	Lowell	46525	42° 37' 55"/ -71° 18' 32"
RVM-008	River Meadow	Howard St.	Lowell	46525	42° 37' 57"/ -71° 18' 49"
RVM-012	River Meadow	Lincoln St.	Lowell	46525	42° 37' 41"/ -71° 19' 05"
RVM-018	River Meadow	Industrial Ave. Marshalls	Lowell	46525	42° 37' 11"/ -71° 19' 08"
RVM-022	River Meadow	Industrial Ave. Crosspoint	Lowell	46525	42° 36' 53"/ -71° 19' 22"
RVM-027	River Meadow	Glen Ave.	Chelmsford	46525	42° 36' 37"/ -71° 19' 50"

Water Quality Monitoring

Water Quality Sampling Methods

Trained volunteers and OARS staff monitored water quality at sites throughout the watershed (Table 1). Each site is assigned a three-letter prefix for the waterbody name plus a three-number designation indicating river miles above its confluence with the next stream. Water quality monitoring was conducted one Sunday each month in March, May, June, July, August, September, and November. All sites are sampled in June, July, and August. In March, May, September, and November, only selected sites are sampled. From May to September (the growing season) monitoring is conducted between 6:00am and 9:00am, to capture the diurnal low in dissolved oxygen readings. In the non-growing season when dissolved oxygen does not vary dramatically over the day, monitoring is conducted between 6:00am and 12:00pm. Streamflow was calculated from stage readings of OARS' gages using stage/discharge rating curves developed in cooperation with the United States Geological Survey (USGS) or recorded from the USGS real-time gage web pages.

Nutrient, chloride, suspended solids, and chlorophyll-*a* samples were taken using bottles supplied by state-certified laboratories under contract with OARS and were stored in the dark on ice during transport from the field to the lab. Samples were delivered to the lab within 26 hours of collection and analyzed within their respective hold-times. Chlorophyll-*a* samples were delivered to the lab within 6 hours of sampling. *In-situ* readings of temperature, dissolved oxygen, pH, and conductivity were taken using multi-function YSI Pro-series or 6-series meters. Pre- and post-calibration was done by OARS staff. To ensure that samples were representative of the bulk flow of the river, bottle samples and meter readings were taken from the main flow of the river at mid-depth by wading, using a pole, or by lowering the meter from a bridge. Duplicate field samples and distilled water field blanks were taken for 10% of samples. Table 4 summarizes the parameters measured, laboratory methods and equipment used. Detailed descriptions of sampling methods and quality control measures are available in *Quality Assurance Project Plan for OARS' Water Quality and Quantity Monitoring Program* (OARS, 2018b).

Table 4: Water Quality Sampling and Analysis Methods

Parameter	Analysis Method #	Equipment Range/ Reporting Limits	Sampling Equipment	Laboratory
Temperature	---	-5 – 45 degrees C	YSI multi-par. sonde	---
pH	---	0 – 14 units	YSI multi-par. sonde	---
Dissolved oxygen	---	0 – 50 mg/L	YSI multi-par. sonde	---
Conductivity	---	0 – 10,000 µS/cm	YSI multi-par. sonde	---
Total Suspended Solids	SM 2540D	1 – 100 mg/L	bottle	Nashoba Analytical
Total Phosphorus	SM4500-P-E	0.01 – 1 mg/L	bottle	Nashoba Analytical
Orthophosphate	SM4500-P-E	0.01 – 1 mg/L	bottle	Nashoba Analytical
Nitrate-N	EPA 300.0	0.05 – 10 mg/L	bottle	Nashoba Analytical
Ammonia-N	SM4500-NH3-D	0.1 – 10 mg/L	bottle	Nashoba Analytical
Chloride	EPA 300.0	1 – 1000 mg/L	bottle	Nashoba Analytical
Chlorophyll – *a*	SM 10200 H.3	2 – 100 µg/L	bottle	Alpha Analytical

Bacteria Sampling Methods

Trained volunteers collected bacteria water samples at six sites throughout the watershed (Figure 2 and Table 2). OARS selected the six sites based on the MA DEP 303d list of river segments impaired by bacteria (MA DEP, 2021) and current OARS water quality monitoring sites.

Volunteers also collected bacteria samples at an additional fourteen sites in and around River Meadow Brook in support of OARS' special study of bacteria in the lower Concord River (Table 3).

Bacteria monitoring was conducted each Monday morning from June to September between 6:00am and 8:00am. *E. coli* samples were taken using sterile bottles supplied by the state certified lab under contract with OARS and were stored in the dark on ice during transport from the field to the lab. Samples were delivered to the lab within 6 hours of collection and analyzed within 8 hours of collection. To ensure that samples were representative of the bulk flow of the river, bottle samples were taken from the main flow of the river at 6 inches depth by wading or using a pole. Duplicate field samples and field blanks of sterile water were taken for 10% of the samples. Table 5 below summarizes laboratory methods and equipment used. Detailed descriptions of sampling methods and quality control measures are available in *Quality Assurance Project Plan for OARS' Bacteria Monitoring Program* (OARS, 2019).

Table 5: Bacteria Sampling and Analysis Methods

Parameter	Analysis Method #	Equipment Range/ Reporting Limits	Sampling Equipment	Laboratory
E. coli	EPA 1603 (Modified m-TEC)	10 CFU/100mL *	bottle	Nashoba Analytical

* CFU = colony-forming unit

Water Quality Review Methods

Water quality measurements were compared with the Massachusetts Water Quality Standards (MA DEP, 2013) (Table 6). All mainstem river sections are designated Class B waters, and all except for the upper Sudbury are Warm Water fisheries (Table 9). The MA Division of Fisheries and Wildlife lists 34 tributary streams in the basin as Coldwater Fishery Resources (CFRs) (MA DFW, 2017) (Appendix V). For nutrient concentrations (where the Massachusetts standard is narrative) results were compared with EPA "Gold Book" total phosphorus criteria (EPA, 1986) and with summertime data for Ecoregion XIV subregion 59 (EPA, 2000) (Table 7).

Table 6: MA DEP Class B Water Quality Standards and Guidance (MA DEP, 2013)

Parameter	Standard / Guidance Class B	Standard / Guidance Class B "Aquatic Life"
Dissolved oxygen	≥ 5.0 mg/l for warm water fisheries ≥ 6.0 mg/l for cold water fisheries	≥5.0 mg/l at least 16 hours of any 24-hour period and ≥ 3.0 mg/l at any time
Temperature	≤28.3° C and Δ < 2.8° C for warm water fisheries ≤20.0° C and Δ < 1.7° C for cold water fisheries	≤29.4 ° C and Δ ≤ 2.8° C
pH	6.5 – 8.3 inland waters and Δ < 0.5 outside the natural background range	
Nutrients	"control cultural eutrophication" / Gold Book** standard TP < 0.05 mg/L for rivers entering a lake or impounded section	
Suspended Solids	"free from floating, suspended and settleable solids in concentrations and combinations that would impair any use assigned to this Class"	
Aesthetics	All surface waters shall be free from pollutants in concentrations or combinations that settle to form objectionable deposits; float as debris, scum or other matter to form nuisances; produce objectionable odor, color, taste or turbidity; or produce undesirable or nuisance species of aquatic life.	
E. coli	Geometric Mean 126 CFU/100ml and Single Sample 235 CFU/100ml for primary contact. Geometric Mean 630 CFU/100ml and Single Sample 1260 CFU/100ml for secondary contact.	
Chloride	EPA Recommended Criteria*** 230 mg/L chronic exposure, 860 mg/L acute exposure.	

** EPA, 1986, Gold Book; *** EPA, 2002 National Recommended Water Quality Criteria

Table 7: Reference Conditions for Ecoregion XIV (subregion 59) Streams (EPA, 2000)

Nutrient Parameter	25th percentile of summer data	50th percentile of summer data
Total Phosphorus	25 μg/L	50 μg/L
Orthophosphate	10 μg/L	25 μg/L
Total Nitrogen	0.44 mg/L	0.74 mg/L
NO2 + NO3 (as N)	0.34 mg/L	0.43 mg/L
Chlorophyll *a* (Spec A method)	2.00 μg/L *	4.00 μg/L *

* Chlorophyll-a data is available only for subregion 63

<u>Long-term Trend Analysis</u>

Summer (June/July/August) trends have been analyzed for most parameters from 1992 to the present (where available). Over the years, the list of actual sites has evolved significantly, so it is important to understand which sites have been added or discontinued over the trend time-period. Sites that are less than 0.1 river miles apart and where there are no significant river changes (e.g., tributaries joining) were considered the same (e.g. ABT-311/ABT-312). Table 8 lists the long-term sites used and their sections.

Table 8: Sites for trend analyses

Sections	Sites	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21
Assbt. Head	ABT-311/ABT-312	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Upper Assabet	ABT-301	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	ABT-280					X	X	X	X	X	X	X	X	X	X	X	X	X	X												
	ABT-263/ABT-262								X	X	X																				
	ABT-253/ABT-252								X	X	X																				
	ABT-242	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X												
	ABT-238/ABT-237	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	ABT-220								X	X	X																				
	ABT-196					X	X	X	X	X	X																				
	ABT-182								X	X	X																				
	ABT-159									X	X																				
	ABT-144*	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Lower Assabet	ABT-077	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	ABT-065	X	X	X	X	X	X	X	X																						
	ABT-063/ABT-062								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	ABT-047								X	X																					
	ABT-044									X	X																				
	ABT-033	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X												
	ABT-026	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	ABT-010								X	X	X	X	X	X	X	X	X	X	X	X	X	X									
Concord	CND-009													X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	CND-036																														X
	CND-045																	X	X	X	X	X	X	X	X	X	X	X	X	X	
	CND-093													X	X	X	X														
	CND-110																	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	CND-161													X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Lower Sudbury	SUD-005																		X	X	X	X	X	X	X	X	X	X	X	X	X
	SUD-064																		X	X	X	X	X	X	X	X	X	X	X	X	X
	SUD-086																		X	X	X	X	X	X	X	X	X	X	X	X	X
	SUD-096																					X	X	X	X	X	X	X	X	X	X
	SUD-098																		X	X	X	X									
	SUD-144																		X	X	X	X	X	X	X	X	X	X	X	X	X
Upper Sudbury	SUD-236																														X
	SUD-293																														X
Hop Sudbury	HBS-016																		X	X	X	X	X	X	X	X	X	X	X	X	X
	HBS-098																														X
Tributary Streams	HOP-011											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	NTH-009											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	DAN-013											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	ELZ-004											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	CLD-030											X	X	X	X	X	X	X	X												
	FTM-012											X	X	X	X	X	X														
	RVM-005													X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	RVM-038													X	X	X	X	X	X												
	SPN-003											X	X	X	X	X	X														
	NSH-047																	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	NSH-002											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

* ABT-144 was moved from above to below the Gleasondale dam in 2000.

River Reaches and Tributaries

For data analysis, the water monitoring sites are divided into sections: (1) Upper Assabet mainstem, (2) Lower Assabet mainstem, (3) Upper Sudbury mainstem, (4) Lower Sudbury mainstem, (5) Concord mainstem, (6) Sudbury and Assabet Headwater sites, and (7) all Tributary sites. For some analyses, the headwater and tributary sites are combined. The Hop Brook in Sudbury (HBS-016, HBS-098), a tributary to the Sudbury River, is sometimes analyzed separately from the other tributaries because it receives the discharge from the Marlborough

Easterly wastewater treatment plant. Table 10 lists tributary and mainstem basin characteristics calculated using USGS's StreamStats program.

Table 9: MA DEP River Segment Water Quality Designations

River	Section	Designation
Assabet	Headwaters to Westborough Wastewater Treatment Plant	Class B, Warm Water, High Quality Water
Assabet	Westborough Wastewater Treatment Plant to confluence with the Sudbury	Class B, Warm Water
Concord	Confluence of the Assabet and Sudbury to the Billerica drinking water withdrawal	Class B, Warm Water, Treated Water Supply
Concord	Billerica withdrawal to Roger's St. in Lowell	Class B, Warm Water
Concord	Rogers St. to confluence with the Merrimack	Class B, Warm Water, CSO
Sudbury	Headwaters at Cedar Swamp Pond to Fruit St. in Hopkinton	Class B, Warm Water, Outstanding Resource Water
Sudbury	Fruit St. to the outlet of Saxonville Pond in Framingham	Class B, Warm Water, High Quality Water
Sudbury	Saxonville Pond to Hop Brook	Class B, Aquatic Life, High Quality Water
Sudbury	Hop Brook to confluence with the Assabet	Class B, Aquatic Life
Tributaries	Most tributaries	Class B, Cold Water

Table 10: StreamStats Drainage Basin Statistics

	Statistics at Mouth of River or Tributary[a]				
Mainstem Rivers Headwaters Tributary Streams	Latitude/Longitude at Mouth	Drainage Area (sq.mi.)	Stratified Drift Area (sq.mi.)	% area stratified drift	Slope [b] (%)
Assabet River, Concord	42.4652/-71.3596	177.81	73.00	41.1	3.01
Assabet @ Maynard St, Westboro	42.2741/-71.6322	7.16	1.72	24.0	3.67
Hop Brook, Northboro	42.2887/-71.6449	7.87	2.09	26.6	3.57
Cold Harbor Brook, Northboro	42.3238/-71.6413	6.86	1.97	28.7	5.01
North Brook, Berlin	42.3576/-71.6188	16.89	4.12	24.4	4.38
Danforth Brook, Hudson	42.3897/-71.5666	7.17	2.06	28.7	3.58
Fort Meadow Brook, Hudson	42.3975/-71.5169	6.25	1.76	28.2	3.77
Elizabeth Brook, Stow	42.4217/-71.4776	19.09	6.93	36.3	3.73
Nashoba Brook, Concord	42.4592/-71.3942	48.05	19.05	39.7	2.29
Sudbury River, Concord	42.4637/-71.3578	162	49.13	30.3	2.52
Sudbury @ Cedar St, Hopkinton	42.2649/-71.5364	20.8	8.51	40.9	3.22
Hop Brook, Sudbury	42.3627/-71.3733	22.0	14.5	65.9	2.44
Concord River, Lowell	42.6351/-71.3015	400.0	197.97	49.5	2.63
River Meadow Brook, Lowell	42.6318/-71.3087	26.32	16.18	61.5	1.91

[a] Calculated using USGS's StreamStats program (https://streamstats.usgs.gov/ss/)
[b] Slope is the mean basin slope calculated from the slope of each grid cell in the designated basin (1:250K DEM).

Precipitation and Streamflow

The two years 2020 and 2021 differed dramatically in precipitation (Figure 3 and Figure 4). The summer of 2020 was noteworthy for its lack of precipitation, and the summer of 2021 was extreme in its excess precipitation. According to the U.S. Drought Monitor (https://droughtmonitor.unl.edu), drought conditions were noted in the SuAsCo watershed in 2020 from June to December and for a short period in 2021 in April (Figure 5). The 2020 drought was so severe that it reached level D3 (extreme drought) in October. At the end of September, 2020, the Massachusetts Water Resources Commission reported a 9-month Standardized Precipitation Index of -1.36 standard deviations, which corresponded to severity level 3 out of 4 (MA DCR, 2020). In September, 2021, the 9-month SPI was completely the opposite at +96% (MA DCR, 2021).

Figure 3: Annual summer precipitation (1999-2021)

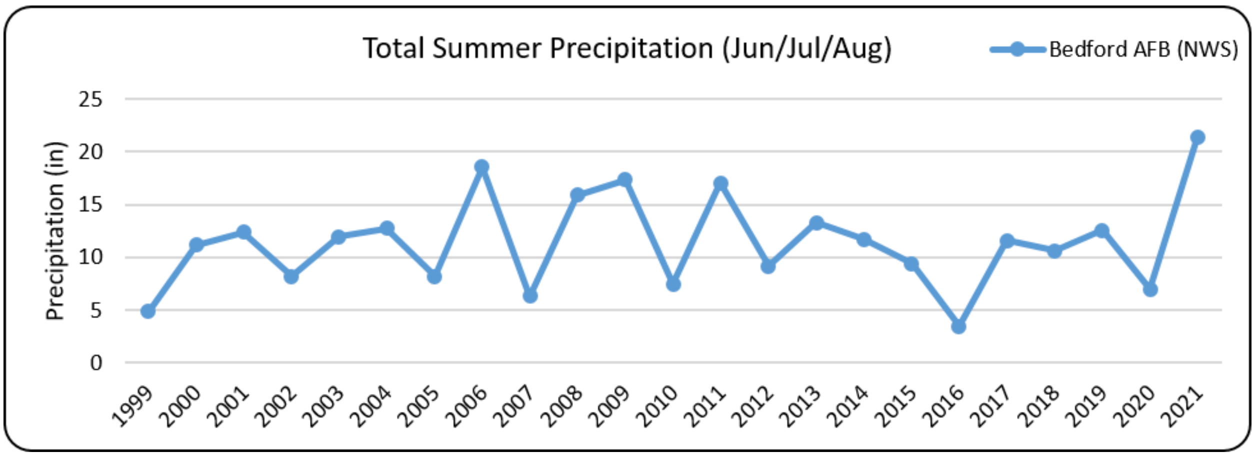
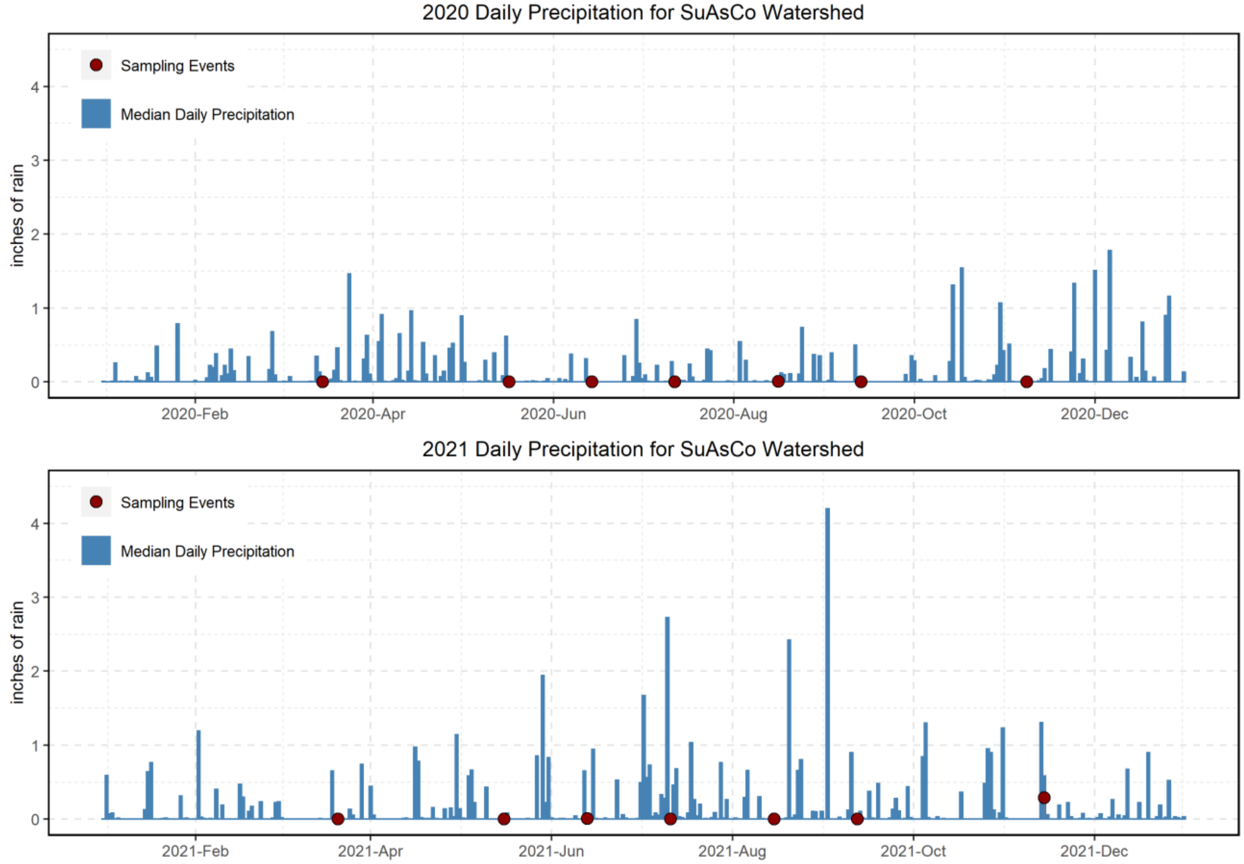
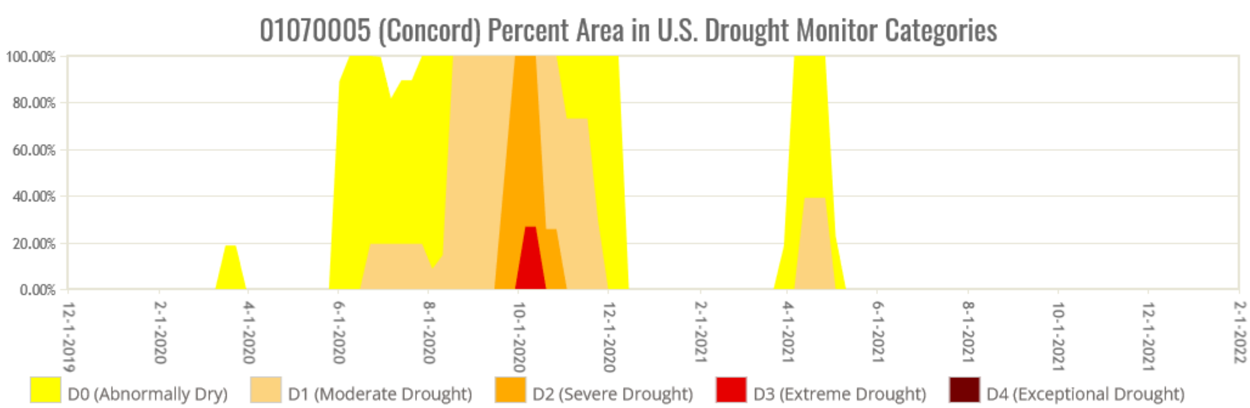


Figure 4: Daily rainfall with sampling dates 2020-2021



(Precipitation data sourced from CoCoRaHS, for box bounded by 42.22852/-71.70227 and 42.51766/-71.31912. https://www.cocorahs.org/ViewData/)

Figure 5: U.S. Drought Monitor status for SuAsCo watershed (HUC 8) 2020-2021



(graph from https://droughtmonitor.unl.edu/DmData/TimeSeries.aspx)

Figure 7 shows mean daily streamflow for 2020 and 2021 at the Assabet, Sudbury, and Concord River gages compared with the historic mean streamflow for the period of record. The Concord River is mainly a reflection of the combined flows of the Assabet and Sudbury. In 2020, streamflow for all rivers was well below average from the beginning of June through the end of

November. In 2021, streamflow was at or above average, but was heavily affected by large precipitation events and major fluctuations in flow. Figure 6 shows year-on-year average summer streamflow for the Assabet and Sudbury for the 40 years since 1982. The summer of 2020 had the third or fourth lowest streamflow over this period, and 2021 had the second highest streamflow for the period.

Figure 6: Average summer streamflow (June/July/August)

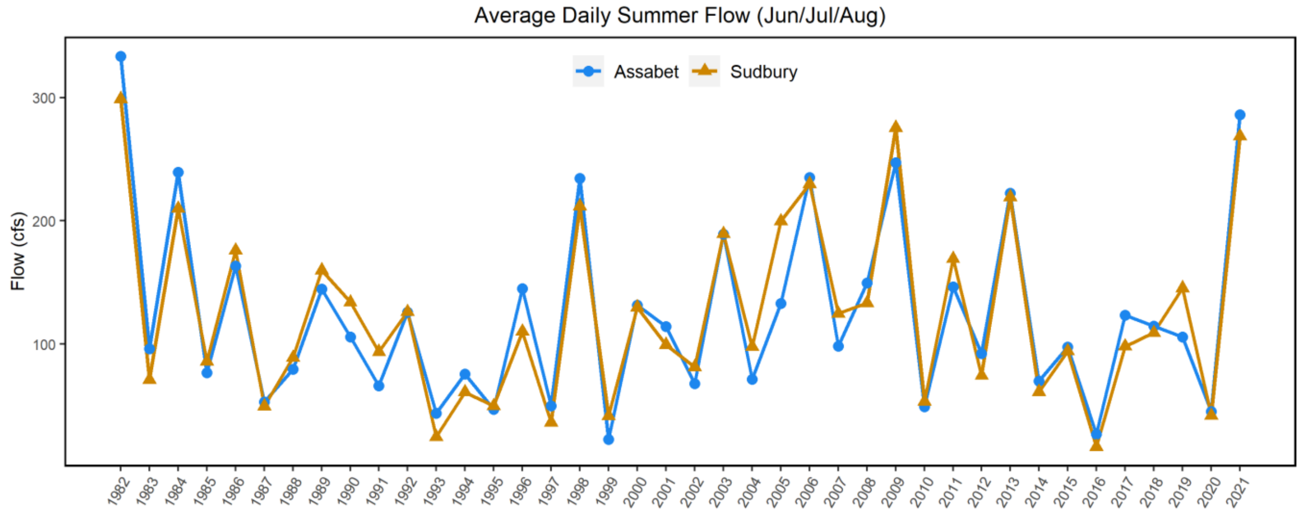


Figure 7: Mean Daily Streamflow, by River, 2020-2021

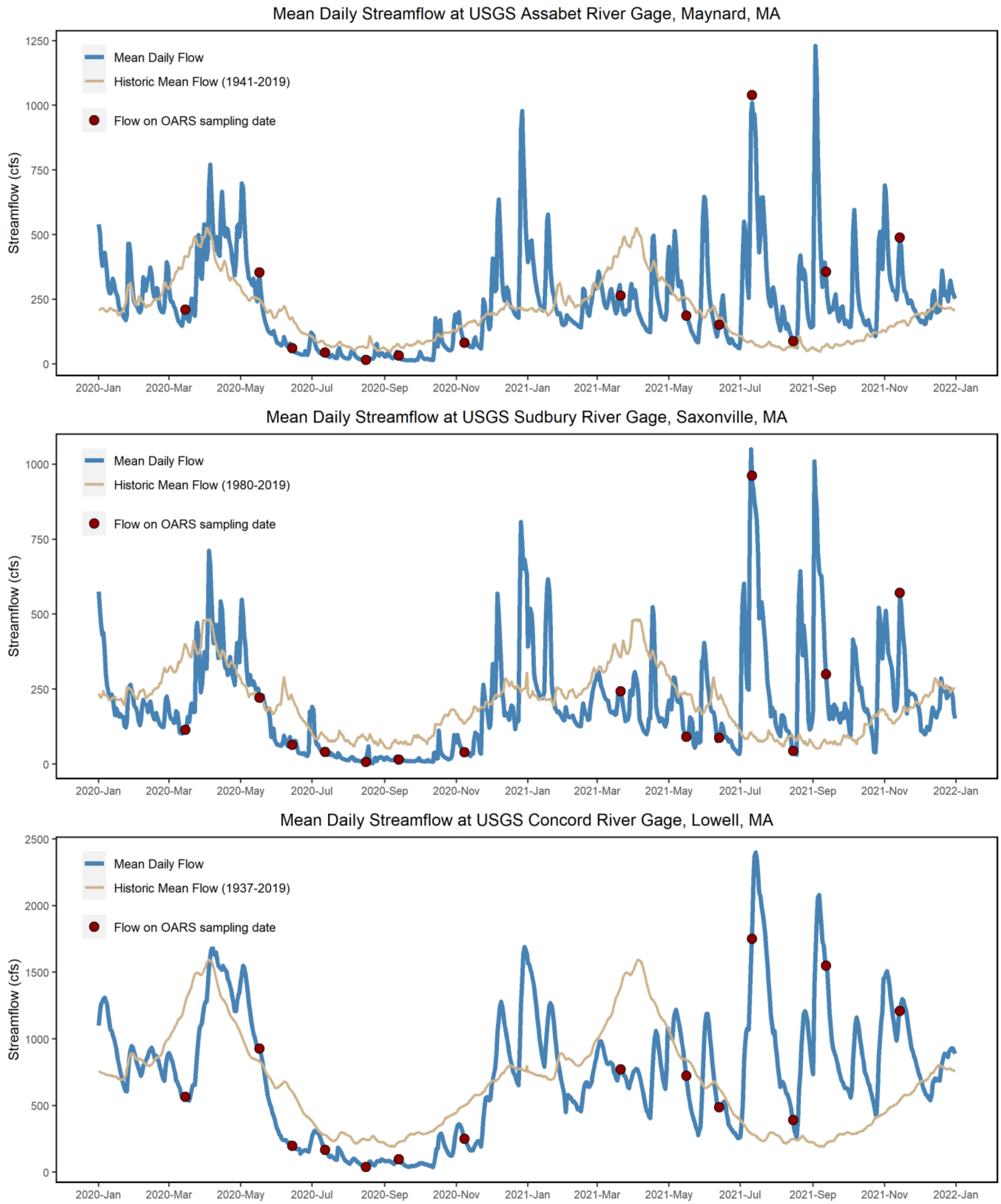
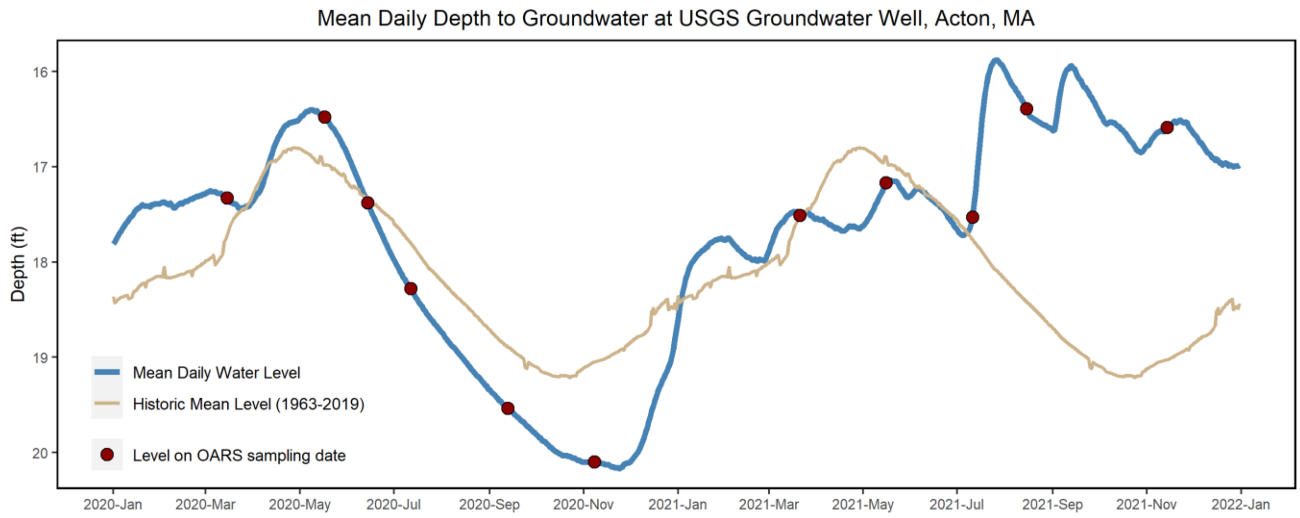


Figure 8 shows groundwater levels in 2020 and 2021 compared with historic mean levels from the USGS monitoring well in Acton (USGS 422812071244401 MA-ACW 158 ACTON, MA). Groundwater levels tracked the major precipitation trends with well below average levels in 2020 and well above average levels in 2021. Changes in groundwater levels reflect precipitation and evapotranspiration rates and, in turn, affect baseflow to the streams.

Figure 8: Groundwater Levels (USGS Monitoring Well Acton, MA)



Precipitation, and the associated increased stormwater runoff and streamflow changes, are correlated in our data with concentrations of total suspended solids, total phosphorus, and nitrate. For the purposes of this project, sampling dates were classified by visual inspection of the hydrograph of the nearest available real-time USGS gage as rising, falling, or flat hydrograph (Table 11). Samples collected on a rising hydrograph may include "first flush" runoff and the higher load of pollutants associated with the first flush. Note that flow at the Sudbury River gage in Saxonville/Framingham is sometimes affected by dam manipulations upstream. Sampling events that were preceded by more than 0.1 inches of rain in the previous 48 hours (the standard definition of a "wet" weather sampling) are highlighted.

Table 11: Hydrographic and Precipitation Data 2020-2021

	Hydrograph at USGS gage			Precipitation (inches)
Sampling Date	Assabet River at Maynard	Sudbury at Framingham	Concord at Lowell	Previous 48 hours
Mar 15, 2020	Flat	Flat	Flat	0.13
May 17, 2020	Rising	Falling	Falling	0.62
Jun 14, 2020	Flat	Flat	Falling	0 *(0.31 prev. 72 hrs)
Jul 12, 2020	Falling	Falling	Falling	0.27
Aug 16, 2020	Flat	Flat	Flat	0.01
Sep 13, 2020	Flat	Flat	Flat	0 *(0.5 prev. 72 hrs)
Nov 8, 2020	Falling	Falling	Falling	0
Mar 21, 2021	Falling	Falling	Falling	0 *(0.65 prev. 72 hrs)

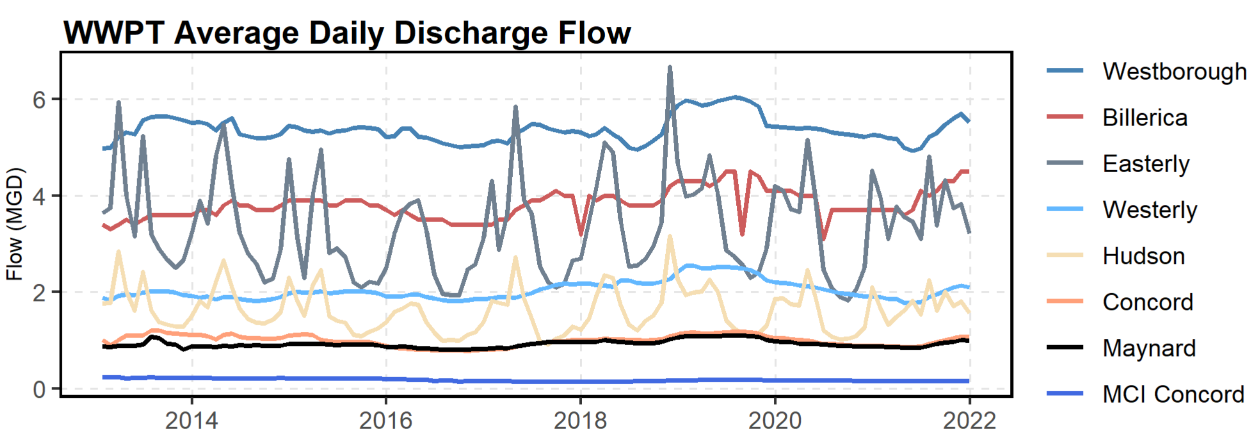
	Hydrograph at USGS gage			Precipitation (inches)
Sampling Date	Assabet River at Maynard	Sudbury at Framingham	Concord at Lowell	Previous 48 hours
May 16, 2021	Falling	Flat	Falling	0
Jun 13, 2021	Rising	Flat	Flat	0.66
Jul 11, 2021	Rising	Rising	Rising	2.73
Aug 15, 2021	Falling	Falling	Falling	0
Sep 12, 2021	Falling	Falling	Falling	0.01 *(0.91 prev. 72hr)
Nov 14, 2021	Rising	Rising	Rising	1.60

Wastewater Treatment Plant Discharge

There are eight wastewater treatment plants discharging significant volumes of water into the three rivers (Figure 9). During low flow times, the discharge of these treatment plants can represent a significant portion of the total flow of the rivers. This is particularly true for the Assabet River.

Streamflow measured at the Assabet River gage in Maynard includes effluent discharges from three of the four municipal wastewater treatment plants on the river (Hudson, Marlborough Westerly, and Westborough). The three treatment plants discharged a combined average of 13.2 cfs and 13.7 cfs to the river from May through September in 2020 and 2021 respectively (EPA, 2022). This compares with the average flows for this period at the Assabet River gage of 91 cfs and 296 cfs respectively and the minimum flows of 14 cfs and 60 cfs respectively. Since the WWTP flows are fairly stable, there are times when they may represent > 50% of total flow. In September of 2020, treatment plant flow may have constituted almost 100% of the flow.

Figure 9: WWTP Discharge Flow (daily - 2013-2021)



* Note that we believe there is an issue with the EPA Discharge Monitoring Report that provides this discharge flow data. It appears that Westborough, Billerica, Marlborough Westerly, Concord, Maynard, and MCI may be reporting a 12-month rolling average flow instead of a monthly average flow. We are working with the EPA to get the monthly average flow data.

Water Quality Results

Reach and tributary statistics for all water quality parameters are provided in tabular form in Appendix I. Raw data is available in Appendix III. Individual parameters are discussed here, with separate discussions by parameter. For each parameter, similar data views are provided: by-site detail for 2020 and 2021, by-month detail for 2020 and 2021, year-on-year results for the full monitoring history, and year-on-year load calculations where relevant. Maps and additional graphs are also provided where relevant. Many of the graphs are boxplot type graphs, because they give a good understanding of the range of the results. In a boxplot graph, the box represents the middle 50% of the data, the line in the middle of the box is the median, the lower whisker represents the bottom 25% of the data, and the upper whisker represents the upper 25% of the data. In past years, we have calculated Mann-Kendall tests for trends based on flow-weighted concentrations, but this year we chose to report load-based trends instead. Load is the total amount (mass) of a nutrient or pollutant that is carried downstream per day. Since load is based on flow, it naturally incorporates flow into the trend analysis.

Water Temperature

Water temperatures at all sites met the Class B warm water fisheries standard (28.3°C) on all of the regular testing dates in 2020 and 2021 (Figure 10). The Lower Assabet, Sudbury, and Concord Rivers came very close to this threshold in July 2020 (27.8°C at CND-045) and again in August 2021 (27.1°C at CND-110) (Figure 11). Many of the tributary streams support or have supported cold water fisheries, therefore, tributary and headwater temperature readings are compared with the cold water standard of 20.0°C, which is the recommended single-reading maxima for brook trout (23.9°C for brown trout). In the dry summer of 2020, almost all of the tributaries (except Danforth Brook) tracked well above 20.0°C, but in the wet summer of 2021, most of them averaged below this threshold (Figure 10). *The tributary sites are easy to see in the chart, because they are all grouped together, from DAN-013 to RVM-005.*

Year-on-year comparisons of temperature data show very little statistical change in water temperatures for the period of record (Figure 12). Trend lines are level for most sections except the Concord, but the Concord upward slope seems to be a function of the fact that measurements only started in 2005. In the 2019 Annual Report, we noted an upward trend in temperatures for many of the tributaries. This was mostly caused by higher temperatures in 2019, and it has disappeared for most streams due to lower temperatures in 2021. However, there is still a slight upward trend visible for the Assabet headwater site (just below the George Nichols Reservoir) and for River Meadow Brook, which is highly urban (Figure 13).

Figure 10: Water temperature by site, summer (2020, 2021)

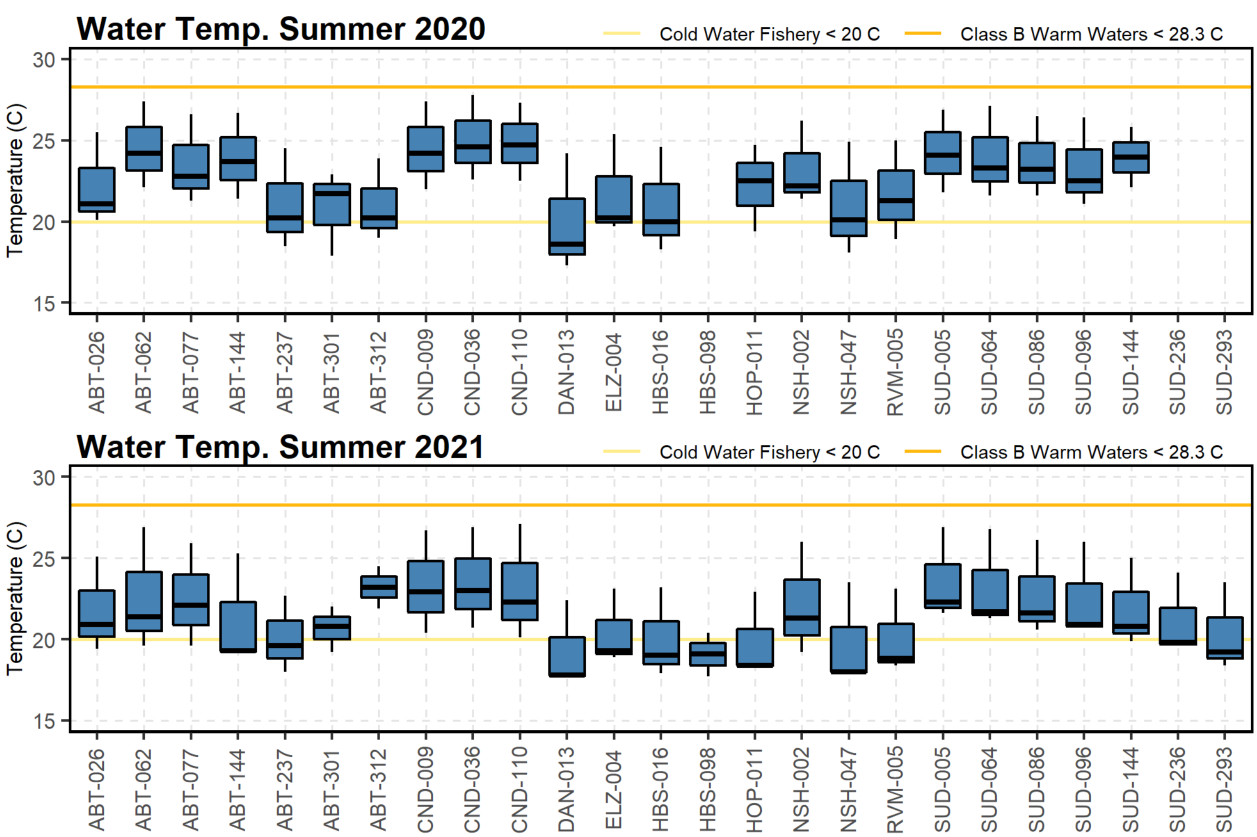


Figure 11: Water temperature by month (2020, 2021)

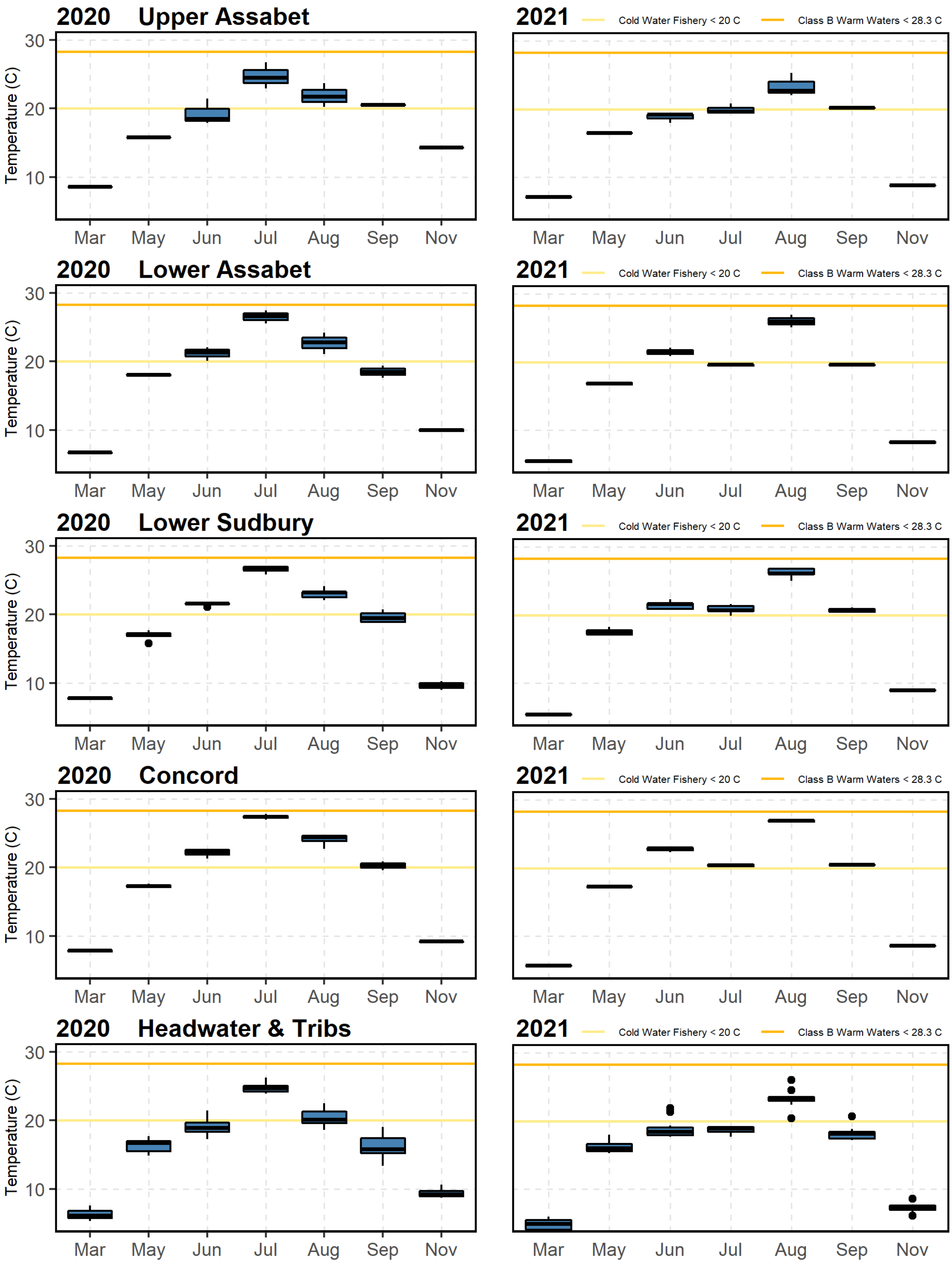


Figure 12: Year-on-year summer water temperature by section (June/July/August)

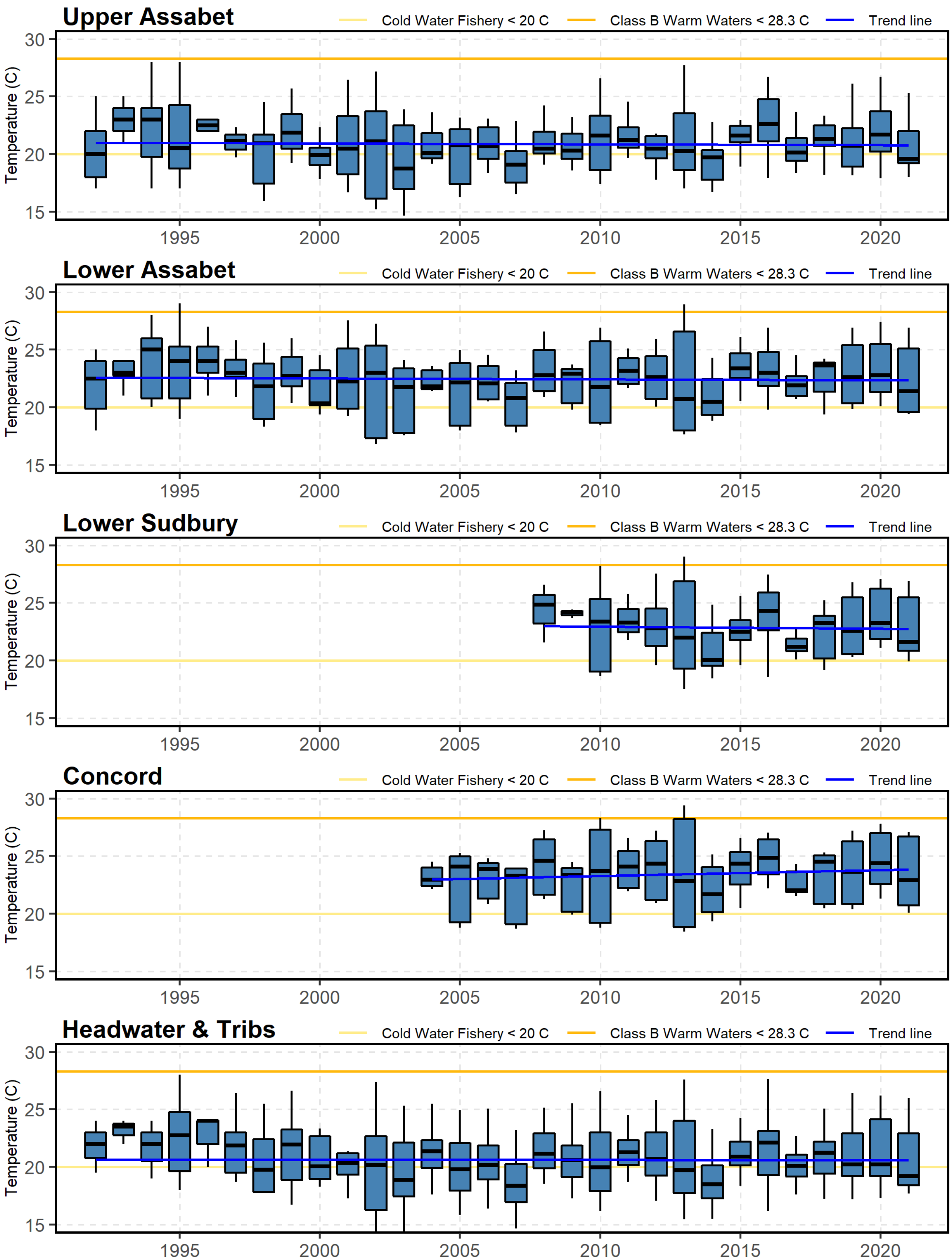
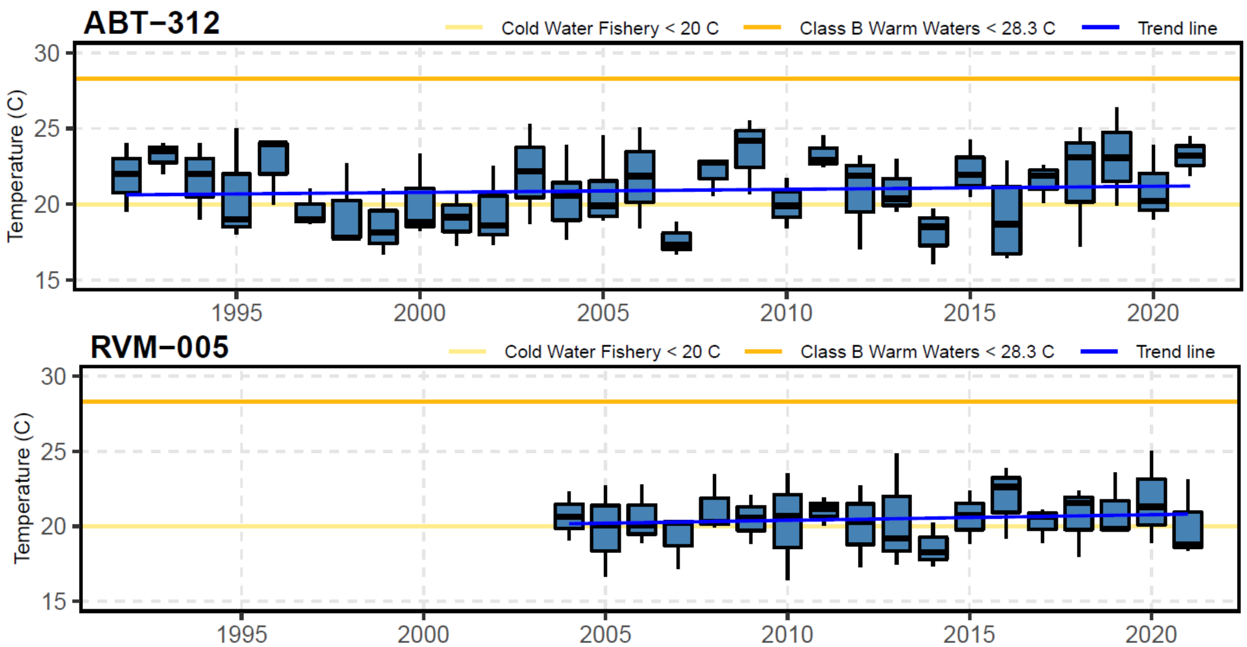


Figure 13: Year-on-year summer water temp. for Assabet Headwater and River Meadow Brook



Conductivity

Conductivity is an indirect indicator of pollutants such as effluent, non-point source runoff (especially road salt), and erosion. A survey of field studies indicated that streams supporting good mixed fisheries have a range between 150 and 500 µS/cm (Ellis, 1944). Most of OARS' mainstem sites are above that range. In 2020, this was clear, but in 2021, conductivity levels were lower due to heavy rain (Figure 14). The Assabet sites tend to have the highest conductivity levels, driven by WWTP discharge, with ABT-301 (below Westborough WWTP) at very high levels in dry years. Some of the headwater and tributary sites (ABT-312, DAN-013, ELZ-004) are generally within the fishery range. However, OARS has conducted surveys of two tributaries (River Meadow Brook and Fort Pond Brook) and shown that conductivity hot spots can be very localized (jumping from 400 to 1400 µS/cm in short distances of the same brook), driven by road and parking-lot runoff. River Meadow Brook and the Northborough Hop Brook consistently have the highest readings out of the tributaries. Figure 17 shows time-series data for these two sites.

Year-on-year analysis of conductivity shows a clear upward trend for all river sections (Figure 16). The year 2021 only deviated from this trend because of extreme precipitation. This is a trend that is being noticed throughout New England, and it is believed to be a direct result of road-salt application (Daley, 2009; Zuidema, 2018; Evans, 2018). See the section on chloride below.

Figure 14: Specific conductance by site, summer (2020, 2021)

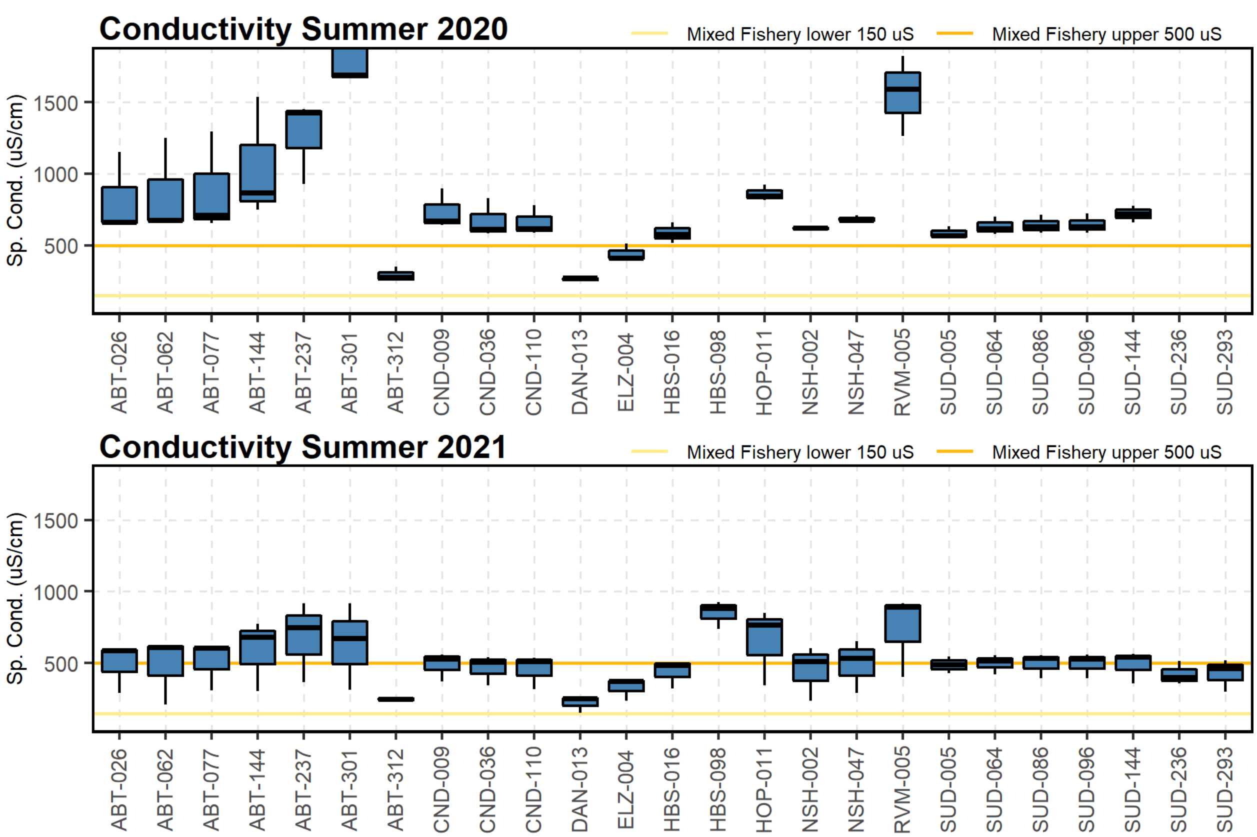


Figure 15: Conductivity by month (2020, 2021)

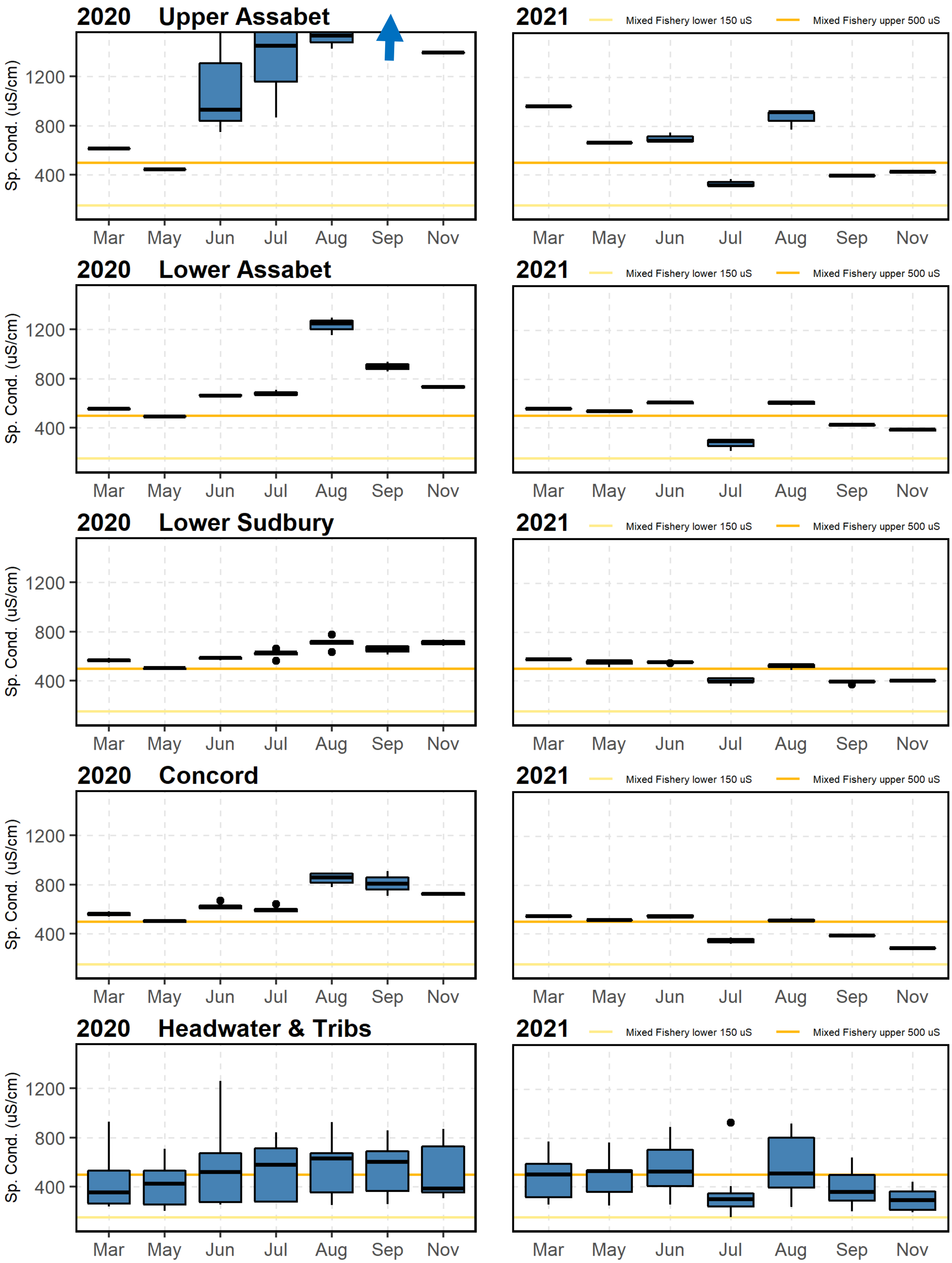


Figure 16: Year-on-year summer conductivity by section (June/July/August)

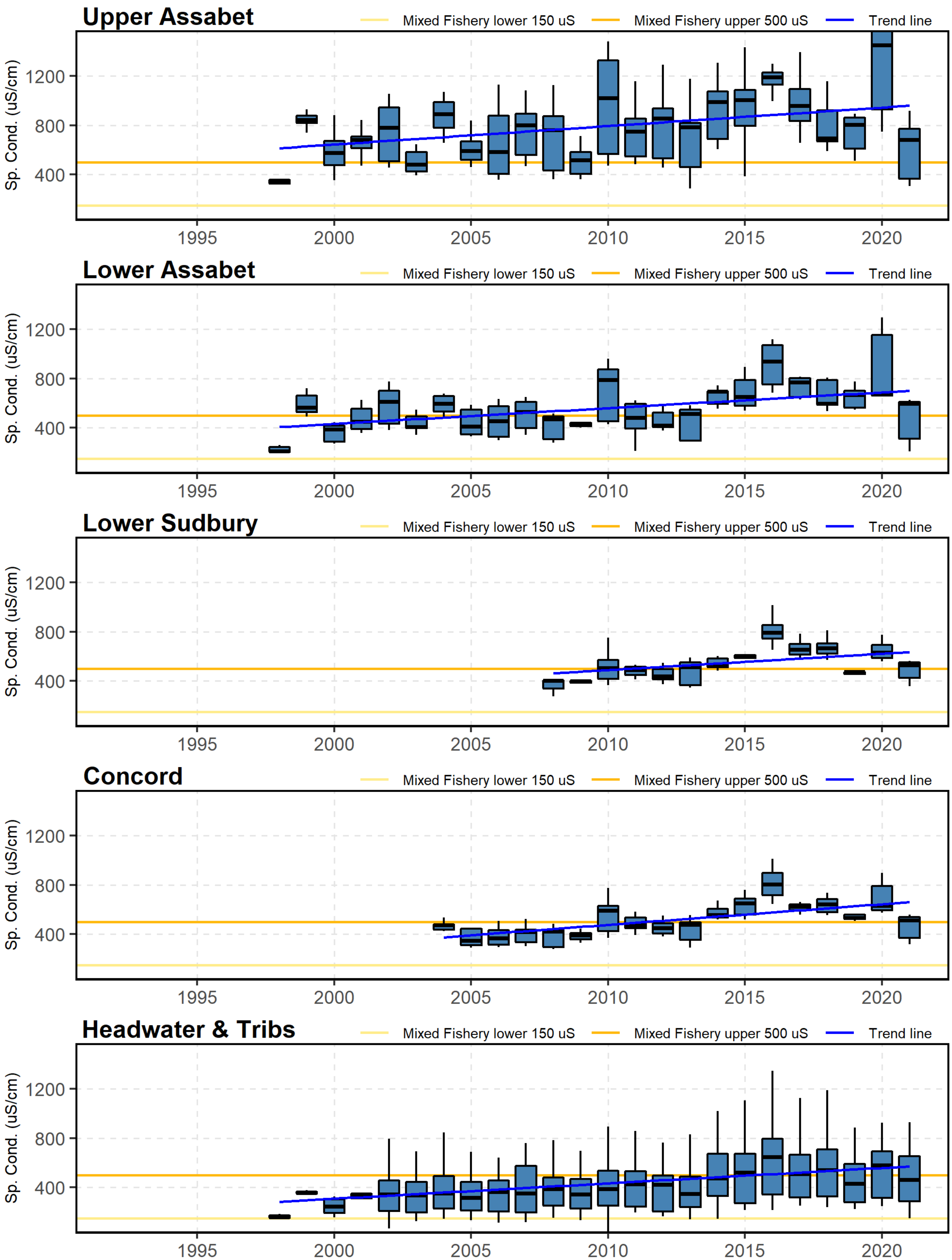


Figure 17: Year-on-year summer conductivity for River Meadow Brook and Hop Brook

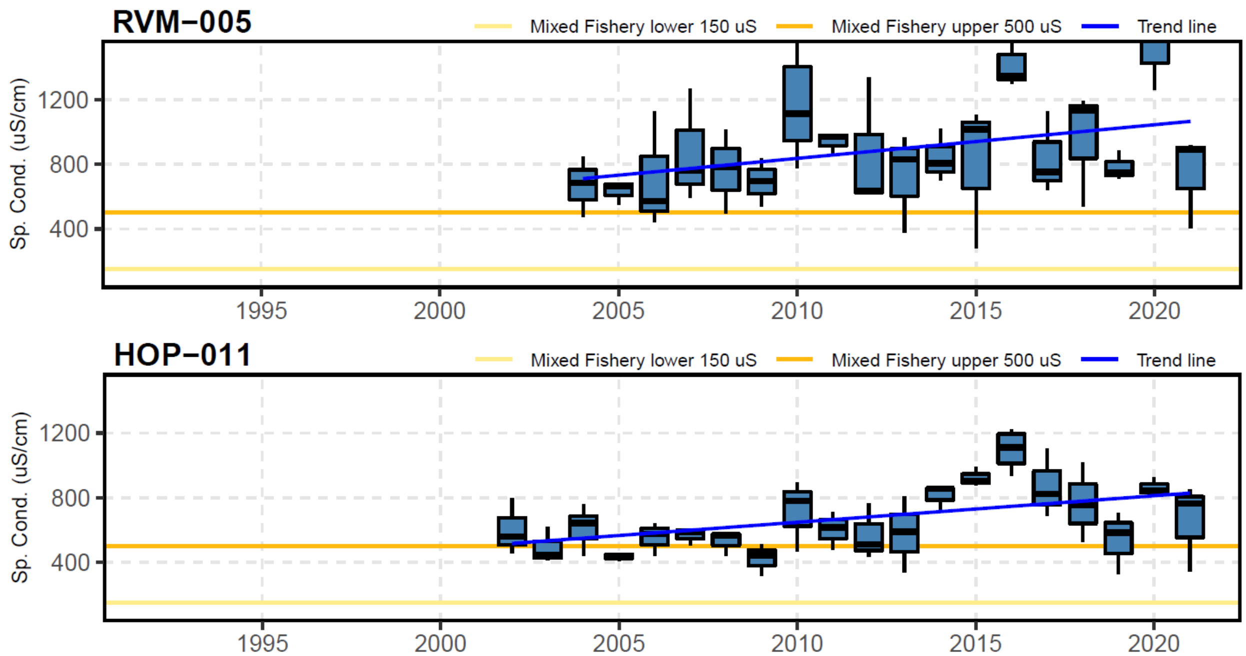
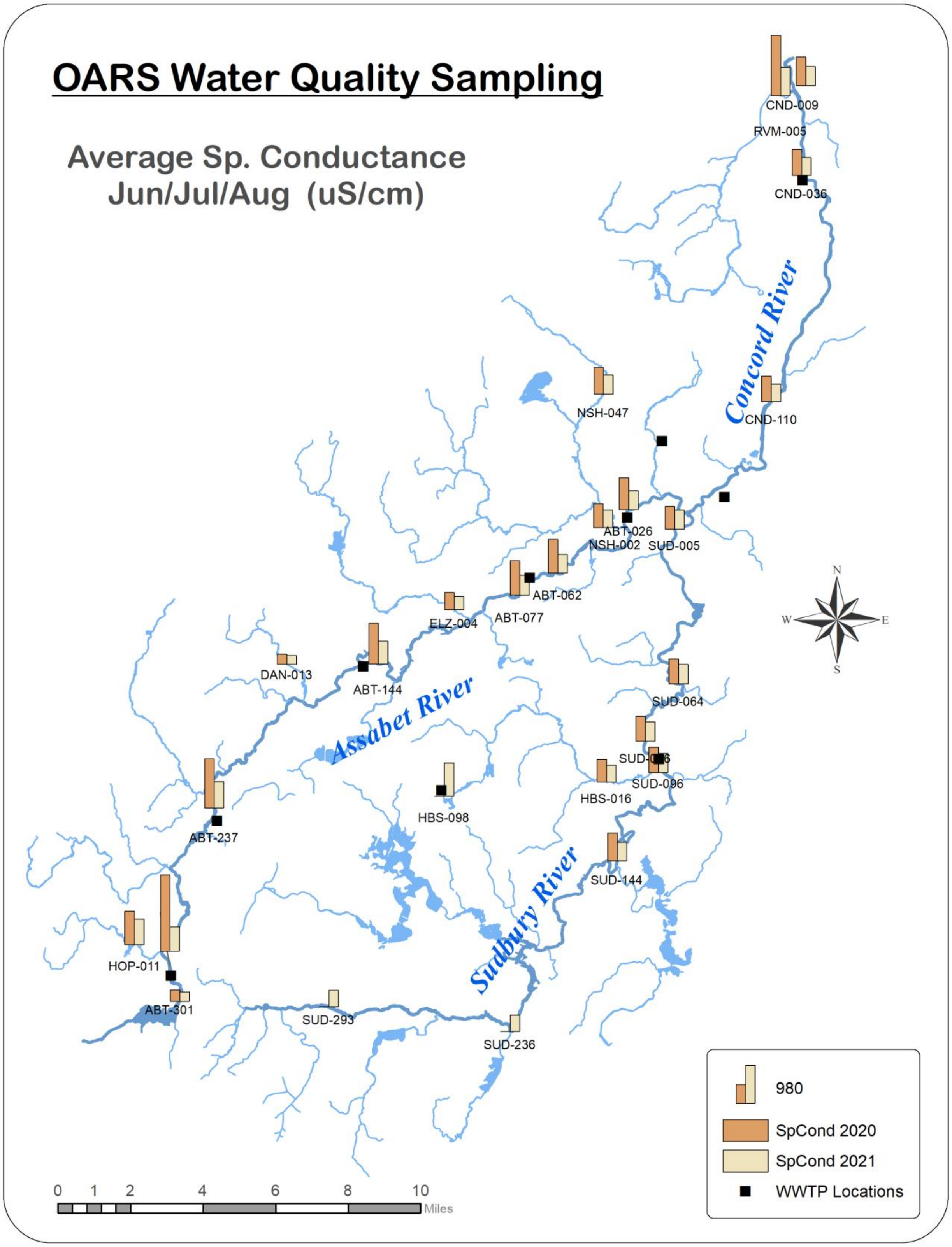


Figure 18: Map of average summer conductivity by site (2020, 2021)



Acidity (pH)
There are a number of factors that can affect pH. Rainwater can lower pH (increase acidity). WWTP discharge can raise pH (Westborough's average discharge pH is 7.6). Carbon dioxide dissolved in water can lower pH, and thus can indicate high levels of respiration or eutrophication. In 2020, summer pH levels in the Assabet were particularly high, driven by low precipitation and a higher proportion of WWTP discharge. The site ABT-062 (downstream of the Maynard WWTP) has the highest pH levels in the rivers almost every year, and 2020 was no exception (Figure 19). In 2021, pH levels in all rivers tended lower as a result of the heavy precipitation. July 2021 levels were particularly low as a direct result of very heavy rains and flows (Figure 20).

Year-on-year analysis of summer pH shows a visible upward trend in pH for the Assabet River (Figure 21). This may be a positive effect of reduced phosphorus in the WWTP discharge. Reducing nutrients reduces biomass, resulting in less respiration from decomposition, less dissolved carbon dioxide, and higher pH. This hypothesis is also supported by the corresponding improvement in dissolved oxygen shown below (Figure 25).

Site ELZ-004 (Elizabeth Brook) had notably low pH in 2020. It also had low DO in 2020 (Figure 23), which could be an indicator of high respiration levels or eutrophication. A time-series review of ELZ-004 shows that 2020 and 2021 are deviations from the norm (Figure 22).

Figure 19: pH by site, summer (2020, 2021)

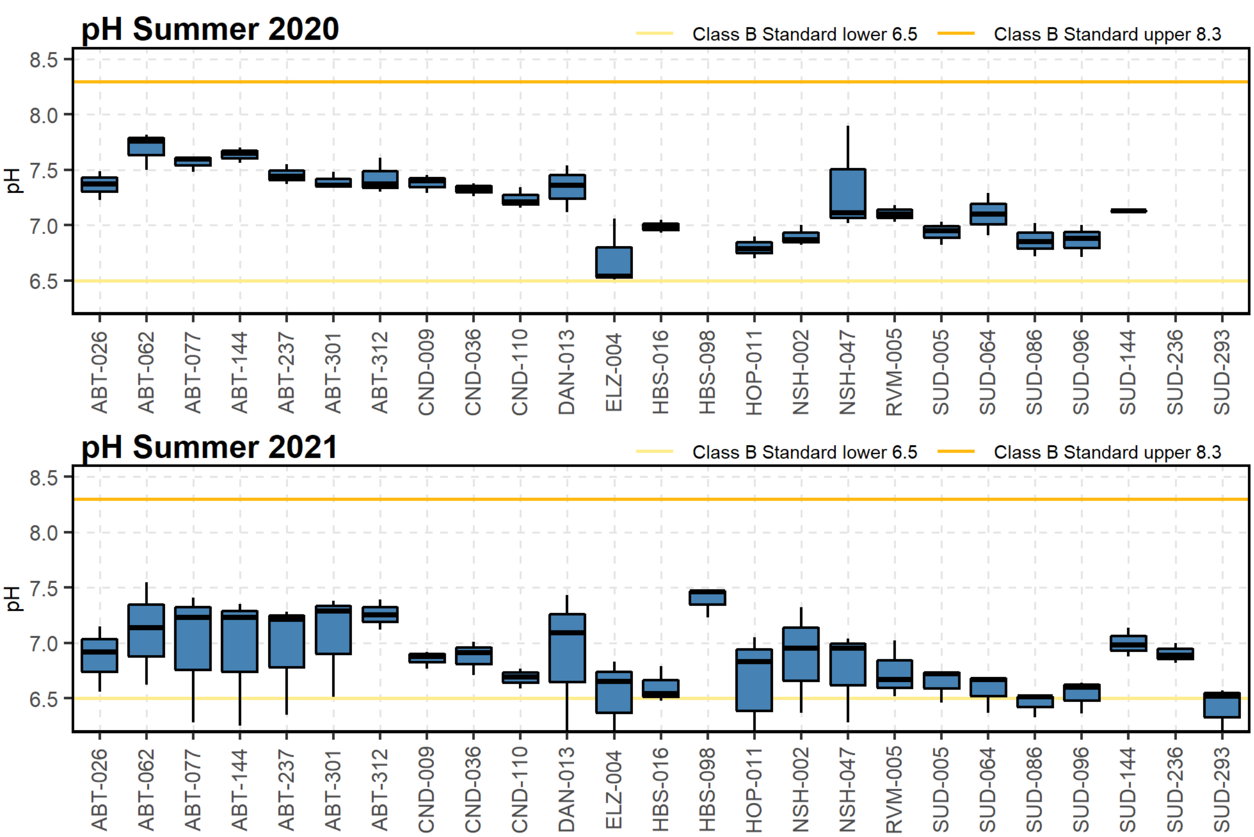


Figure 20: pH by month (2020, 2021)

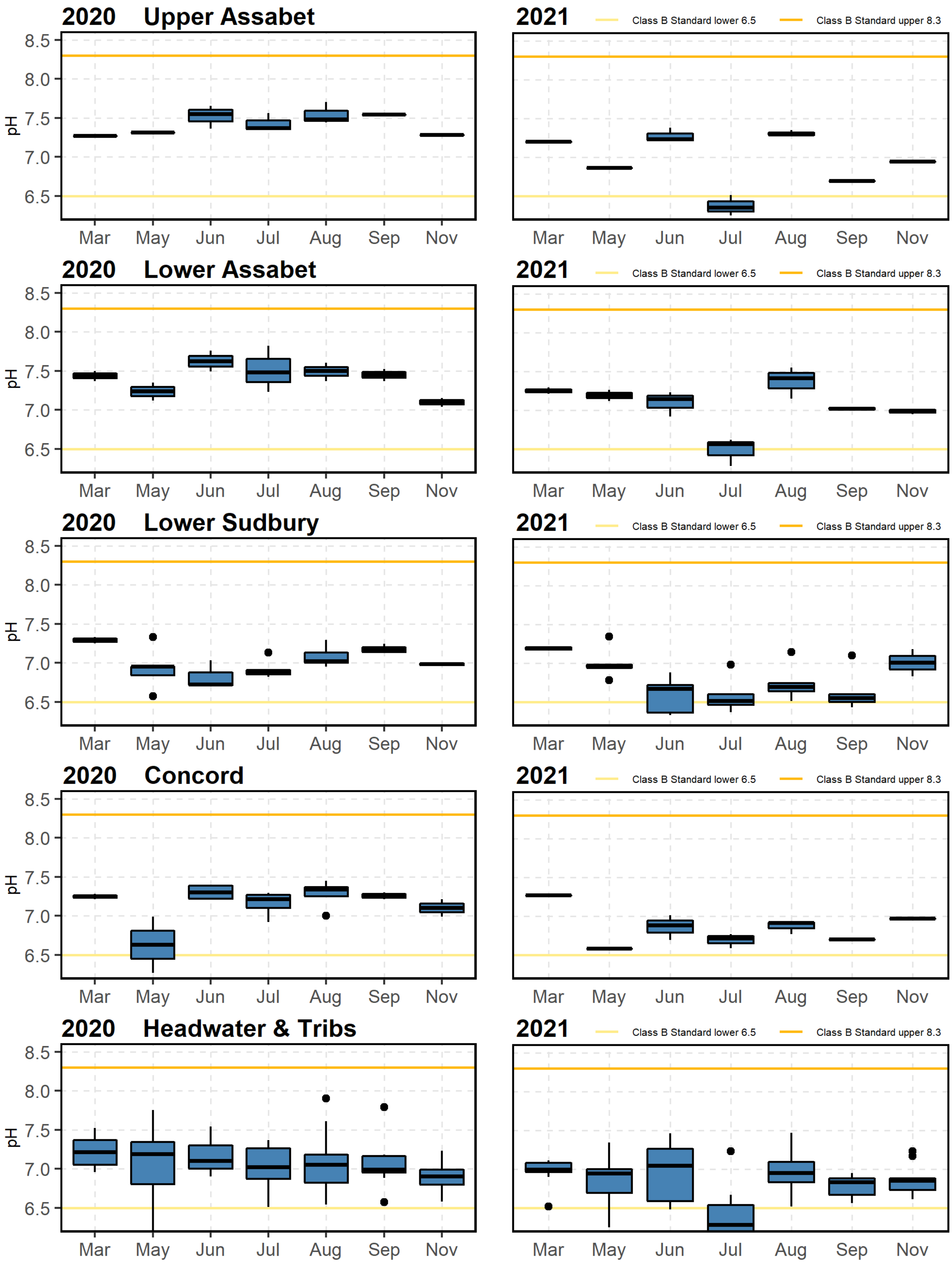


Figure 21: Year-on-year summer pH by section (June/July/August)

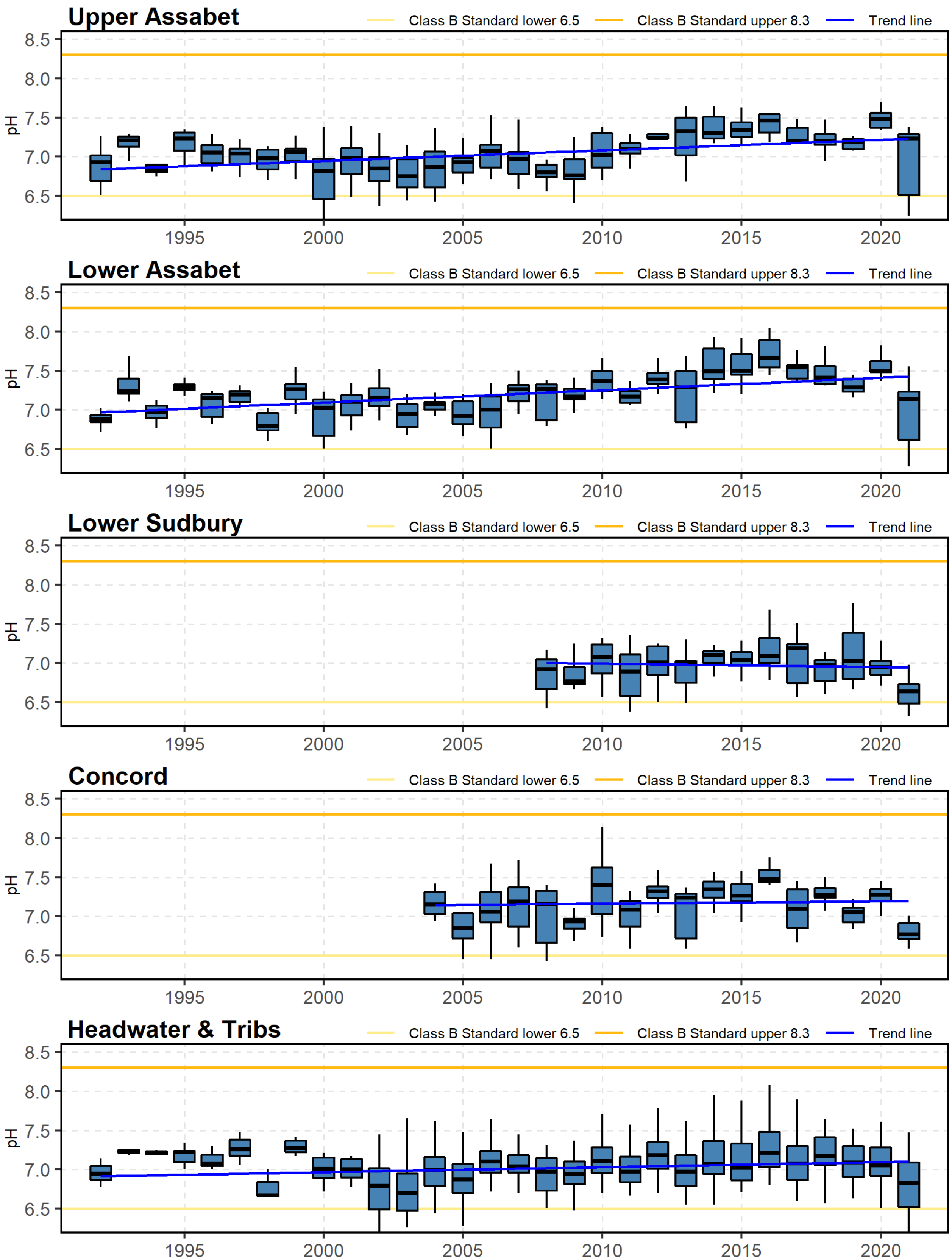
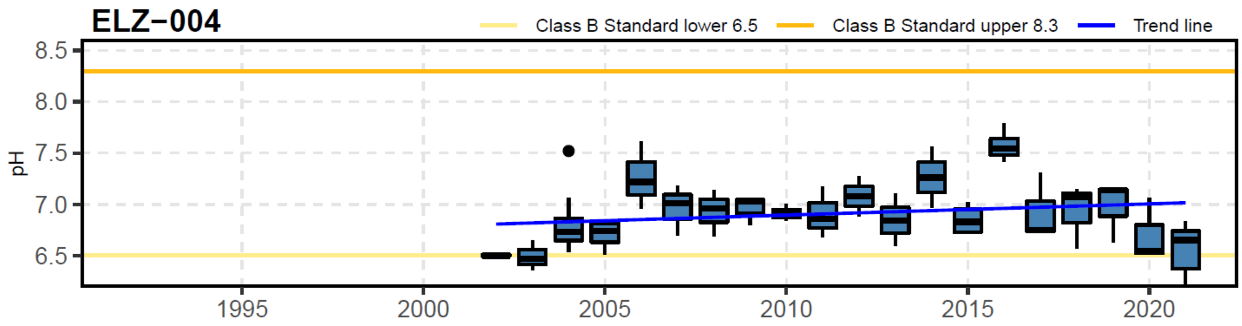


Figure 22: Year-on-year summer pH for Elizabeth Brook



Dissolved Oxygen

Dissolved oxygen (DO) concentrations during the growing season are generally lowest between 5 am and 8 am after plant and microbial respiration has removed oxygen from the water column overnight. This is the time period we target for sampling. Low minimum DO concentrations and large diurnal variations in DO can indicate eutrophic conditions and violate water quality standards. For 2020 and 2021, the Assabet River sites were consistently above the minimum water quality standards (Figure 23). However, the Lower Sudbury sites generally had very low summer DO concentrations and in 2021 were often below the Class B Aquatic Life standard (>3.0 mg/L) (Figure 24). The Lower Sudbury is surrounded by large wetland areas, and wetlands naturally have low DO levels due to still water and high respiration, so these conditions may not be in violation of WQS. In the pH discussion above, it was noted that low DO levels can correspond with low pH in eutrophic conditions. This is especially evident for Elizabeth Brook (ELZ-004) and the Sudbury headwaters (SUD-293).

Year-on-year analysis of dissolved oxygen shows several interesting trends. DO levels in the Assabet River have improved significantly over the period of record (Figure 25), especially in 2000 when all four wastewater plants had implemented treatment to reduce summer phosphorus discharge concentrations below 1 mg/L. The Hop Brook site (HBS-016) shows a distinct improvement in DO since 2015, which is the same year upgrades were completed at the Marlborough Easterly WWTP (Figure 26). There has also been a significant decline in DO concentrations in the Lower Sudbury starting in 2017. It is not known what is causing this.

Figure 23: Dissolved Oxygen concentration by site, summer (2020, 2021)

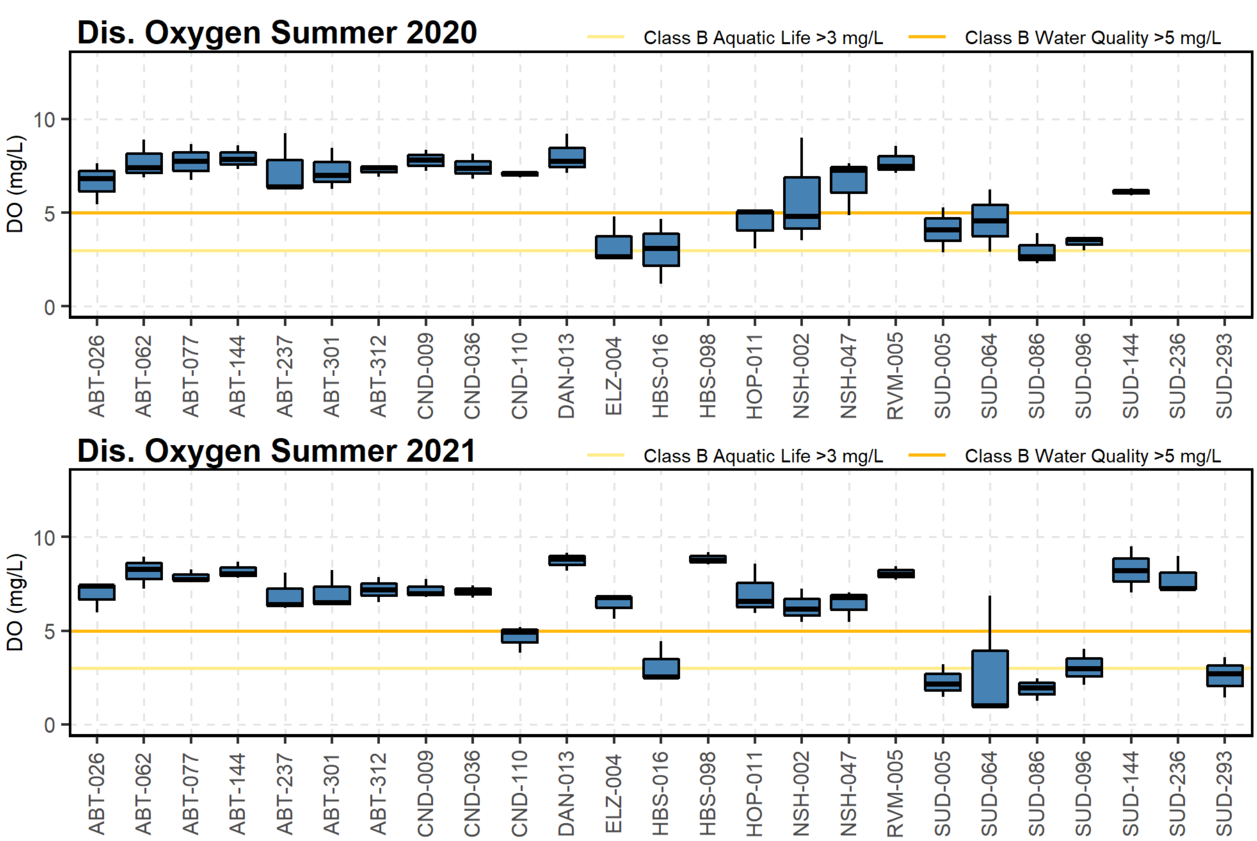


Figure 24: Dissolved Oxygen by month (2020, 2021)

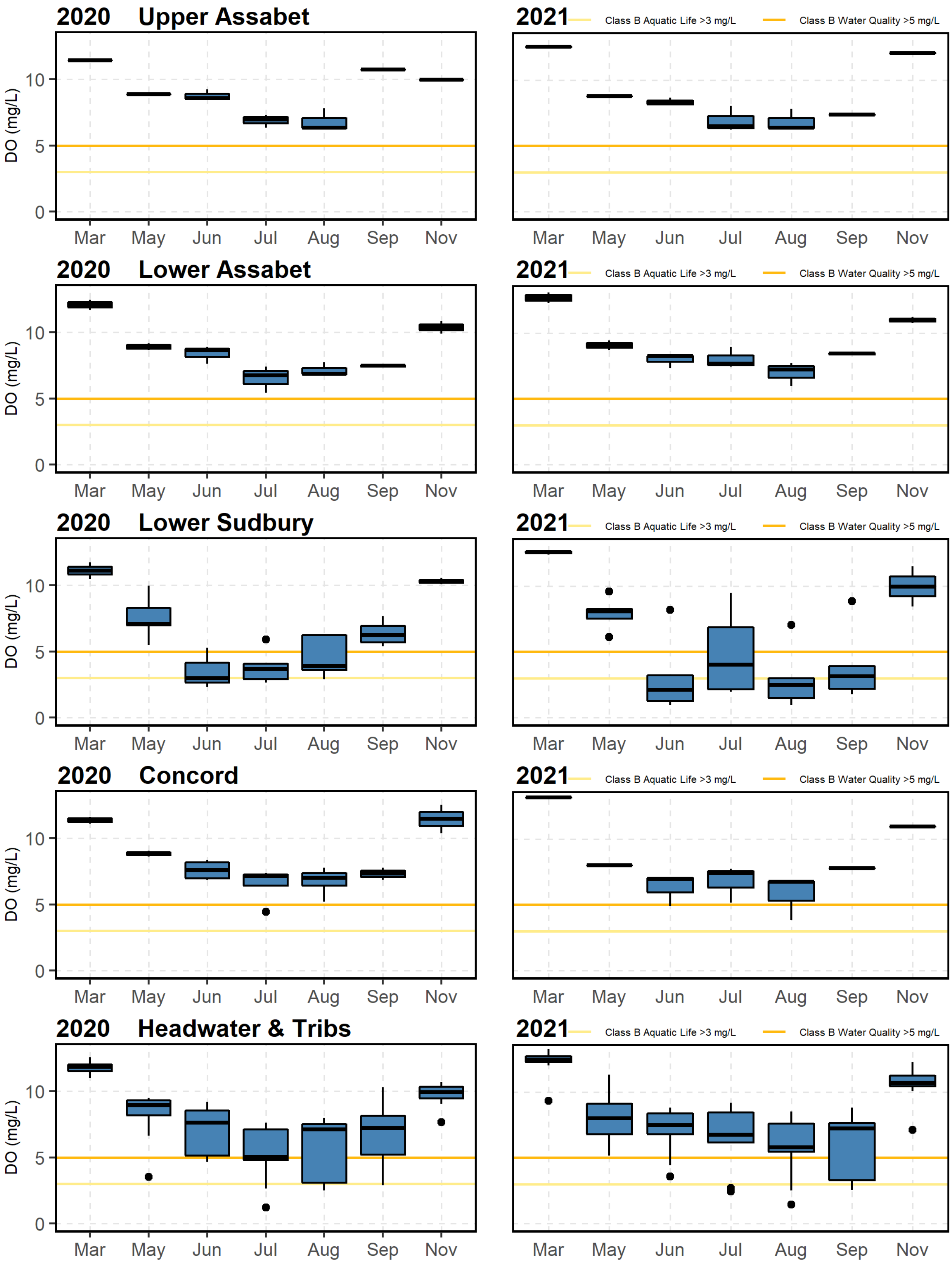


Figure 25: Year-on-year summer Dissolved Oxygen by section (June/July/August)

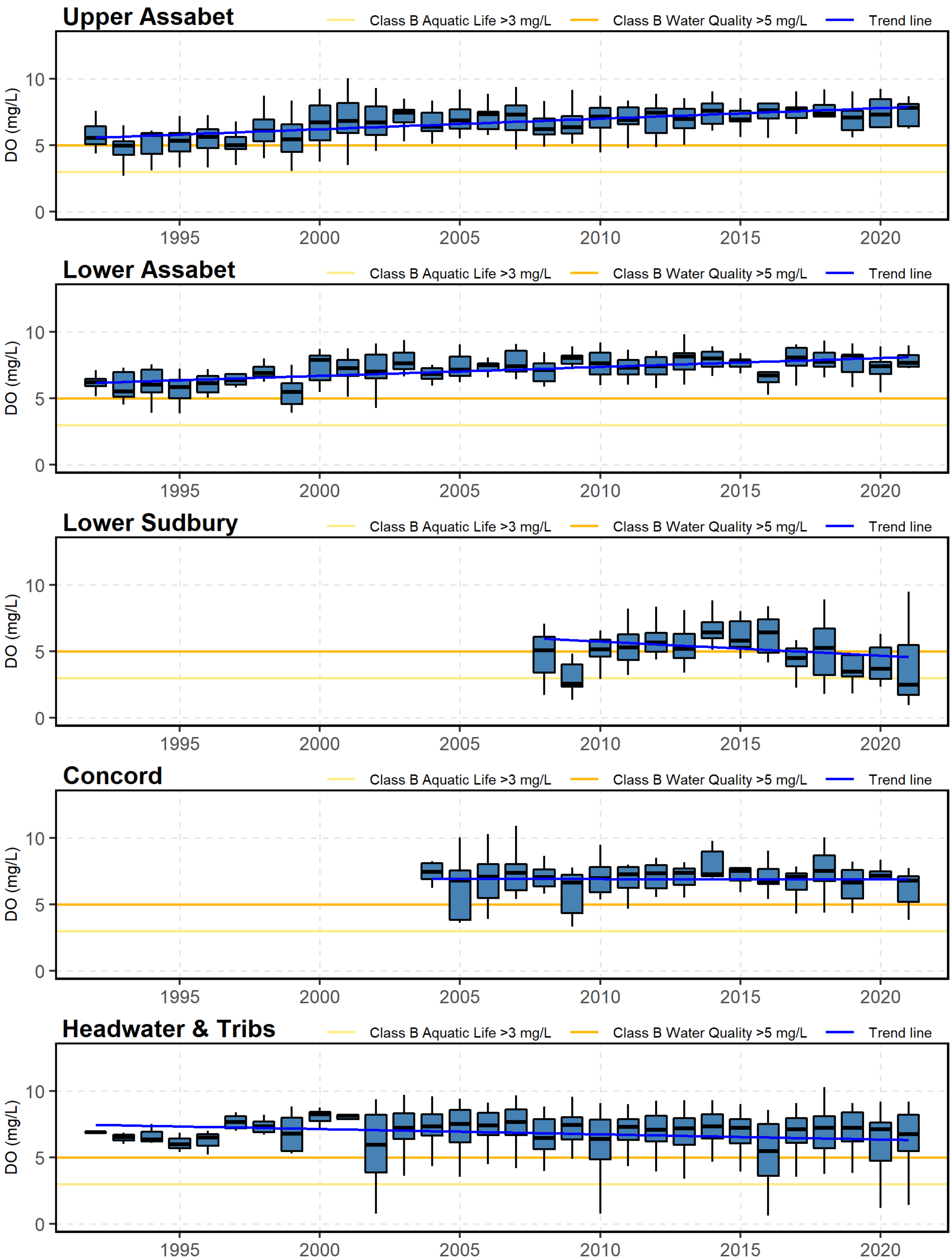
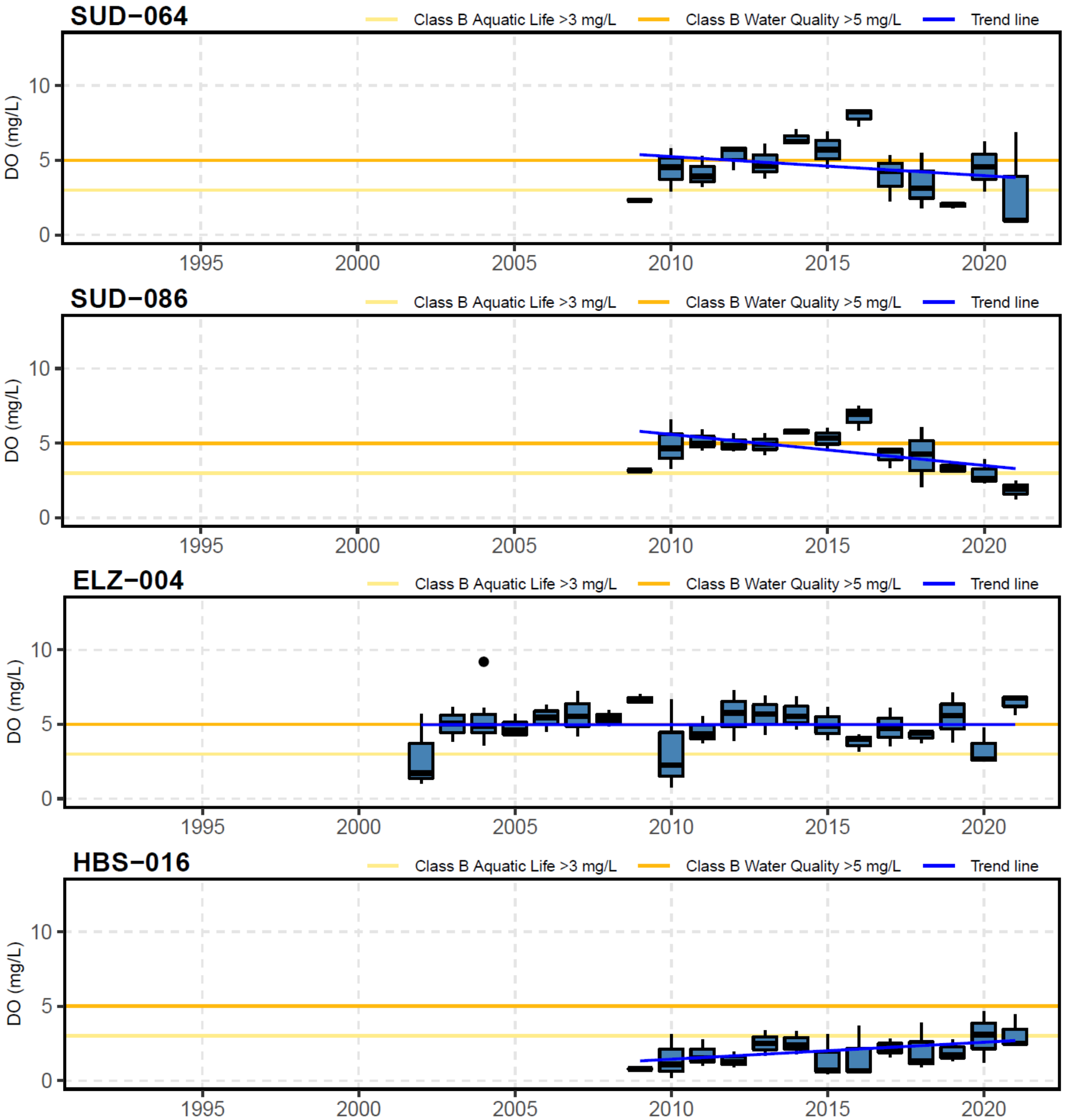


Figure 26: Year-on-year summer dissolved oxygen for selected Sudbury and tributary sites



Total Phosphorus

Phosphorus is considered the limiting nutrient for primary production in freshwater systems, because it is available in much lower proportions per biological need than the other essential nutrients, nitrogen and carbon. For this reason, OARS focuses heavily on phosphorus levels and a TMDL for phosphorus was established for the Assabet River in 2004 (MA DEP, 2004). In 2020 and 2021, Total Phosphorus (TP) concentrations for the Assabet River hovered slightly above the EPA "Gold Book" recommendation of 0.05 mg/L (Figure 27). The two years differed significantly in precipitation and flow, but TP concentrations in the Assabet did not differ much. However, in the headwater and tributary sites there was a noticeable difference, with higher TP concentrations during the dry year, probably due to lack of dilution. The Lower Sudbury sites also showed slightly higher TP concentrations in 2020, which was probably also a dilution effect, but it is worth noting that very low DO, which is common in the Sudbury, may imply anoxic conditions in bottom waters. It is known that anoxic conditions at the bottom sediment-water interface can cause diffusion of phosphorus from the sediments (ENSR, 2001).

A monthly analysis of all the sections except the Upper Assabet shows a pattern of higher TP concentrations during summer months, especially in the headwaters and tributaries (Figure 28). This is often attributable to lower summer flows and less dilution, as it was in 2020, but that was not the case in 2021. Instead, we suspect it is a result of summer biological uptake from sediments, or nonpoint source pollution in runoff during the heavy 2021 rains. It is also worth noting that the sampling event in May 2020 happened right after very heavy rains at the peak of the hydrograph. Upper Assabet TP concentrations were off the scale (0.9 mg/L), and an analysis of all sites showed higher TP levels than were typical for May sampling, especially in headwaters and tributaries. This implies a very large spring phosphorus flush, and we hypothesize that phosphorus was retained in the system for the following months or longer.

Year-on-year analysis of TP shows the improvements delivered by the Assabet WWTP upgrades in 2000 and 2012 (Figure 29). Major progress in reducing phosphorus concentrations has been achieved as a result of the NPDES permits and plant upgrades. However, 2019, 2020, and 2021 have shown a concerning increase in concentrations in all river sections. The cause of this increase is unknown, but 2020 and 2021 were notable for abnormal precipitation. One was extremely dry, resulting in less dilution, and the other was extremely wet, resulting in more nonpoint source runoff.

Looking at load instead of concentration shows a much different picture (Figure 30). Load is the total amount of phosphorus, measured in kilograms, that is carried downstream in the water per day. It is calculated by multiplying concentration (mass per volume of water) by flow (volume per day). We track flow at many locations on the rivers, and we can estimate flow at the other locations. Using the graph of annual summer loads (Figure 30), a clear connection can be drawn with the years of highest flow (Figure 6). The years 2003, 2006, 2009, 2013, and 2021 are all examples of high flow years with high TP loads. The magnitude of the high-flow loads is telling, because it demonstrates how a single high-flow event can inject quantities of phosphorus into the river system at orders of magnitude greater than periods of normal flow, possibly nullifying savings due to low concentrations. High flows also carry phosphorus out of the system, so the net effect is not clear, but this could explain high TP levels in summer 2020, following the May 2020 high flow event mentioned above.

WWTP discharge concentrations and loads are also included for reference (Figure 32, Figure 33, Figure 34, Figure 35). It is noteworthy that the total amount of phosphorus (load) discharged by the WWTPs to the Assabet in 2020 was about 30% greater than in 2018, providing another possible explanation for high 2020 river concentrations. Also note the dramatic reduction in TP discharge at the Marlborough Easterly WWTP as a result of the 2015 plant improvements (Figure 33). This reduction was significant, but the downstream Hop Brook site (HBS-016) still consistently has the highest TP concentrations in our watershed and Hop Brook is known for its eutrophic conditions. We believe this is due to loading of legacy phosphorus from the sediments in the numerous impoundments in Hop Brook. To this end, OARS has been working on a special study of Hop Brook with the Hop Brook Protection Association since 2020.

Figure 27: TP concentration by site, summer (2020, 2021)

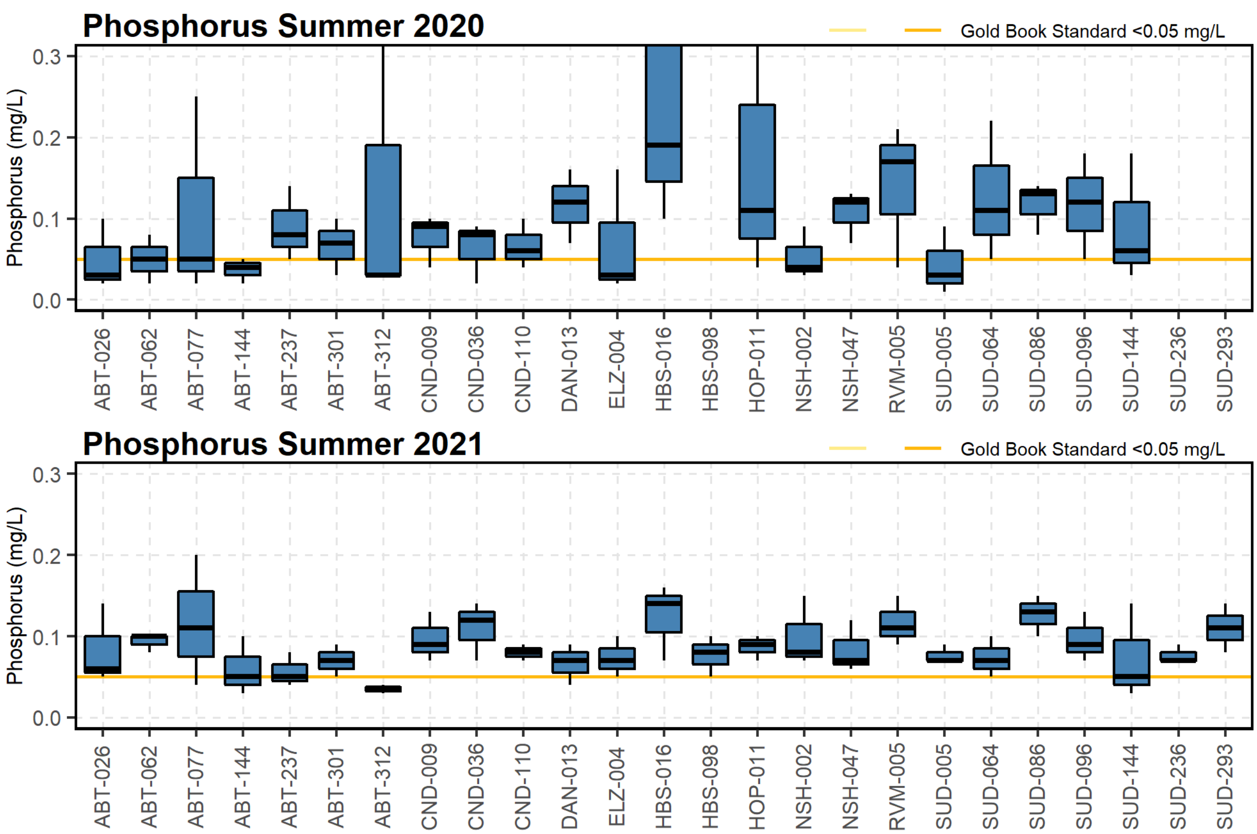


Figure 28: TP concentration by month (2020, 2021)

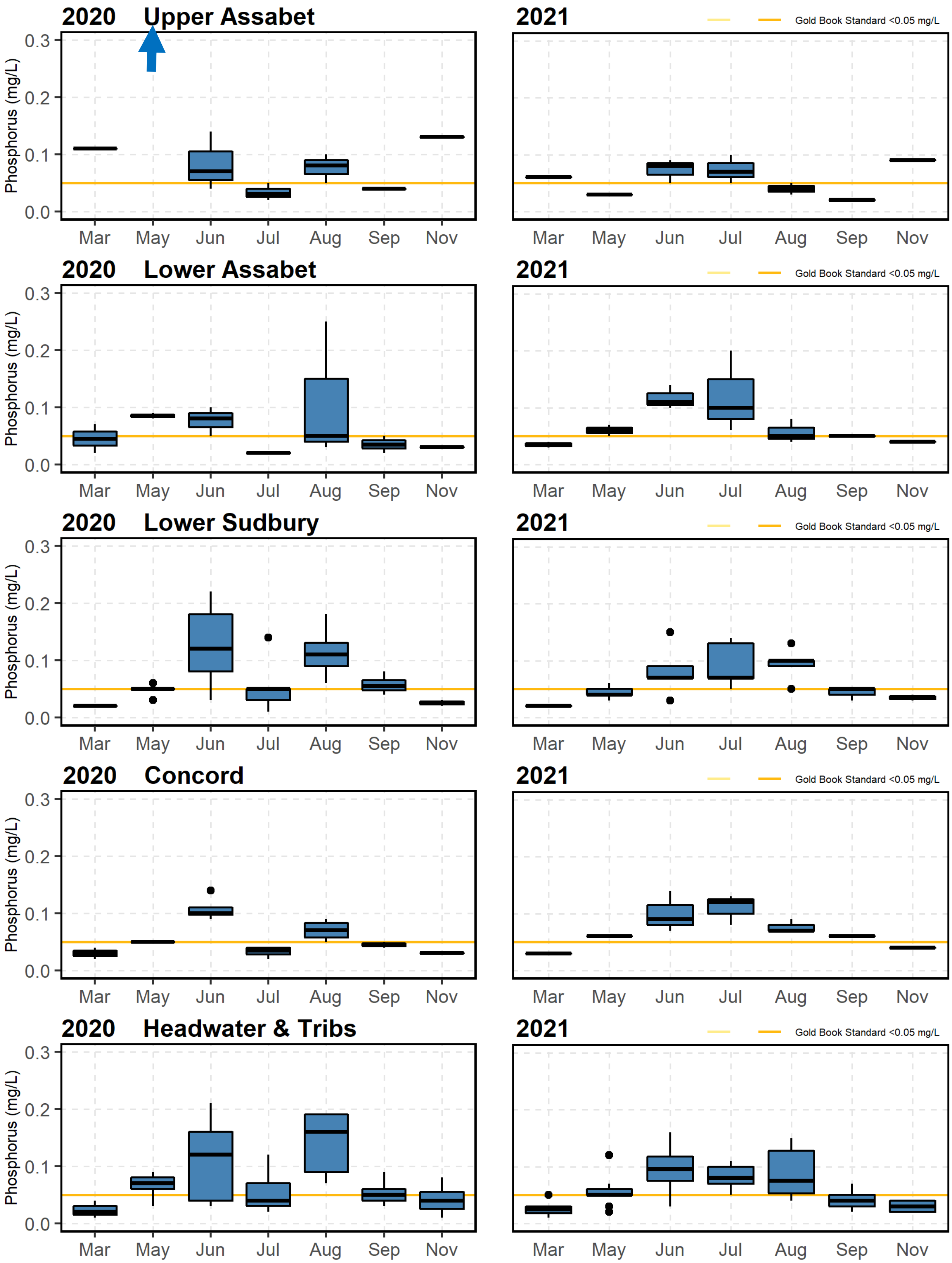


Figure 29: TP concentration, year-on-year summer by section (June/July/August)

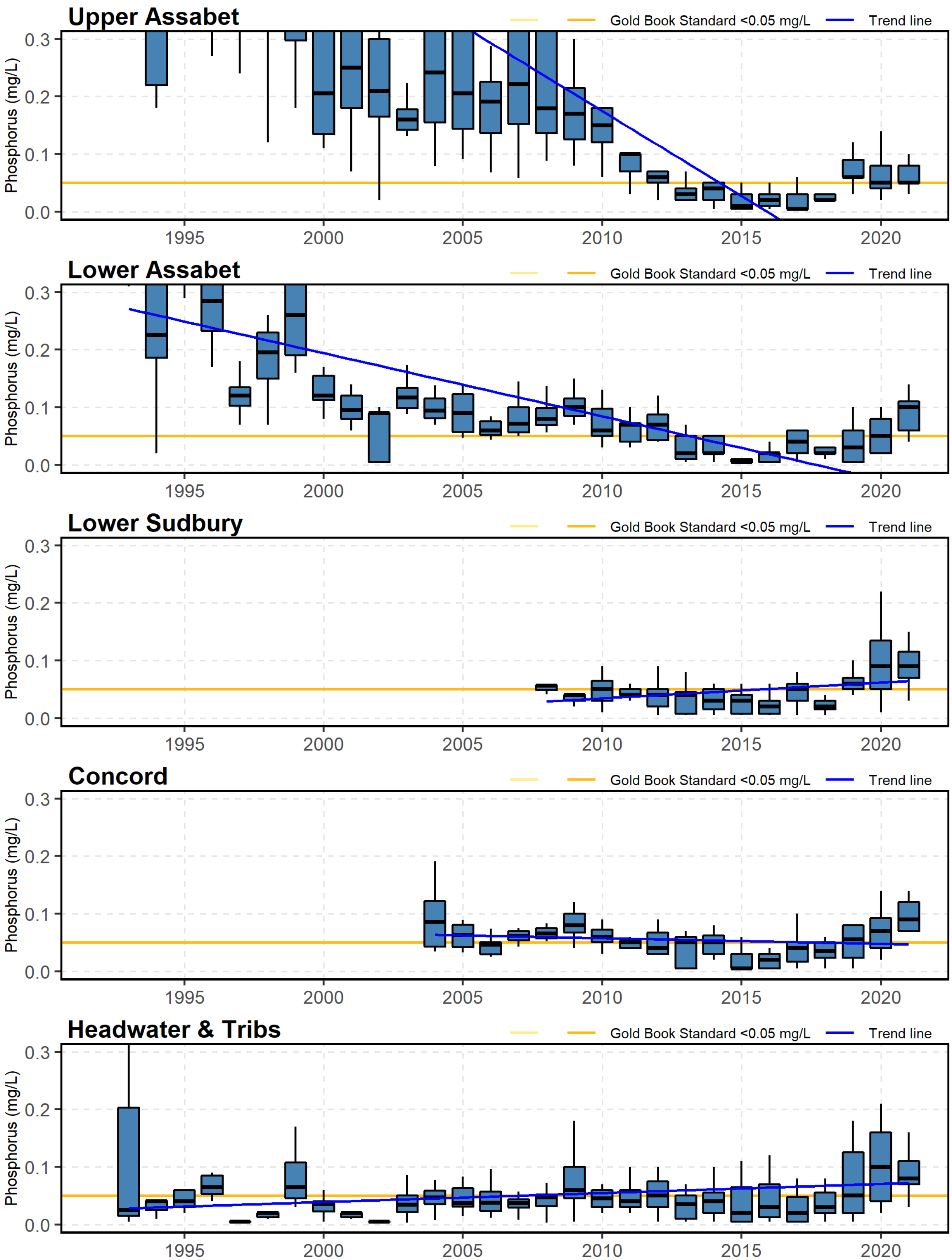


Figure 30: TP estimated load, year-on-year summer by section (June/July/August)

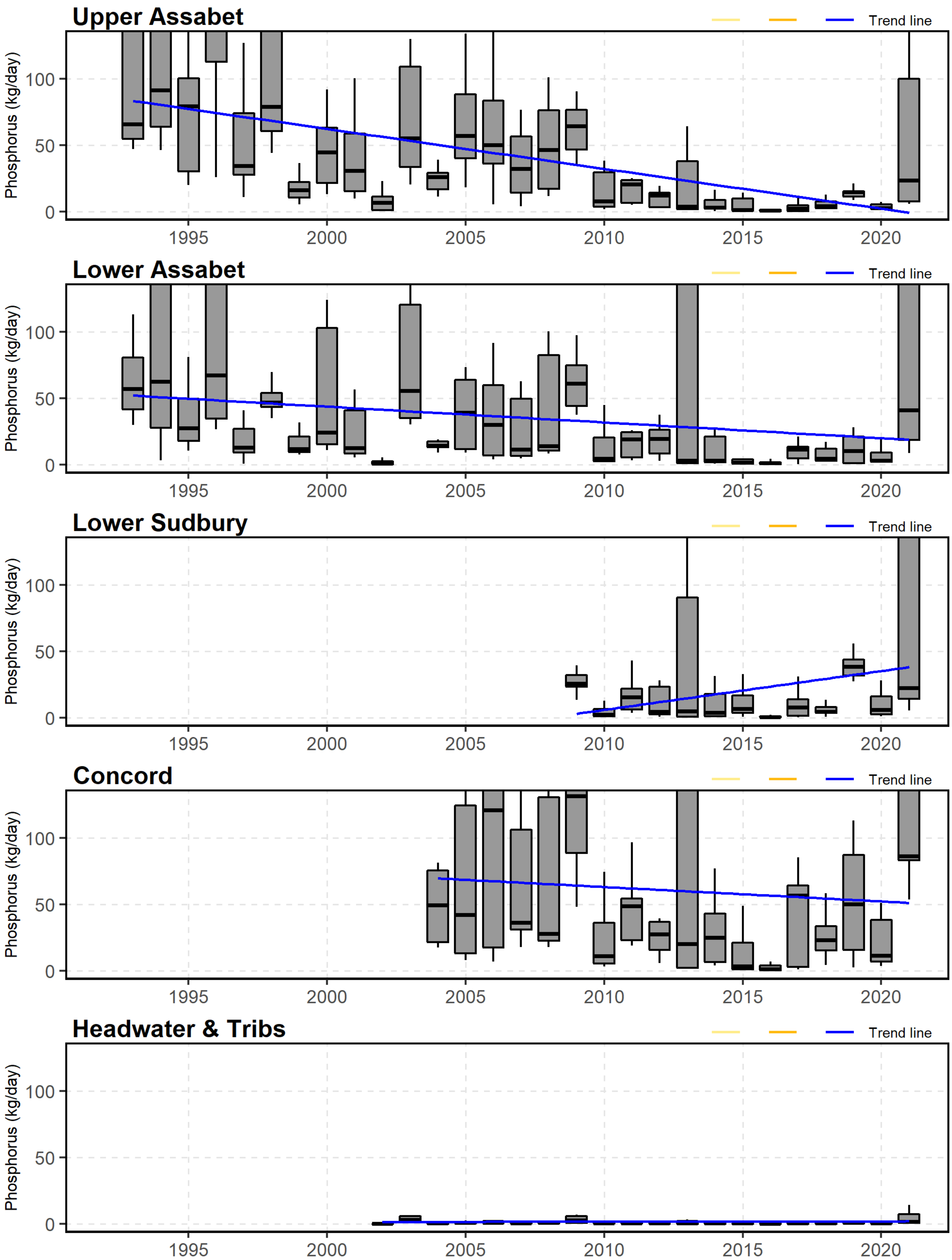


Figure 31: Map of average summer Total Phosphorus by site (2020, 2021)

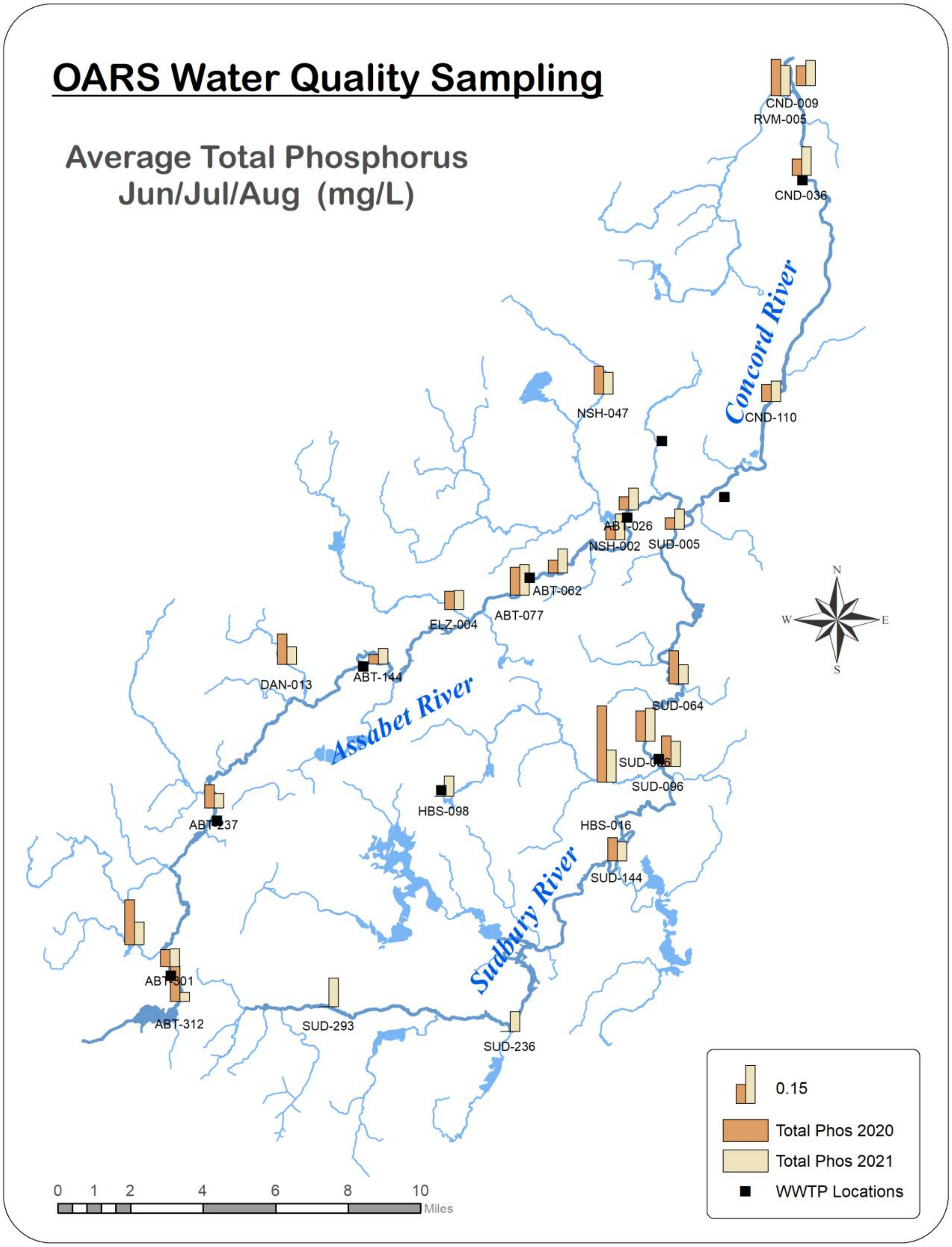
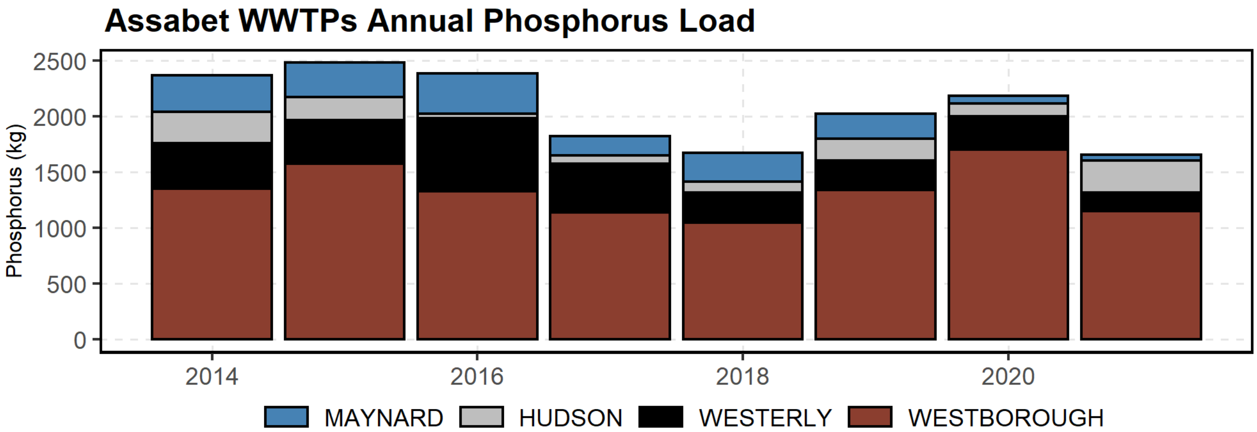
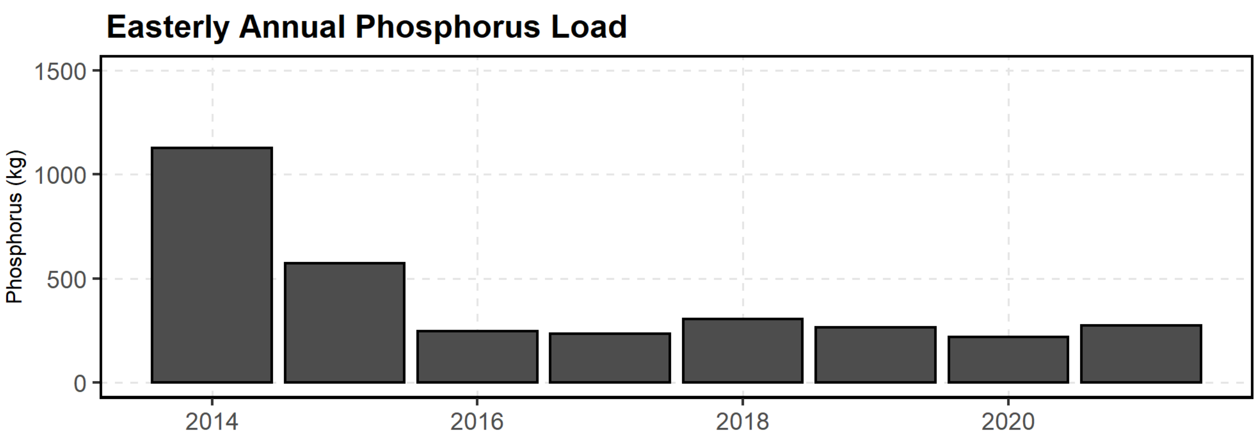


Figure 32: Major Assabet WWTPs TP discharge (2014-2021)



* Annual discharge is calculated as effective annual discharge for the summer period – sum of November through October.

Figure 33: Marlborough Easterly WWTP TP discharge (2014-2021)



* Annual discharge is calculated as effective annual discharge for the summer period – sum of November through October.

Figure 34: WWTP Daily TP Discharge - summer (2020-2021, Apr-Oct)

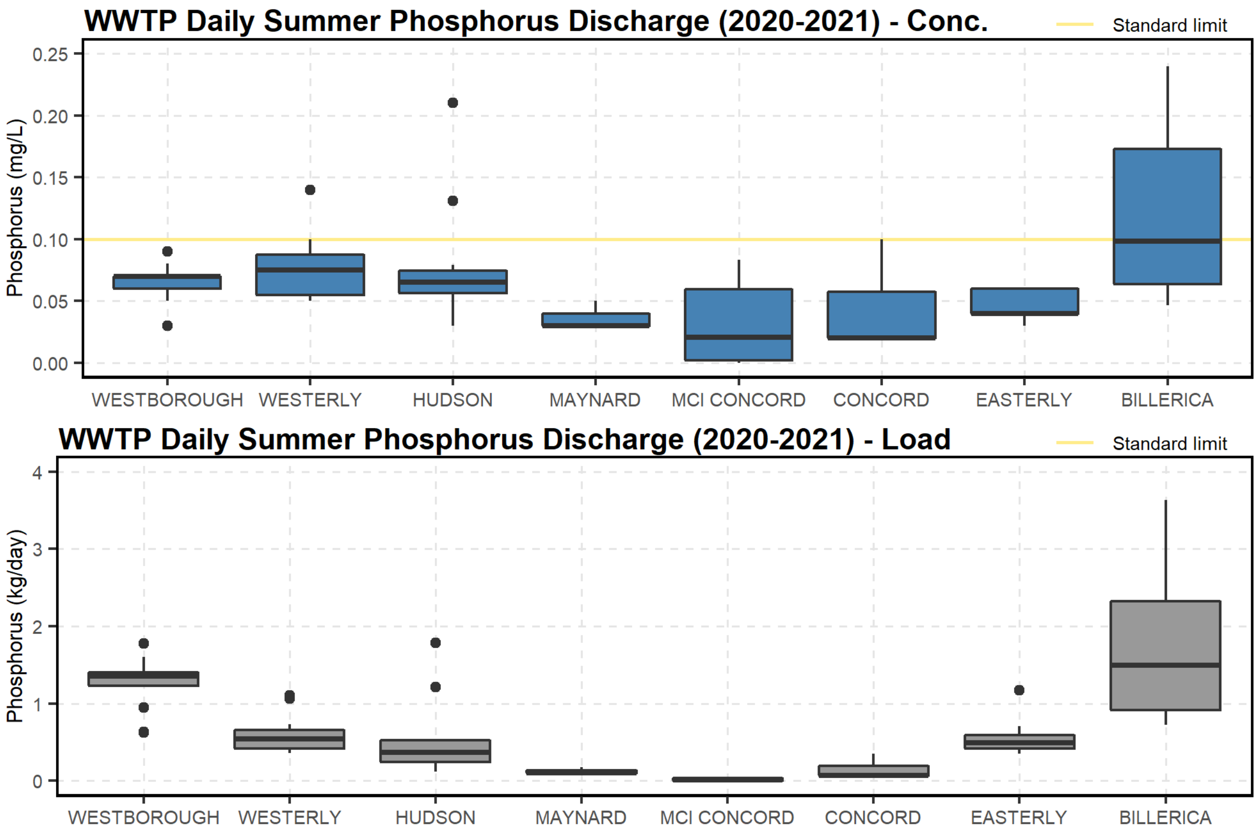
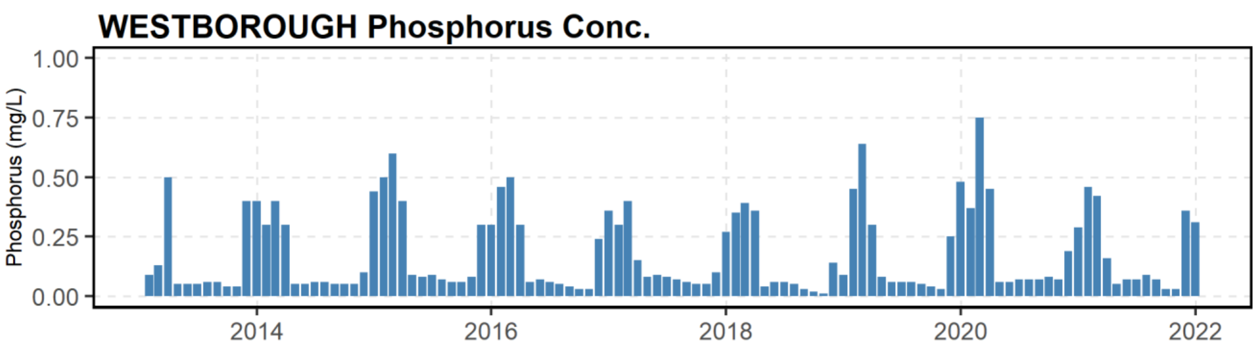


Figure 35: Westborough WWTP TP discharge by month (concentration)



<u>Orthophosphate</u>

Orthophosphate represents the portion of Total Phosphorus that is bioavailable and in dissolved form in water. It is inorganic phosphorus that is the main constituent in fertilizers and the main form of phosphorus discharged by wastewater treatment plants. Analysis of orthophosphate shows that bioavailable phosphates represented from 11% to 59% of TP during the summer in 2020 and 2021 (Figure 36). The site with the highest levels of orthophosphate, HBS-016 (Hop Brook) averaged 59% of TP in the wet year and 23% in the dry year. The TP concentration was lower in the wet year, most likely due to dilution, but the proportion that was in dissolved form was much higher. Many of the other sites exhibited similar but less extreme patterns. This is somewhat contrary to intuition, but seems to imply that phosphorus that is added to the rivers when precipitation and flows are high is predominantly in dissolved form and bioavailable.

Monthly analysis of orthophosphate data shows very high concentrations and proportions of TP in the Upper Assabet in March and November (Figure 37). This corresponds to the higher winter discharge limits at the Westborough WWTP. Also visible in the Upper Assabet's year-on-year plots is a change in orthophosphate's proportion of TP, with lower proportions after the WWTP upgrades in 2011 (Figure 38).

Figure 36: Ortho-P concentration by site, summer (2020, 2021)

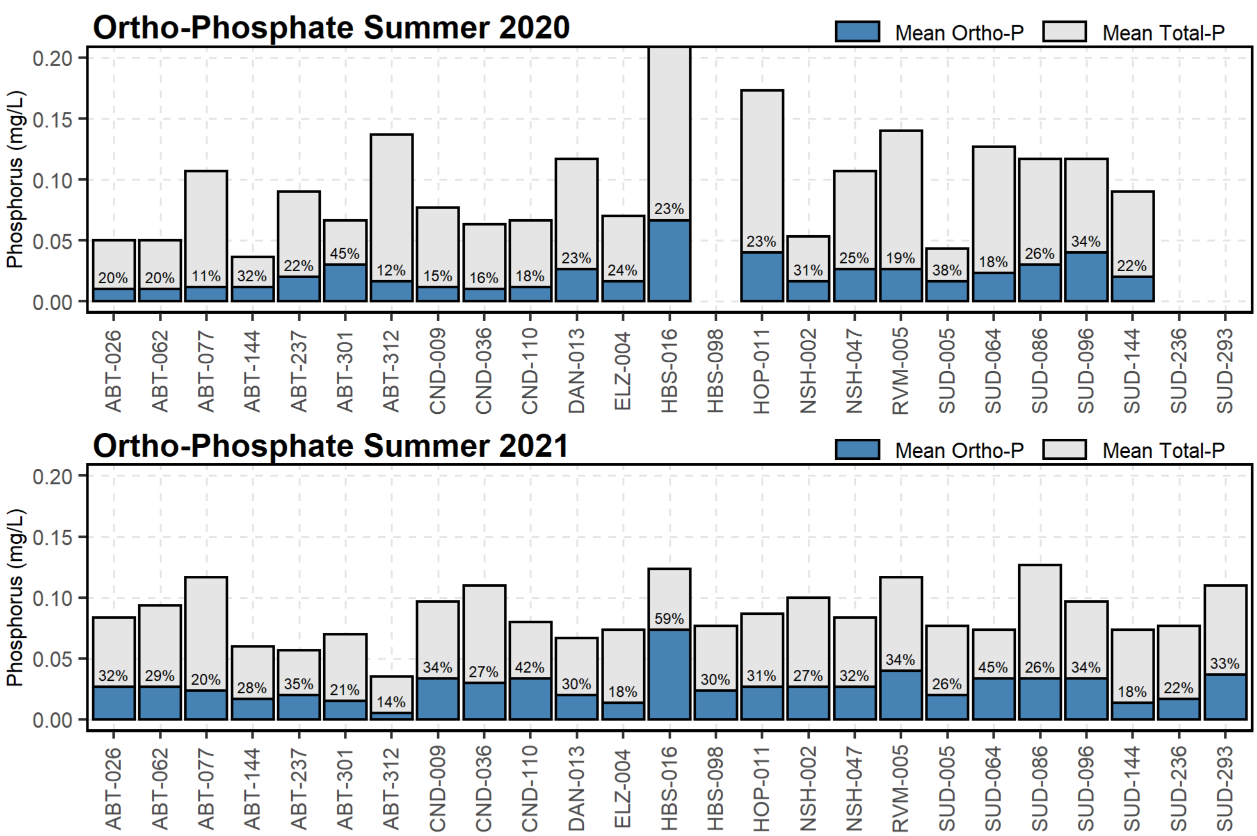


Figure 37: Ortho-P concentration by month (2020, 2021)

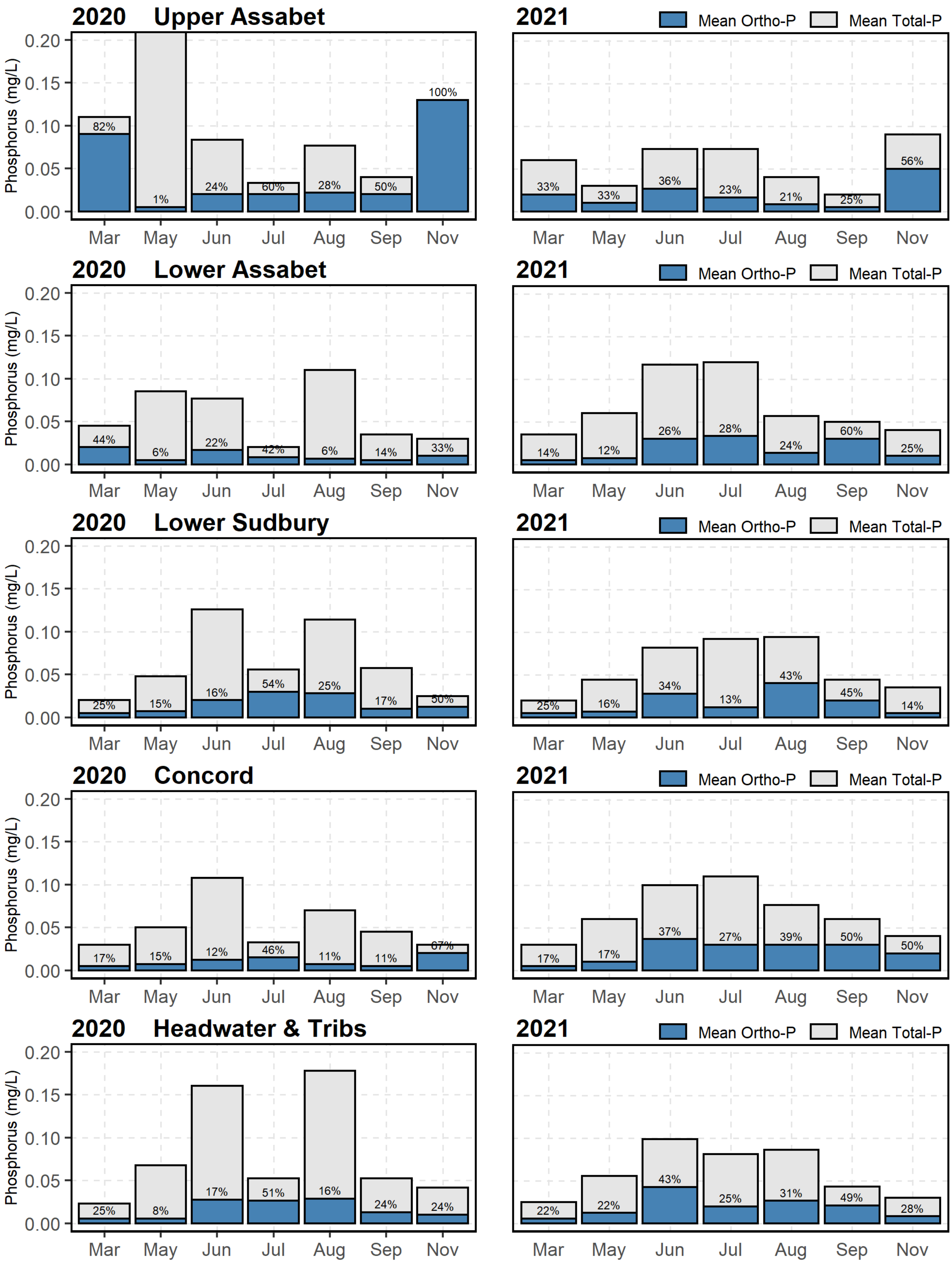
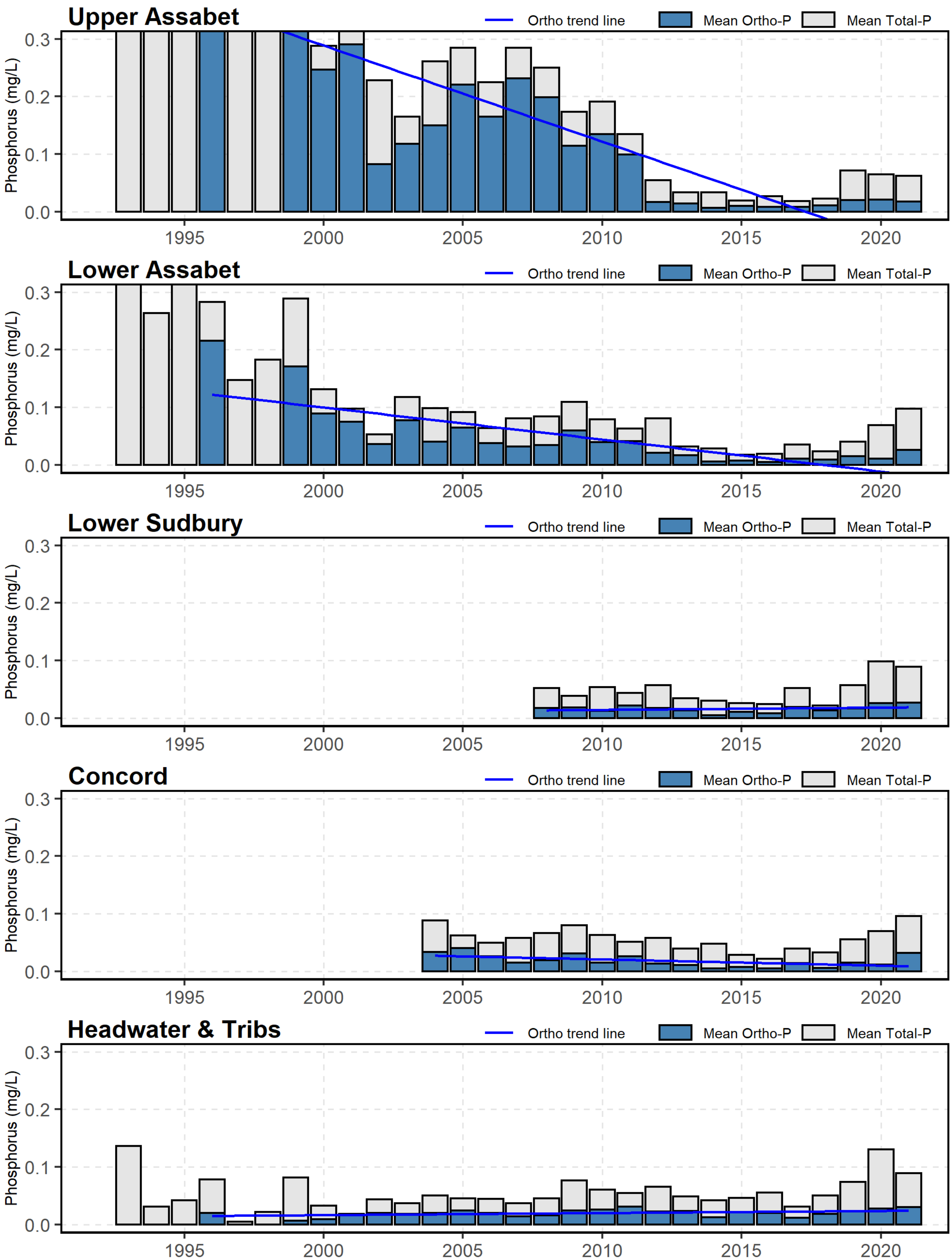


Figure 38: Ortho-P concentration, year-on-year summer by section (June/July/August)



<u>Nitrate</u>

Nitrate (NO_3) is the secondary nutrient of concern in fresh waters, secondary because it is not the limiting nutrient. However, there are some conditions where this is not the case, such as anoxic bottom waters of impoundments (ENSR, 2001). In anoxic bottom waters, phosphorus can be sourced from the sediments and atmospheric nitrogen is not available. Plants that derive nutrients from the bottom water, such as filamentous green algae, could be limited by nitrate. Additionally, nitrate is the primary nutrient of concern in estuarine environments and it easily flows downstream in dissolved form, so it is critical to track nitrate load flowing downstream. In our watershed, the WWTPs are the primary source of nitrate. The by-site graphs show very high nitrate-N concentrations below the Westborough (ABT-301), Westerly (ABT-237), Hudson (ABT-144), and Easterly (HBS-098) WWTPs (Figure 39). This results in most Assabet sites having concentrations orders of magnitude greater than the Ecoregion reference condition of 0.34 mg/L (for NO_2+NO_3 as N). *Note that we changed sampling plans in 2021 to sample nitrate at fewer sites. In 2022 and going forward, we have decided to return to sampling nitrate at most mainstem sites during the summer.*

Year-on-year analysis of NO_3 shows what seems to be an increasing trend in concentration in the Assabet, heavily influenced by 2020 data (Figure 41). For load, the increasing trend is much more clear (Figure 42). Note that load from the Upper Assabet WWTPs is also clearly visible flowing downstream in the Lower Assabet and Concord. However, two headwater and tributary sites show a distinct decreasing trend since the early 2000s (Figure 43).

Figure 39: Nitrate concentration by site, summer (2020, 2021)

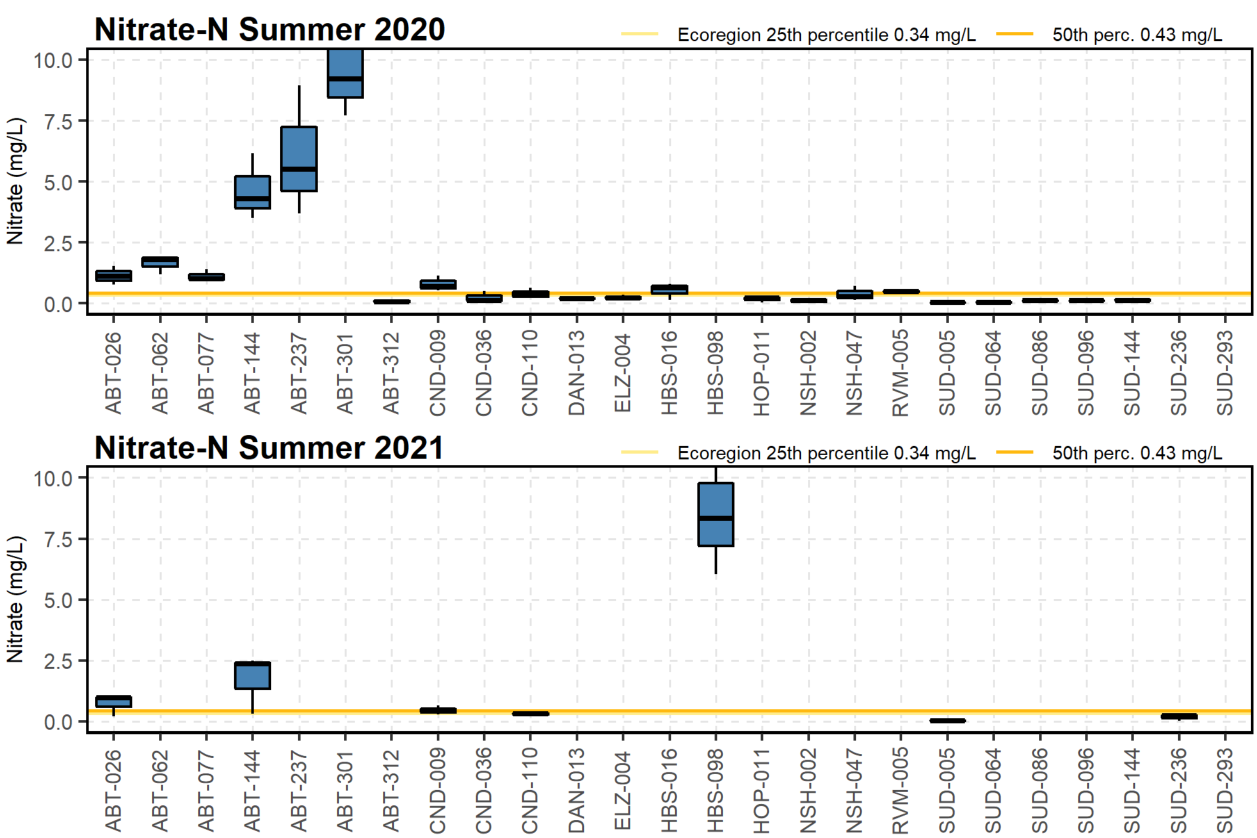


Figure 40: Nitrate concentration by month (2020, 2021)

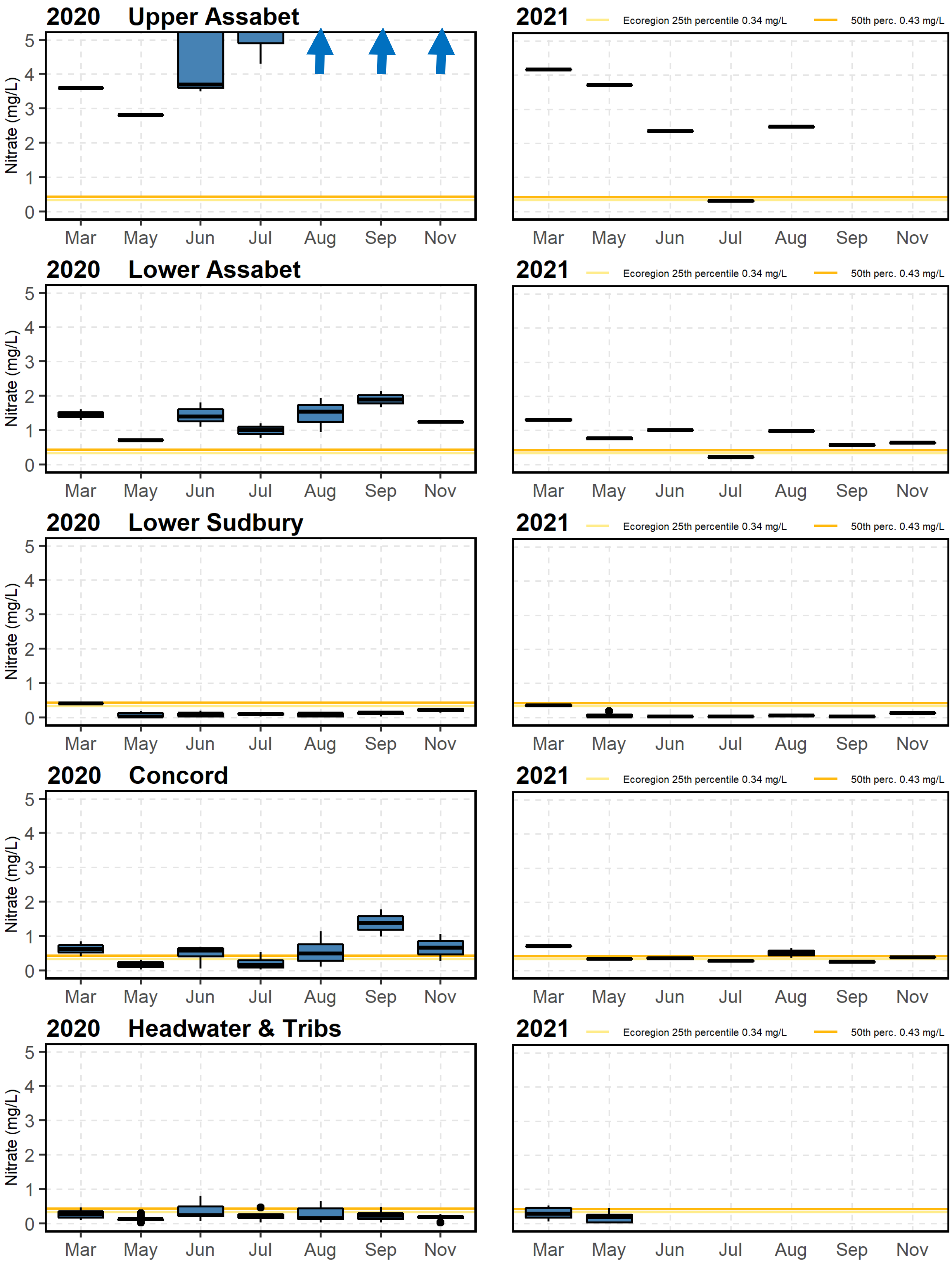


Figure 41: Nitrate concentration, year-on-year summer by section (June/July/August)

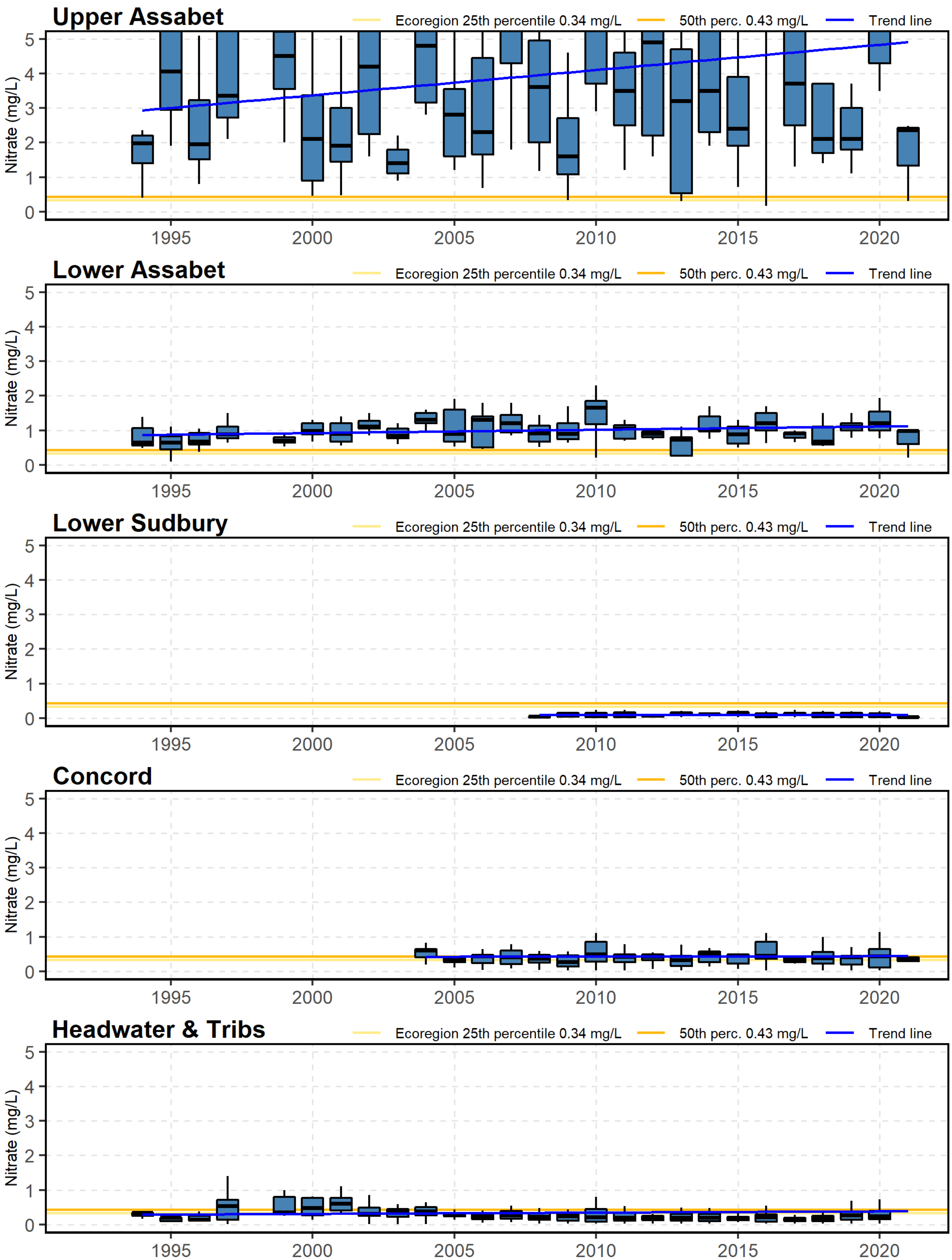


Figure 42: Nitrate estimated load, year-on-year summer by section (June/July/August)

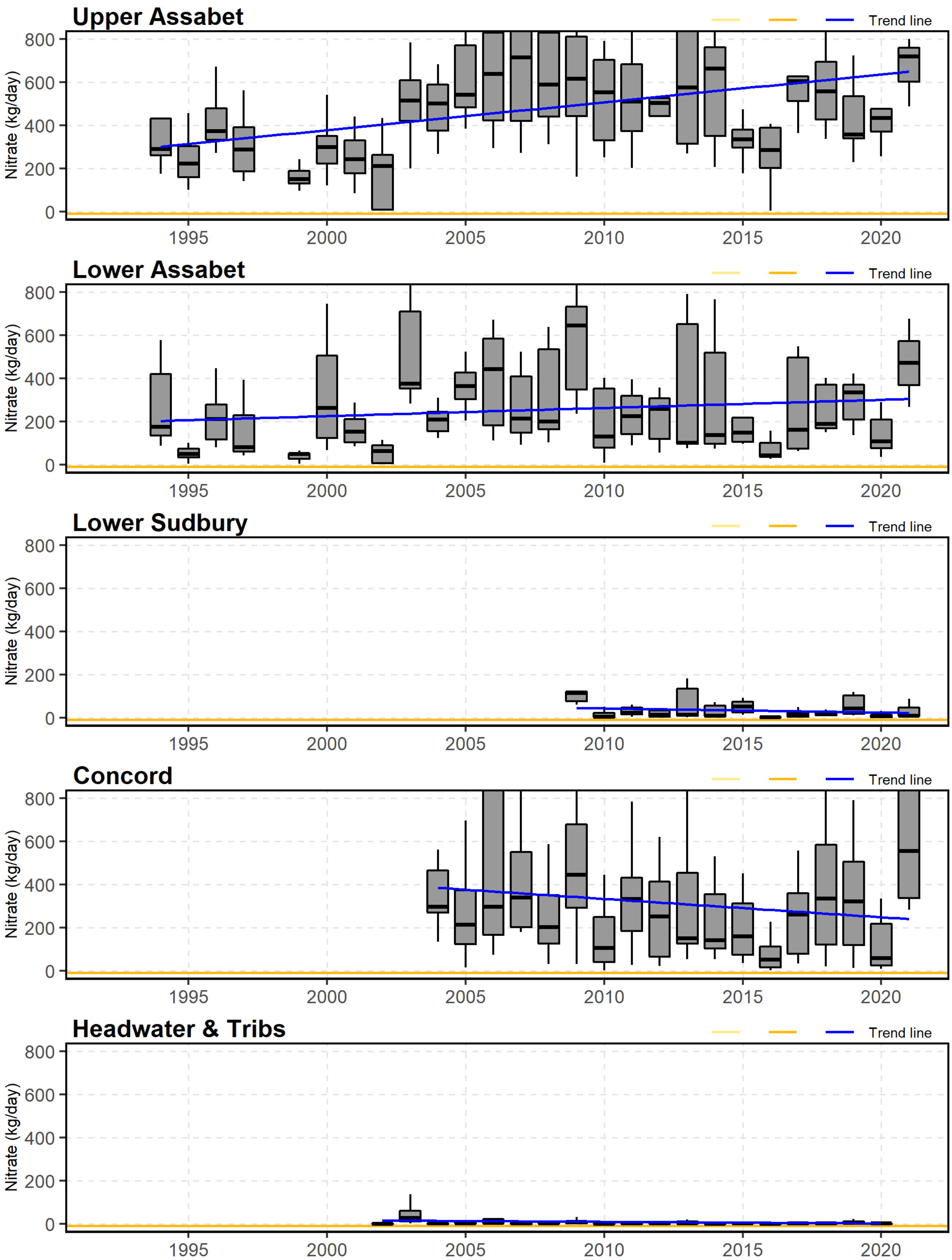
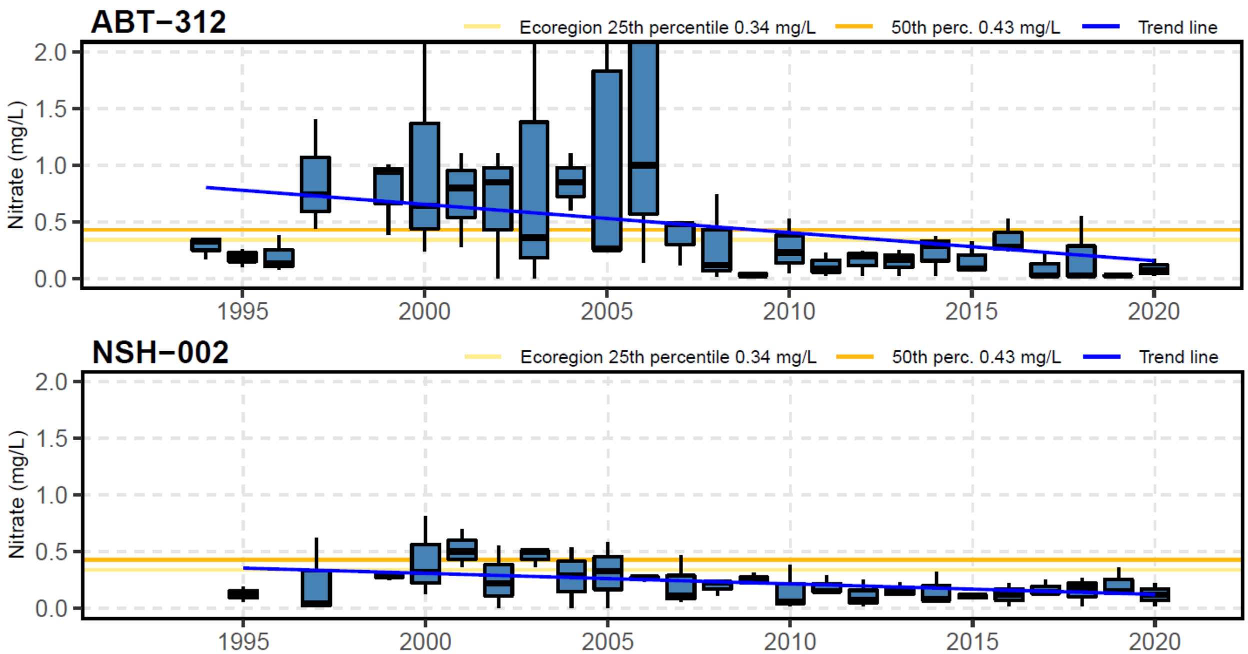


Figure 43: Nitrate concentrations, year-on-year summer, Assabet Headwater and Nashoba Brook



Ammonia

Ammonia (NH_3) is a form of nitrogen that can be toxic to aquatic life at high concentrations. Sources of ammonia include industry (used in a wide range of industrial applications), fertilizer, breakdown of organic waste matter, and natural nitrogen fixation in the environment, and it is produced and excreted by fish. Ammonia maintains an equilibrium in the environment with the ammonium ion (NH_4^+) based on temperature and pH. Un-ionized ammonia (NH_3) is much more toxic than ammonium ion. For our reporting and threshold criteria, we report total ammonia nitrogen (NH_3 and NH_4^+ as N). The toxicity of total ammonia is highly dependent on temperature and pH (more toxic at higher temperature and pH). At pH values of 7.5 (our average maximum value) and water temperatures of 23°C (our average maximum summer temperature), the EPA criteria for ammonia for salmonid fish specify a chronic level of 1.2 mg-N/L and an acute level of 7.2 mg-N/L (EPA, 2013). The maximum level we measured in 2020 and 2021 was 0.24 mg/L, with 90% of samples below 0.1 mg/L (Figure 44). These low levels have been consistent since 2000, with an uptick across all waterbodies in 2017 (Figure 46).

Since 2012, most ammonia measurements have been below the detection limit of 0.1 mg/L. Only a few sites have had frequent results above the detection limit. These include ABT-062 (downstream of Maynard WWTP), HBS-016 (Hop Brook), SUD-096 (downstream of Hop Brook), RVM-005 (River Meadow Brook), and NSH-047 (Nashoba Brook). Note that Maynard WWTP consistently discharges above the EPA chronic threshold (Figure 47).

Figure 44: Ammonia concentration by site, summer (2020, 2021)

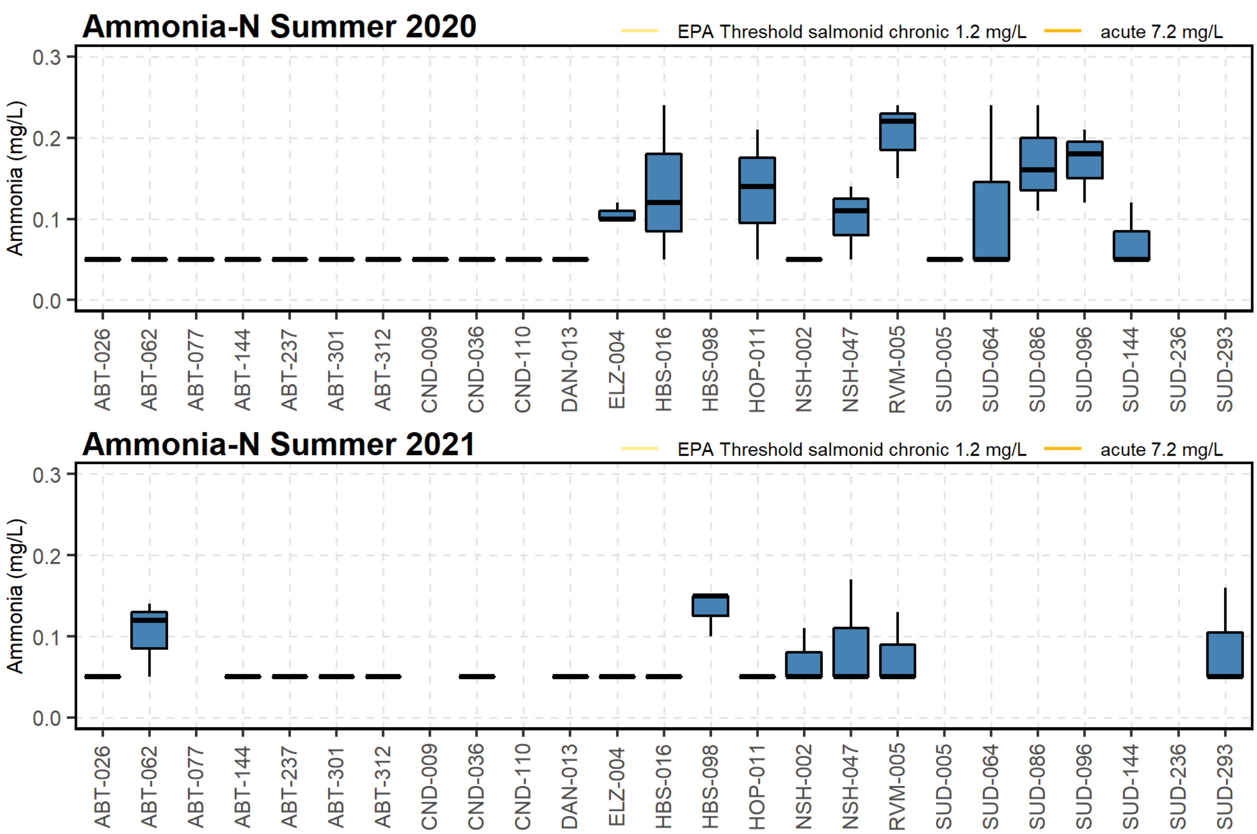


Figure 45: Ammonia concentration by month (2020, 2021)

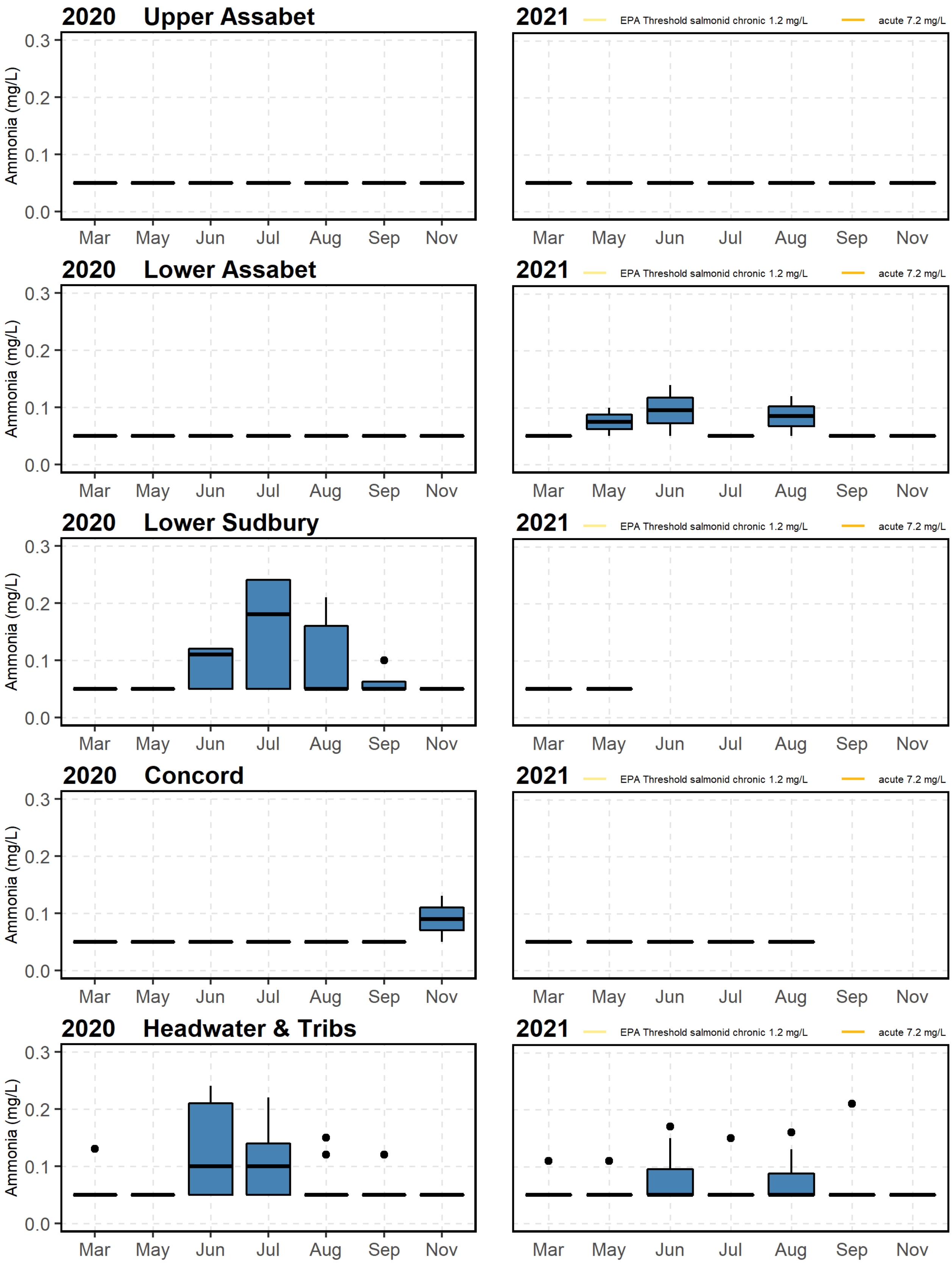


Figure 46: Ammonia concentration, year-on-year summer by section (June/July/August)

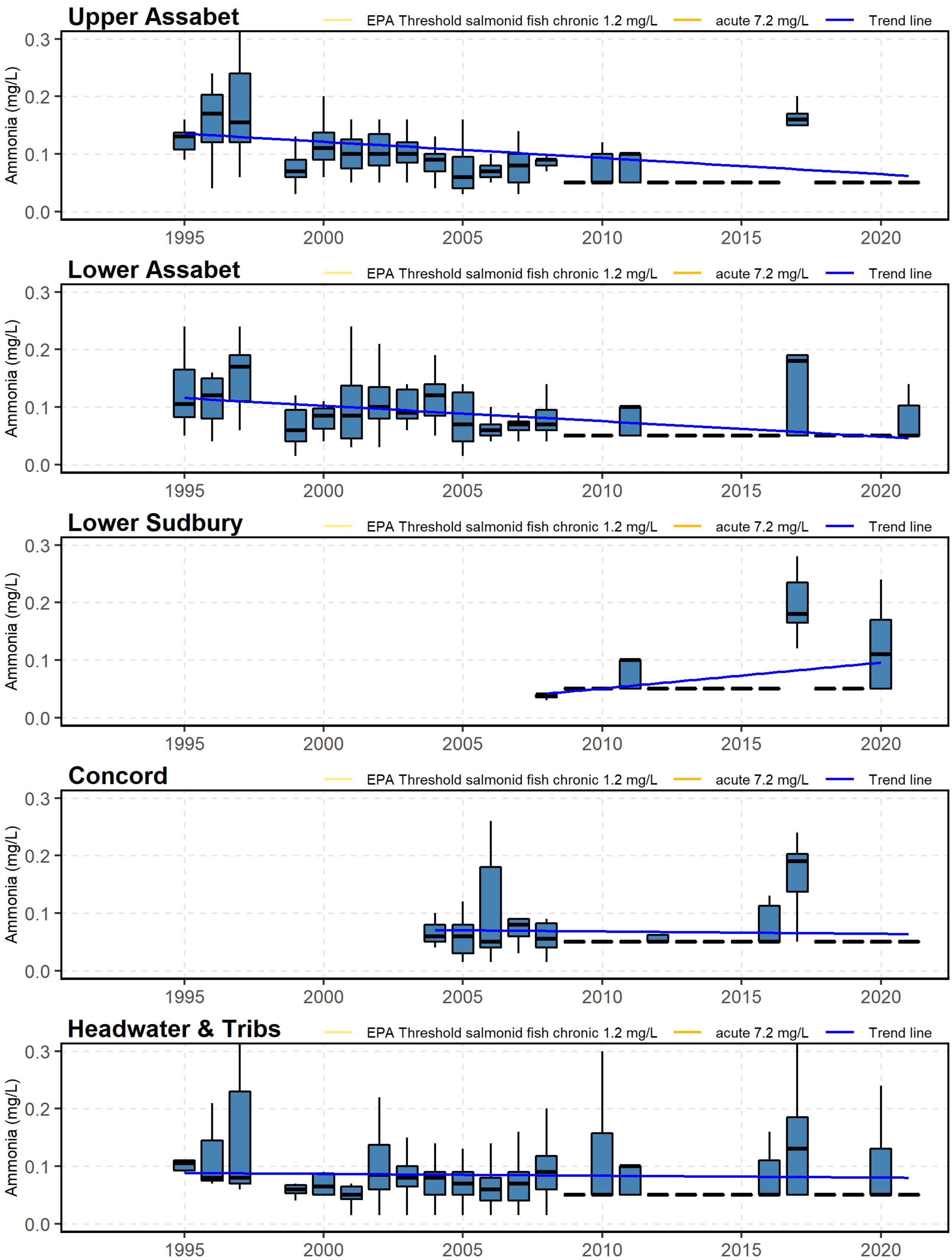
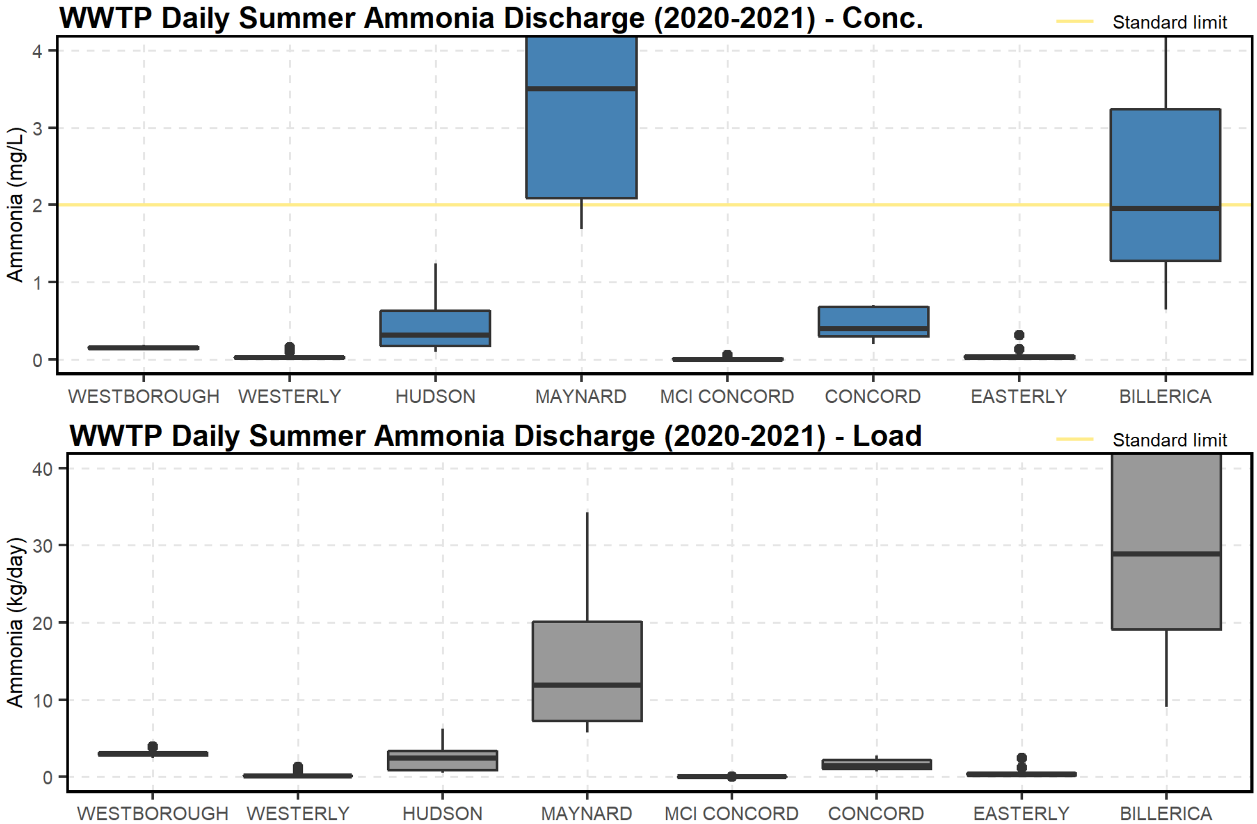


Figure 47: WWTP Daily Ammonia (total ammonia nitrogen) Discharge (2020-2021)



Total Suspended Solids

Total Suspended Solids (TSS) measures all non-dissolved particulates in the water. High concentrations of TSS can indicate erosion, runoff, decaying algae, disrupted sediment, or discharge of sediment-laden water. By-site results show several sites that experienced very high TSS measurements in the 2020 dry year (Figure 48). ABT-312 and HOP-016 are both headwater or tributary sites that were downstream of known weed removal activities that could have resulted in suspended decaying plant matter. NSH-047 and HOP-011 are also tributaries that most likely experienced human-caused sediment disruption during the low flows. In 2021, a more normal picture of TSS is depicted with higher levels downstream of the WWTPs in the Assabet River and Hop Brook.

Year-on-year analysis of TSS shows improving trends in most river sections (Figure 50). It also shows that the Concord tends to have higher than average TSS levels, which is probably due to motorized recreational activity in the Concord and the Talbot Mills Dam. Year-on-year analysis of TSS load shows the effect of high flows on the suspended solids load that was carried downstream in 2013 and 2021 (Figure 51).

Figure 48: TSS concentration by site, summer (2020, 2021)

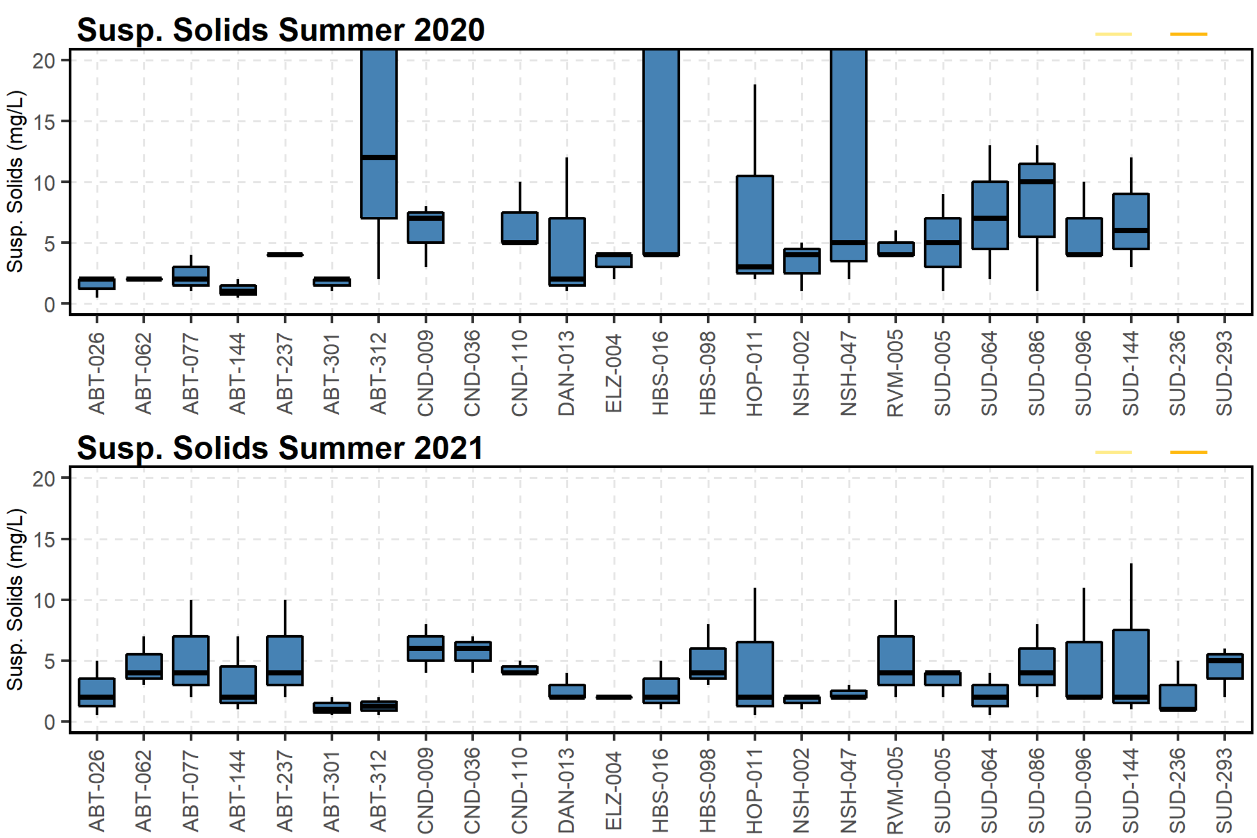


Figure 49: TSS concentration by month (2020, 2021)

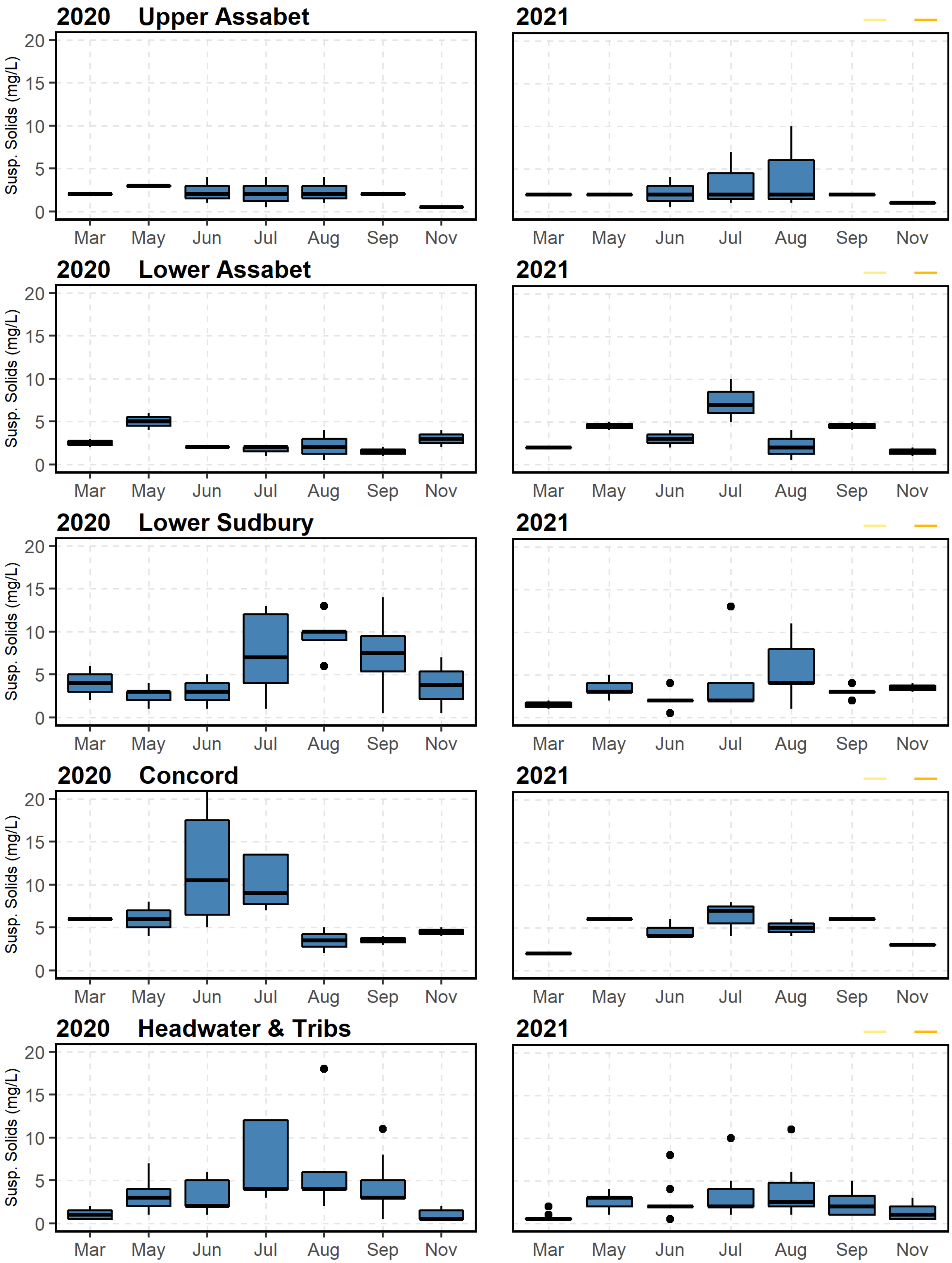


Figure 50: TSS concentration, year-on-year summer by section (June/July/August)

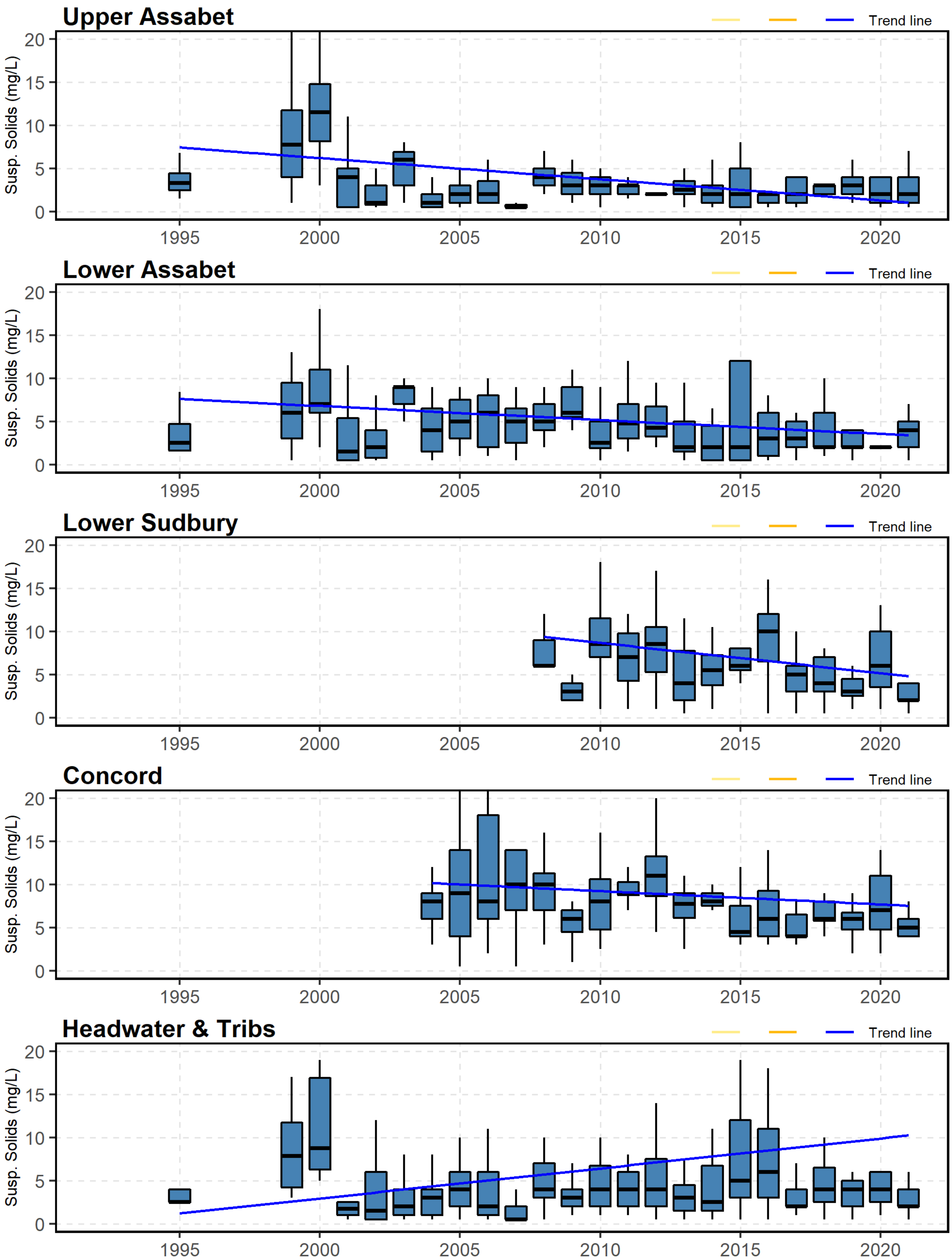
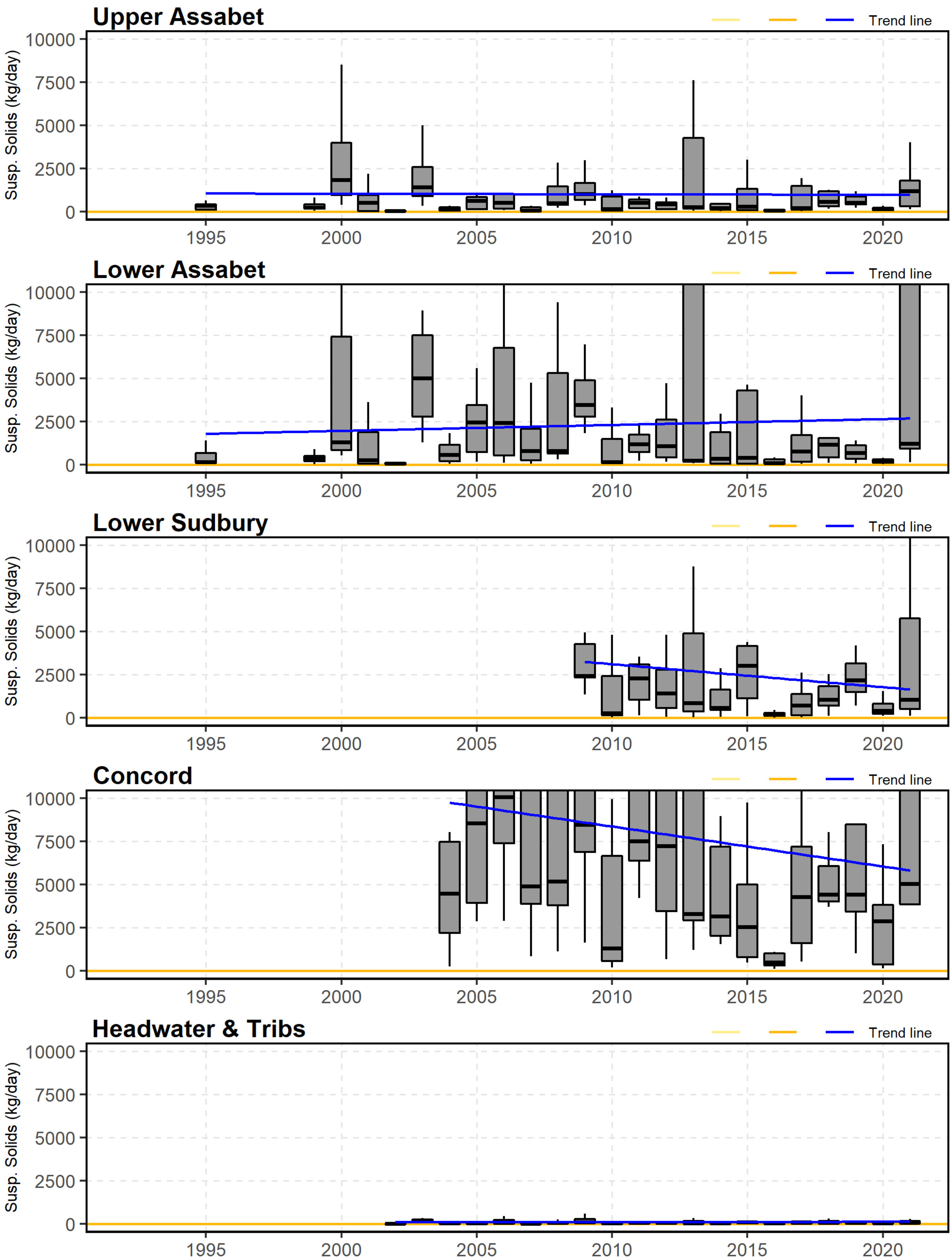


Figure 51: TSS estimated load, year-on-year summer by section (June/July/August)



<u>Chlorophyll *a*</u>

Chlorophyll *a* is the principle photosynthetic pigment in algae and vascular plants. Chlorophyll *a* concentration gives an estimate of the biomass of planktonic algae in the river and is an indicator of eutrophication. However, rivers like the Assabet, whose vegetation is dominated by larger rooted and floating aquatic plants, may have low chlorophyll *a* concentrations and still be considered eutrophic. There is no numeric standard for chlorophyll *a* in Massachusetts waters. Results have been compared to the EPA Ecoregion XIV summer reference conditions (25th percentile 2 µg/L, and 50th percentile 4 µg/L).

Chlorophyll *a* was measured on the Sudbury River and Hop Brook Sudbury in June, July, and August. The Concord and Assabet Rivers are not sampled for chlorophyll *a*. By-site analysis shows concentrations ranging from <2 to 32 µg/L, with all of the sites below Hop Brook averaging above 4 µg/L (Figure 52). Chlorophyll *a* concentrations in the Sudbury tend to increase downstream. By month, chlorophyll *a* concentrations tend to increase from June to August (Figure 53), though this is not a rule and depends on temperature and flow. In 2018, the highest concentrations were in June. Year-on-year analysis of chlorophyll *a* shows what seems to be an improving trend since 2010 (Figure 54).

Figure 52: Chlorophyll *a* concentration by site, summer (2020, 2021)

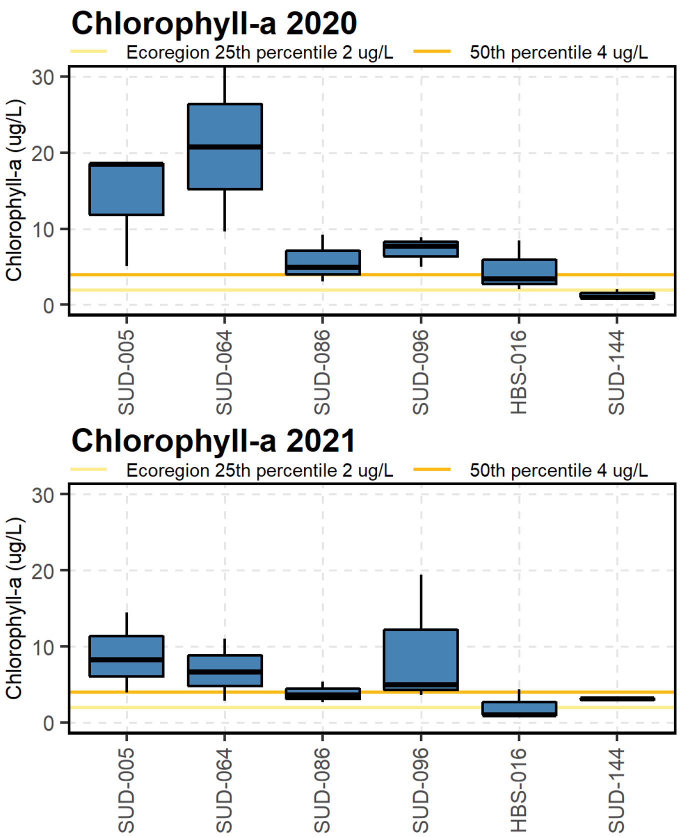


Figure 53: Chlorophyll *a* concentration by month (2020, 2021)

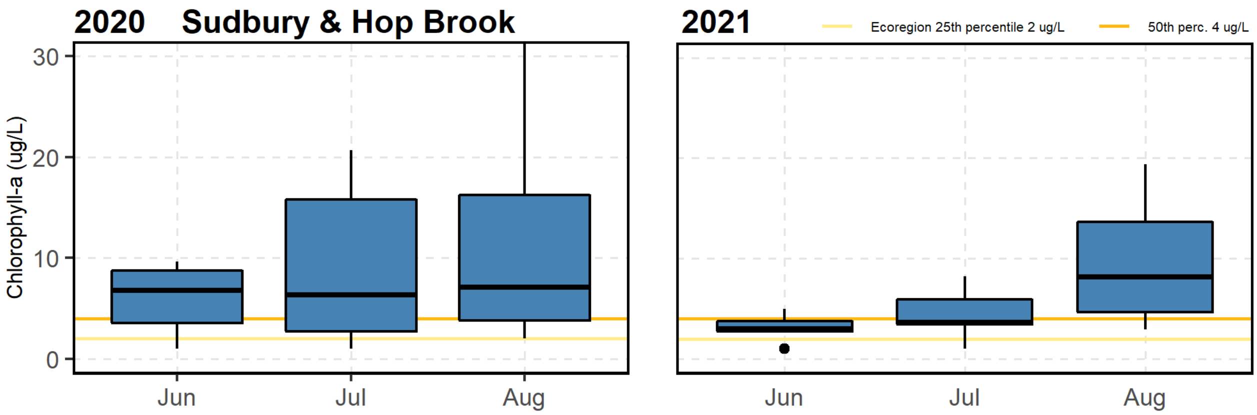
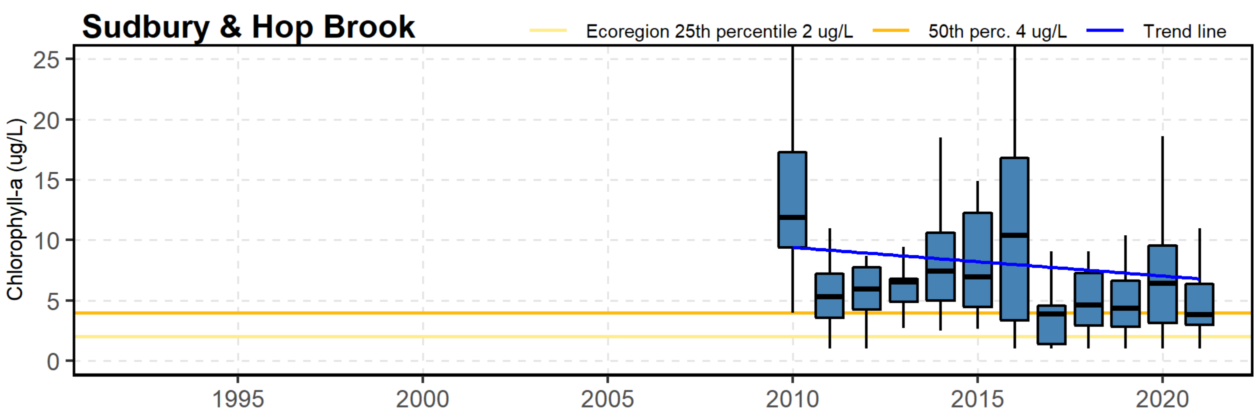


Figure 54: Chlorophyll *a* concentration, year-on-year summer (June/July/August)



<u>Chloride</u>
Chloride is a component of salt and we started sampling for chloride in 2018 to measure the effect of road salt application on the rivers. The EPA has established a Continuous Concentration Criterion for chloride of 230 mg/L and a short-term Maximum Concentration Criterion of 860 mg/L (EPA, 2002). We sampled in March (road salt application season) and August (off-season) to capture peak and off-peak times. Figure 55 shows our 2020 data. We did not sample for chloride in 2021. In 2018 and 2019, chloride was generally higher in March than in August, but in 2020 it was the opposite, most likely due to the 2020 summer drought conditions, which reduced dilution of salt in all waterways. Drought also increases the proportion of flow coming from groundwater, which can store road salt runoff (Kelting, 2012). The year 2020 was also unusual because many of the sites exceeded the continuous criterion of 230 mg/L in the summer in August. In previous years, this only happened in March.

In the New England region, chloride is highly correlated with conductivity because road salt is considered to be the dominant source of dissolved ions in the region's fresh water. The plot in Figure 56 shows all of our chloride measurements since 2018 compared with conductivity measurements taken at the same time. Our linear regression on this data has an R2 value of 0.96, and it lines up very closely with similar regressions conducted by other agencies in our region. This strong correlation allows us to make conclusions with confidence about chloride based on easily collectable conductivity measurements, so we do not have to sample for chloride separately. Based on this correlation, we are able to model chloride trends based on our much larger dataset of conductivity. We have done this with River Meadow Brook (RVM-005 Figure 57) and Elizabeth Brook (ELZ-004 Figure 58), among other sites, and our analysis shows a clear upward trend of chloride concentrations at both. The year-on-year summer conductivity graphs above also show this clear upward trend in conductivity/chloride for all of our rivers (Figure 16). This is a very concerning trend, especially since many of these sites are approaching or exceeding the EPA chloride continuous criterion limit.

Figure 55: Chloride concentration by site (2020)

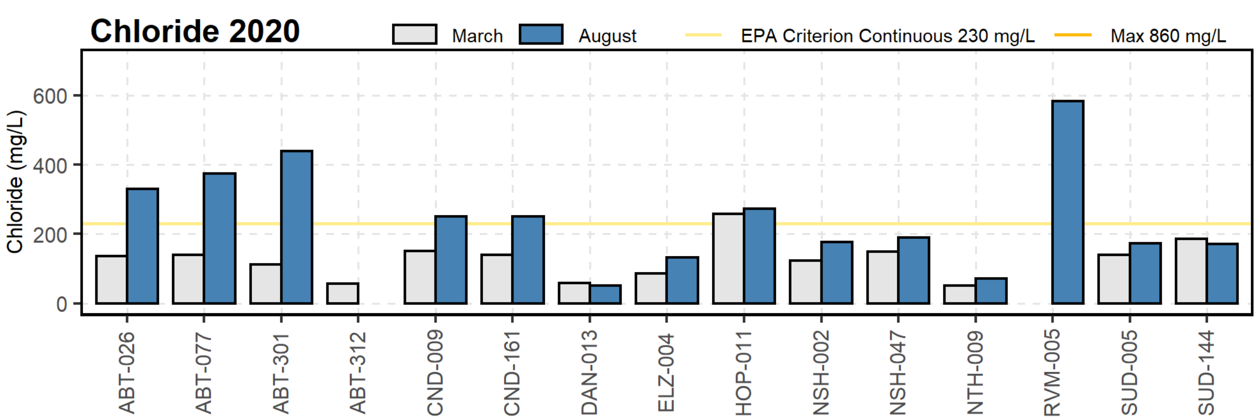


Figure 56: Chloride vs. Conductivity (2018-2020)

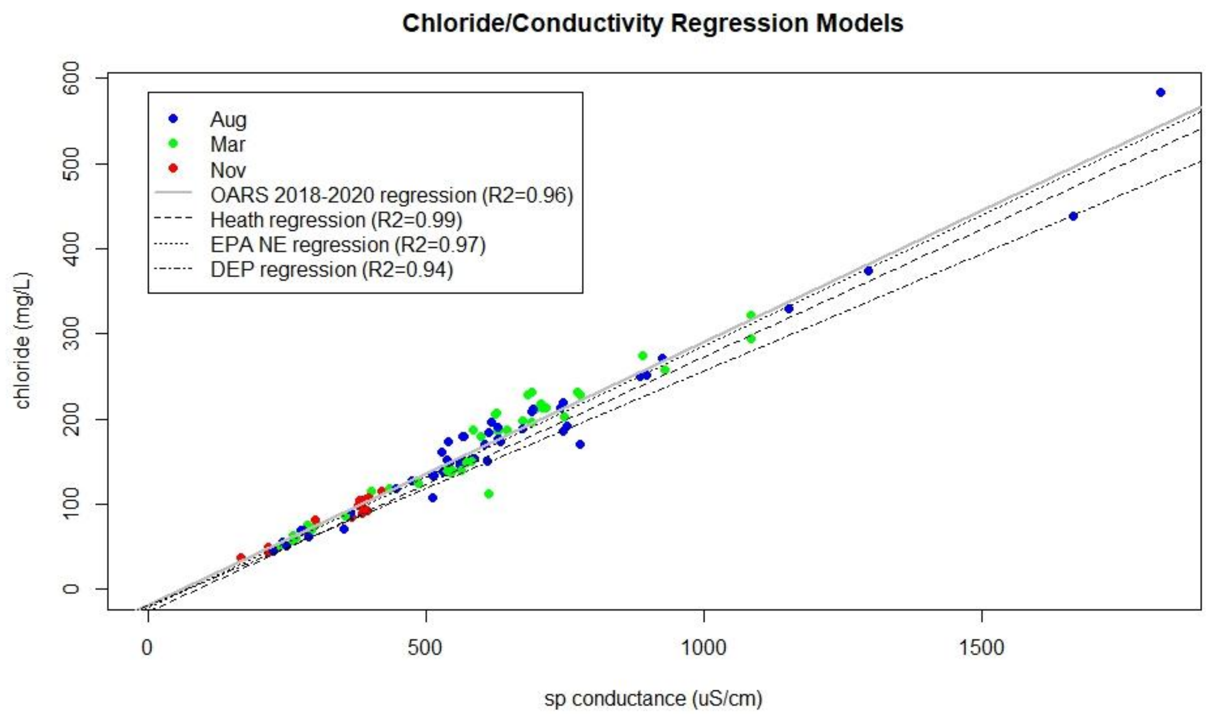


Figure 57: Modeled chloride in River Meadow Brook (2004-2020)

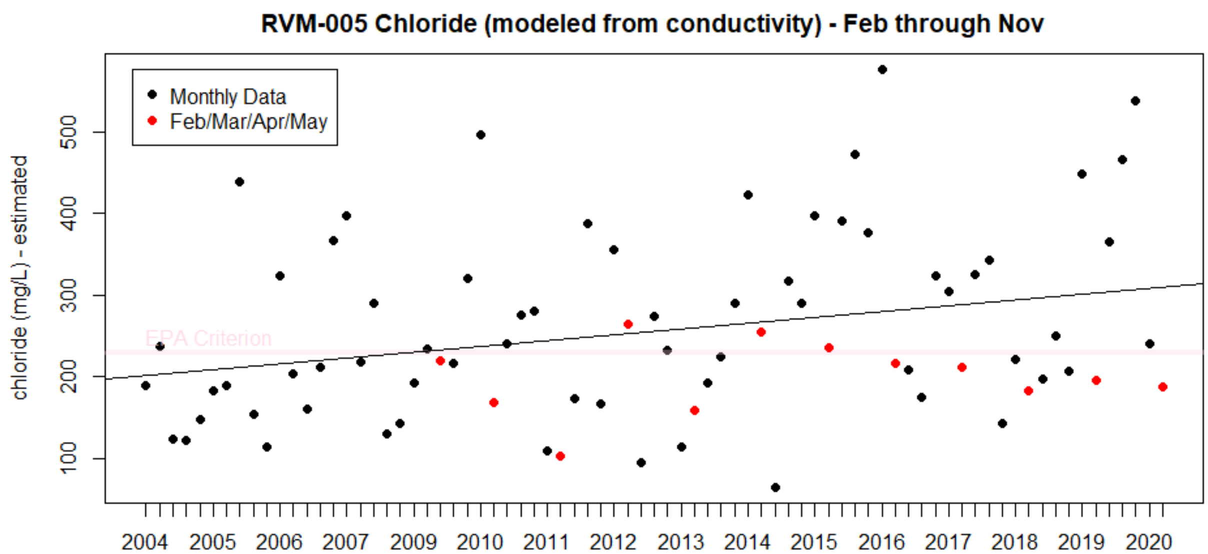
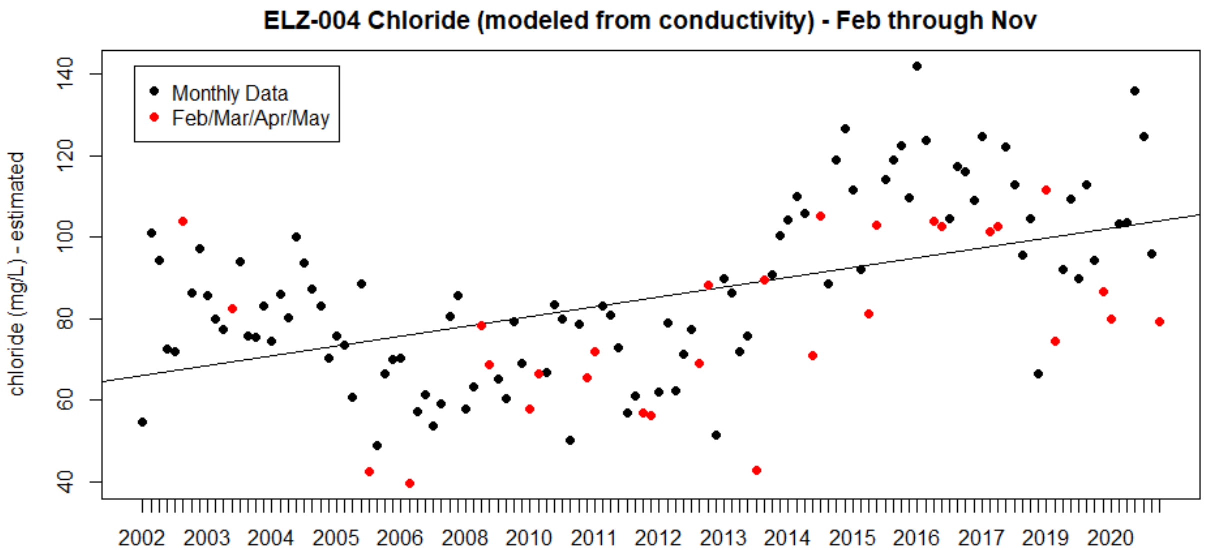


Figure 58: Modeled chloride in Elizabeth Brook (2002-2020)



Water Quality Index Calculations

The Water Quality Index is used to assess water quality in the mainstems of the Sudbury, Assabet, and Concord Rivers. It was developed in 2002 as part of OARS' StreamWatch project in collaboration with United States Geological Survey, the Massachusetts Division of Fisheries and Wildlife, and Massachusetts Audubon. It was designed to rate summer conditions when the river habitat is most stressed. It is also a major component of the OARS River Health Report Card (see https://ecoreportcard.org). For the Report Card, it is calculated for samples taken between May 1st and September 30th at 15 mainstem sampling sites. Calculations for 2020 and 2021 are shown in Figure 59.

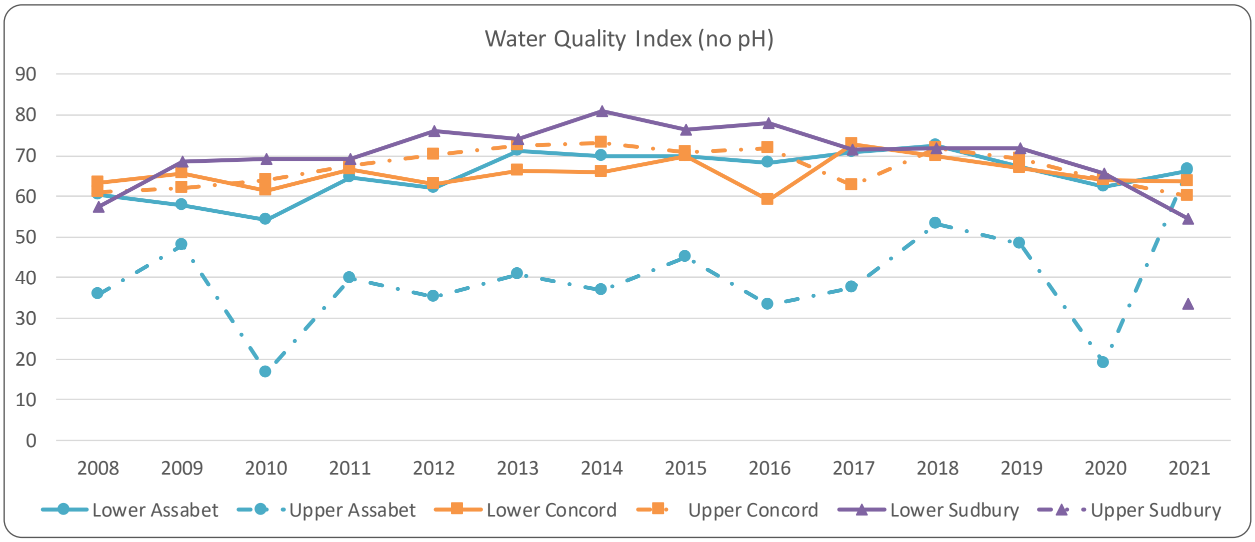
Year-on-year tracking of the Water Quality Index shows a general downward trend since 2018 for most river sections (Figure 60). This is primarily driven by the increases in phosphorus concentrations that were discussed above. The Upper Assabet's index shows large fluctuations, which are primarily driven by fluctuations in nitrate concentration. Nitrate concentrations were very high in 2020, when water levels were low, and relatively low in 2021, when water levels were high.

Figure 59: Water Quality Index calculations (2020, 2021)

2020	Nitrates	TP	TSS	DO	Temp	WATER QUALITY INDEX
Upper Assabet	7	52	83	81	90	19
Lower Assabet	41	60	83	82	88	62
ASSABET (area weighted)	24	56	83	81	89	40
Upper Sudbury	NA	NA	NA	NA	NA	NA
Lower Sudbury	98	52	68	60	89	66
SUDBURY (area weighted)	98	52	68	60	89	66
Upper Concord	77	54	59	71	83	64
Lower Concord	66	55	61	84	81	64
CONCORD (area weighted)	76	55	59	73	83	64
WATERSHED (area weighted)	62	54	73	71	88	54

2021	Nitrates	TP	TSS	DO	Temp	WATER QUALITY INDEX
Upper Assabet	35	58	81	80	95	67
Lower Assabet	57	48	71	85	91	66
ASSABET (area weighted)	46	53	76	83	93	67
Upper Sudbury	100	50	70	19	52	33
Lower Sudbury	99	52	75	48	92	54
SUDBURY (area weighted)	99	51	73	34	73	45
Upper Concord	74	47	68	47	83	60
Lower Concord	71	45	63	79	86	64
CONCORD (area weighted)	74	47	68	51	83	60
WATERSHED (area weighted)	72	51	74	58	84	57

Figure 60: Water Quality Index year-on-year results (2008-2021)



Bacteria Results

OARS monitors for *Escherichia coli* (*E. coli*) bacteria at six locations in the Assabet, Sudbury, and Concord rivers starting in 2019 (Figure 63). *E. coli* is used as an indicator of fecal contamination in water bodies, and MA DEP has defined safety threshold values for recreational swimming and boating (MA DEP, 2013 based on EPA, 1986). The swimming threshold for single samples is 235 CFU/100 ml. The swimming threshold for the geometric mean of all samples for the season is 126 CFU/100 ml. CFU stands for colony-forming unit and is a standard reporting measure for bacteria. Bacteria data are normally analyzed on a logarithmic scale because the bacteria multiply exponentially. For this same reason, averages of bacteria data are calculated using a geometric mean (**geomean**) instead of a normal arithmetic mean.

Bacteria levels in 2021 have generally confirmed the patterns we have observed over the past two years (Table 13). Maynard, Ashland, and Lowell continue to have concerning levels of bacteria, hovering near or above the MA DEP swimming threshold. Also, similar to previous years, Hudson has slightly lower bacteria levels than Maynard in dry weather, but tends to have equivalent or higher levels in wet weather. This indicates a dominance of surface runoff or stormwater contamination sources in Hudson. In Maynard, on the other hand, there is little difference between wet and dry weather, which indicates a high probability of sanitary sewer contamination.

Figure 61 shows a graphical view of bacteria results in relation to rainfall for 2021. Rainfall washes pollutants like bacteria from land into streams and is often closely linked to higher bacteria counts. If bacteria are shown to be linked to rainfall, then it can be deduced that the source of the bacteria is land-based (including storm sewers). If high bacteria levels are not linked to rainfall, then the source is more likely sanitary (wastewater) sewers. The July 19, 2021 data were interesting because bacteria levels were extremely low at all sites. July 19^{th} was the third week in several weeks of very heavy rain and flooding, so the samples were heavily diluted by the large amount of water, and they also reflected the fact that most contaminants had already been washed off the land surface by the continuous rains. July 19^{th} has been excluded from the summary statistics for 2021.

The boxplot analysis in Figure 62 shows a comparison of wet and dry sampling days. A wet day is defined as a day when there was greater than 0.1" of rain in the preceding 48 hours. Bacterial contamination is known to be influenced by precipitation, however this is not a strong relationship for all sites. Maynard (ABT-077) and Bedford (CND-110) do not show any precipitation influence. For the other sites, the influence is only barely statistically significant.

<u>Lowell Bacteria Special Study</u>

During 2020 and 2021, OARS conducted a special study of bacteria levels at the Rogers Street Bridge in Lowell. The study identified River Meadow Brook as the primary source of bacterial pollution in this section of the Concord River. The study confirmed that there is persistent bacterial pollution in several sections of River Meadow Brook and possibly also at low-levels all along the developed sections of the brook. We have not been able to pinpoint exact sources yet, but we believe that the data collected have highlighted the important sections for follow-up and that our analysis can help Lowell and Chelmsford conduct focused testing of outfall pipes in those sections to identify the sources. The maps in Figure 64 show site-level bacteria results for some of the sampling we did on River Meadow Brook. The next level of study may require some bacterial source tracking to differentiate between human and animal sources or detergent or ammonia testing to detect illicit discharges. We are evaluating this as a possible follow up. A full analysis of this study is described in our white paper "OARS River Meadow Brook Bacteria Monitoring Results – 2021", dated Nov. 2, 2021.

Table 12: Bacteria statistical results (2020) (plus 2019 geomean)

Site #	Description	River	Samples	Exceed-ences	% Exceeded	Geo-Mean	2019 Geo-Mean
ABT-077	USGS gage, Maynard	Assabet	15	10	67%	289	121
ABT-162	Cox Street, Hudson	Assabet	15	5	33%	203	161
SUD-096	Route 20, Wayland	Sudbury	15	2	13%	113	51
SUD-236	Rte 135, Ashland	Sudbury	15	8	53%	348	151
CND-110	Rte 225 boat ramp, Bedford	Concord	15	0	0%	27	40
CND-009	Rogers St. Bridge, Lowell	Concord	15	5	33%	216	147

Table 13: Bacteria statistical results (2021 – excluding July 19th data)

Site #	Description	River	Samples	Exceed-ences	% Exceeded	Geo-Mean
ABT-077	USGS gage, Maynard	Assabet	14	3	21%	164
ABT-162	Cox Street, Hudson	Assabet	14	2	14%	119
SUD-096	Route 20, Wayland	Sudbury	14	0	0%	34
SUD-236	Rte 135, Ashland	Sudbury	14	4	29%	169
CND-110	Rte 225 boat ramp, Bedford	Concord	14	0	0%	46
CND-009	Rogers St. Bridge, Lowell	Concord	14	3	21%	153

Figure 61: Graphical view of bacteria vs. rainfall (2021)

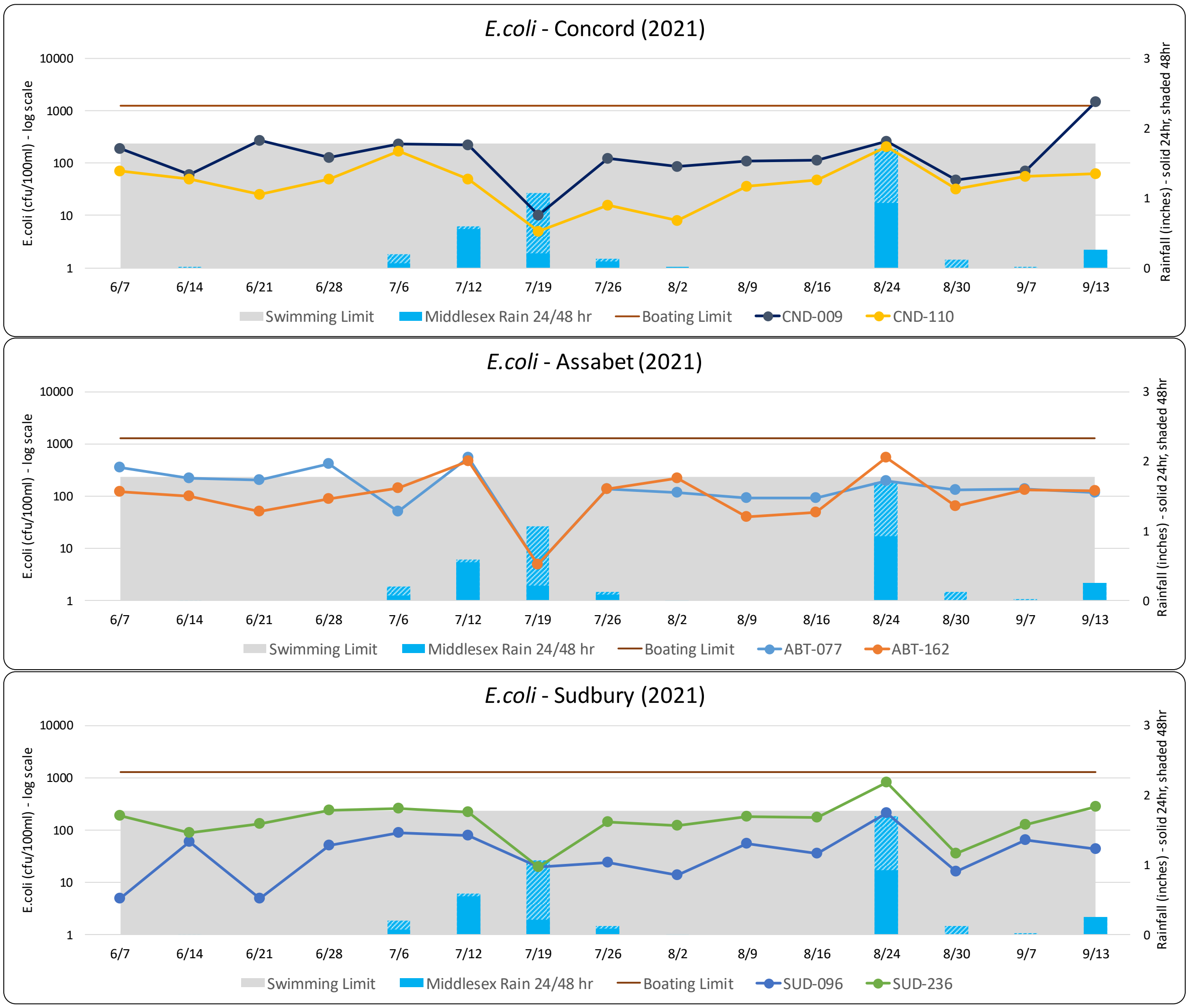


Figure 62: Boxplot analysis of bacteria for wet vs. dry days (2019-2021)

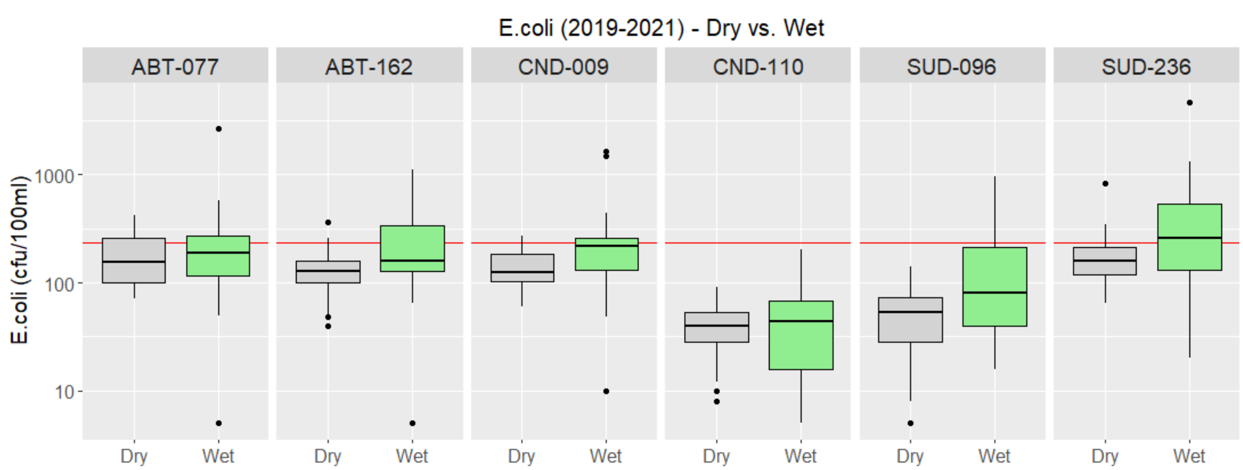


Figure 63: Map of Bacteria Monitoring Results (2019-2021)

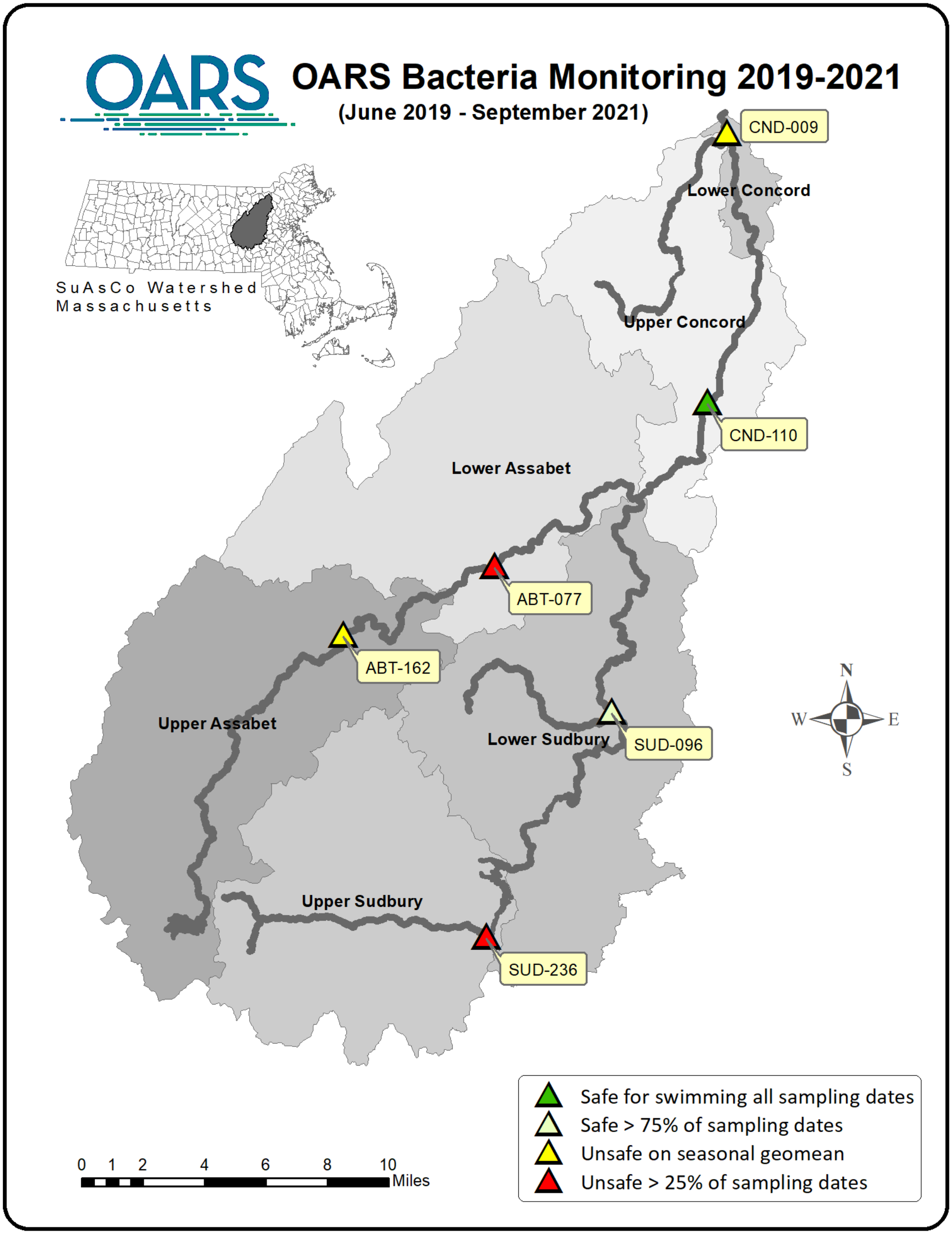
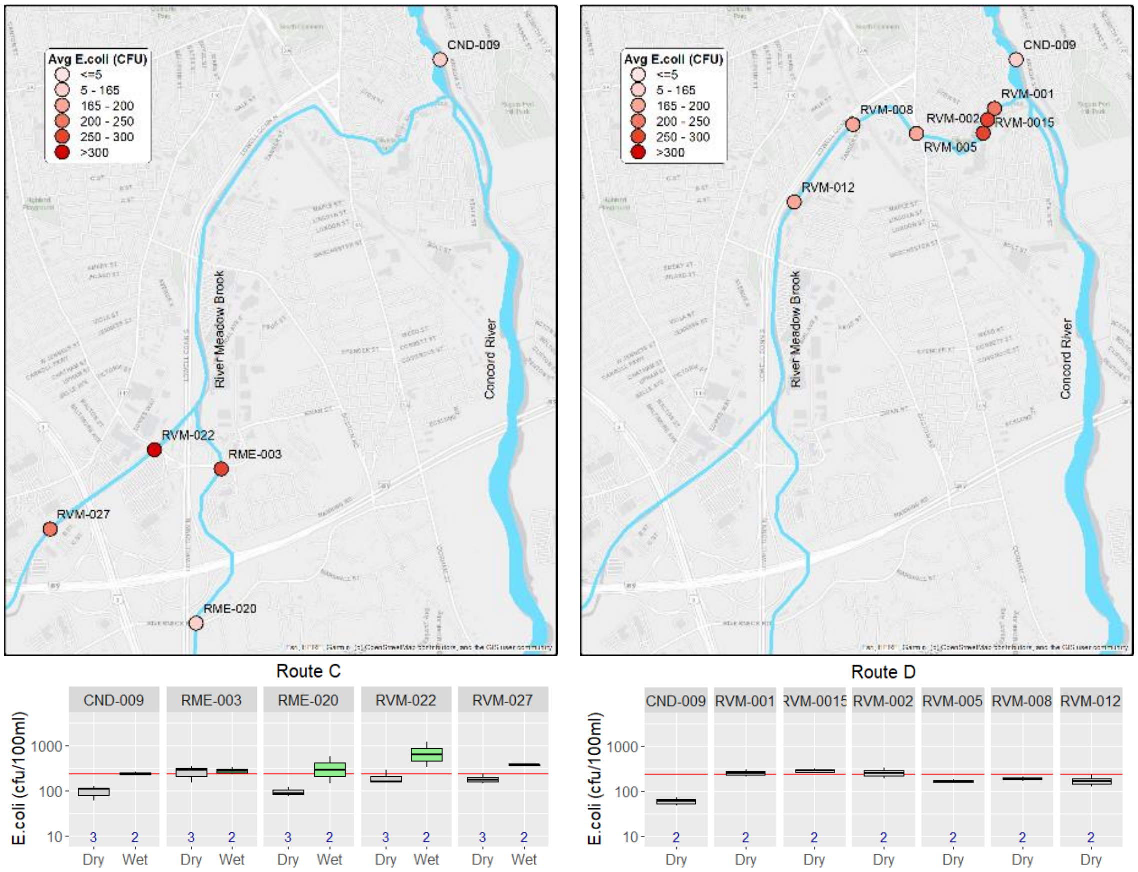


Figure 64: River Meadow Brook Special Study survey routes C and D



Note: The number of samples included in each data set is noted at the bottom of each of the boxplots.

Aquatic Plant Biomass Sampling

Three large impoundments of the Assabet River have been visually surveyed for aquatic plant biomass between mid-August and early September each year since 2005. The goals of the ongoing project are to assess the nature and extent of aquatic plant biomass in the major impoundments of the Assabet River and to assess changes in the river's condition and progress in achieving the TMDL goal. "A substantial reduction in total biomass of at least 50% from July 1999 values is considered a minimum target for achieving designated uses." (MA DEP, 2004)

Biomass Survey Methods

These surveys have focused on three large impoundments as the most eutrophic areas of the river. Impoundment locations include:

(1) Hudson impoundment, Hudson, about 0.5 miles upstream from the dam at Route 85;
(2) Gleasondale impoundment, Stow, about 0.6 miles upstream from the dam near Route 62;
(3) Ben Smith impoundment, Maynard, about 0.7 miles upstream from the dam near Route 62/117.

The rivers are divided into observation grids, based on the grid system originally developed by USGS for MassDEP duckweed monitoring in 2007 (Zimmerman et al., 2011). Using this method, visual observations are conducted by OARS staff from a kayak or canoe at the peak of the growing season each summer. Observations are recorded in the field using hand-held GIS/GPS devices. At each grid cell the following observations are recorded:

- water depth
- visual assessments of…
  - total percent coverage of floating plants
  - percent coverage of duckweed (*Lemna minor*) ignoring the other floating plants
  - percent volume of the grid's water column filled with submerged plants
- dominant and other species in each category (floating, submerged)
- presence of invasive species

To compare conditions between years and between impoundments, total wet weight of the floating plant biomass is calculated for each impoundment. Field estimates of total floating plant cover are converted to consistent classes (0 = 0% coverage, 1 = 1–25% coverage, 2 = 25–50% coverage, 3 = 50–75% coverage, 4 = 75–99% coverage, 5 = 100% coverage). The total grid surface area (from GIS) for each class is summed for each impoundment, and total floating biomass wet weight is calculated using conversion factors developed by OARS: class 1 = 427 g/m^2, class 2 = 1,186 g/ m^2, class 3 = 2,000 g/ m^2, class 4 = 2,855 g/ m^2, class 5 = 3,782 g/ m^2. *Caveat: These conversion factors were developed on a local mixture of floating and rooted aquatic plants, so biomass is relative (i.e. comparable within this analysis but not with analyses done in other water bodies).*

This survey is subjective, depending on estimates by the surveyor. The OARS aquatic scientist conducting the survey changed between 2018 and 2019. Note that starting in 2020, the survey was conducted on the central areas of the impoundments only. Edges were excluded to increase efficiency and in the belief that the real objective of the survey should be biomass in the central portion of the impoundments, not biomass that has collected or grown along the shore. Also, the edge sectors, as drawn, included large portions of exposed land, so percent coverage was *somewhat misleading. All years have been adjusted accordingly. The excluded edges can be seen as a faint gray line in the maps below. Note also that these surveys are conducted in late August, after water chestnut (Trapa natans) has been removed.*

Biomass Results

The calculated wet weight of total floating biomass for the Hudson, Gleasondale, and Ben Smith impoundments from 2005 to 2021 is shown in Figure 65. Trend lines for each impoundment are drawn in the graph. Gleasondale and Ben Smith show no clear trend, but Hudson shows a strong upward trend. The year 2021 was characterized by very heavy precipitation. Summer average rainfall was higher than any other year since these surveys began. All biomass volumes were reduced, especially duckweed. However, the upward trend in Hudson still holds, even with the reduced 2021 volumes. For duckweed there are no visible trends but the effect of precipitation is noticeable, especially in 2009 and 2021 (Figure 66).

Because aquatic plant growth is strongly affected by summer weather conditions, a correlation analysis of biomass vs. temperature or rainfall was calculated (Table 14). Hudson and Ben Smith show a weak positive correlation between biomass and temperature and a weak to strong negative correlation between biomass and rainfall. Gleasondale has no statistical correlation and even biases in the opposite direction for temperature. Duckweed shows a strong negative correlation with rainfall. It is easily washed out by high flows.

Maps showing floating plant biomass in the Ben Smith, Gleasondale, and Hudson impoundments in 2020 are in Figure 67, Figure 68, and Figure 69 respectively. These maps show percent floating plant coverage for all species, and in the inset show which species were the dominant species in sectors with more than 20% coverage. The camera icon indicates the approximate position of the inset photo. One major takeaway from this survey each year is that the Hudson impoundment has the least diverse floating species (mostly filamentous green algae (FGA)), while the Ben Smith impoundment has the most diverse floating species (with very little FGA). Low species diversity can be a sign of eutrophication.

Figure 65: Total floating aquatic plant biomass (2005-2021)

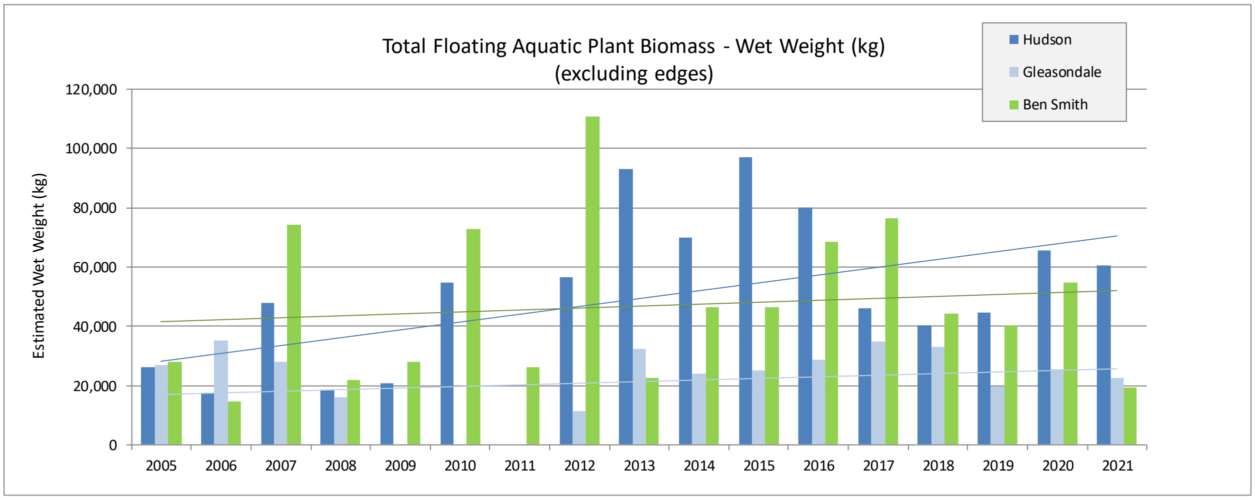


Figure 66: Total duckweed coverage (2007-2021)

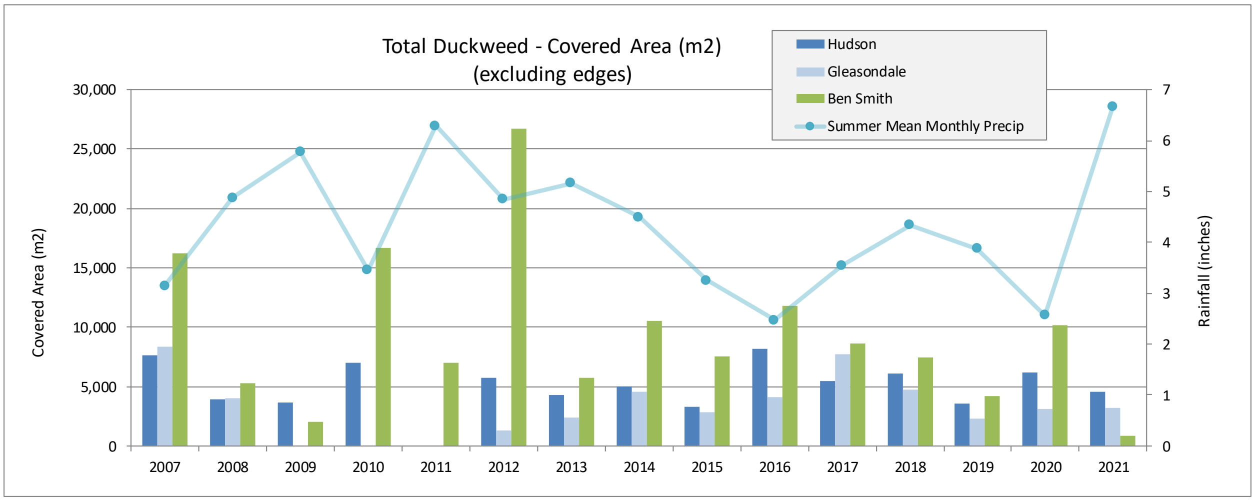


Table 14: Pearson Correlation Coefficients - Biomass vs Temperature and Rainfall

	Hudson	Gleasondale	Ben Smith
Temperature Correlation	0.40	-0.29	0.28
Precipitation Correlation	-0.27	-0.18	-0.51
Duckweed Precipitation Correlation	-0.56	-0.32	-0.44

Figure 67: Total Floating Biomass - Ben Smith

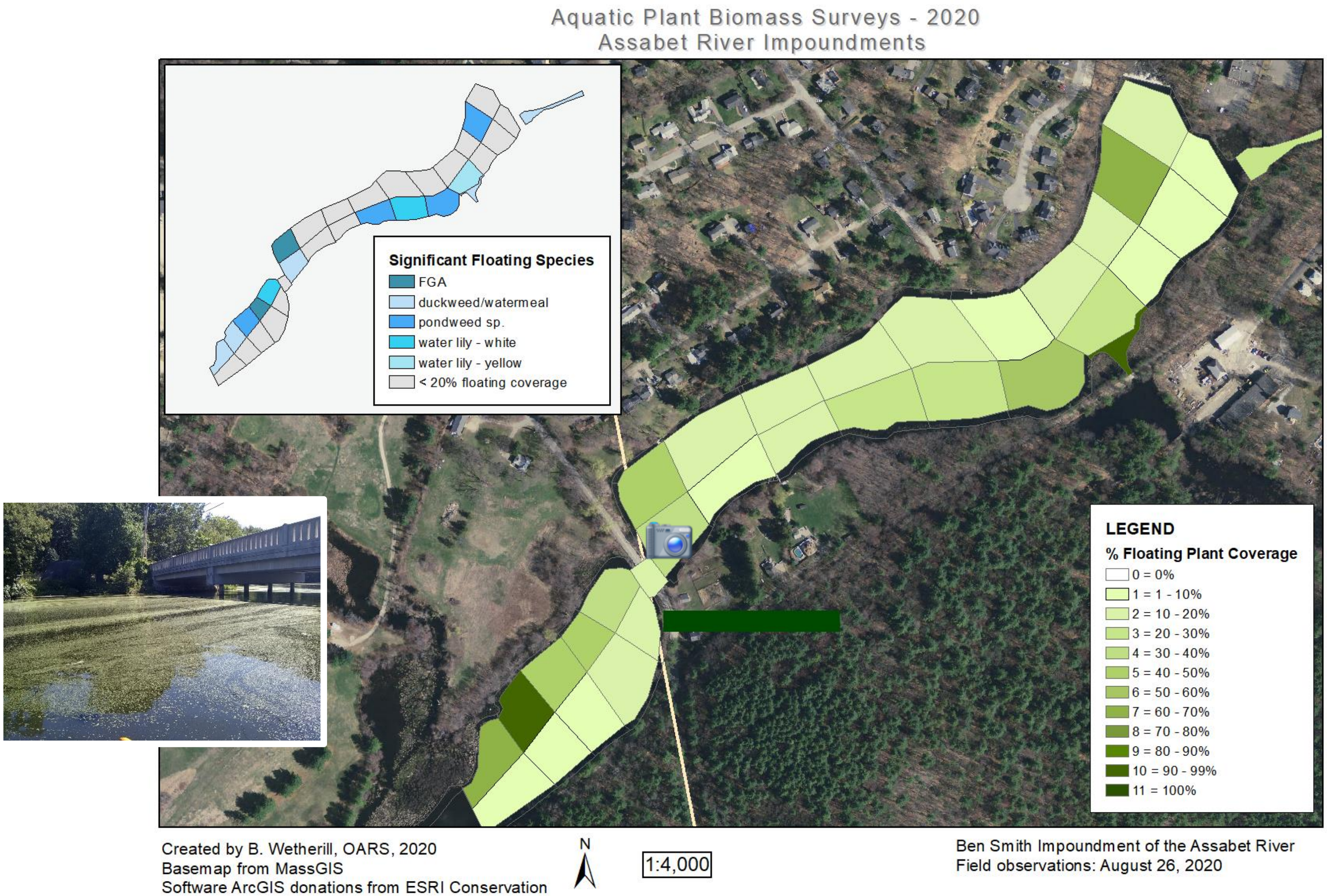


Figure 68: Total Floating Biomass - Gleasondale

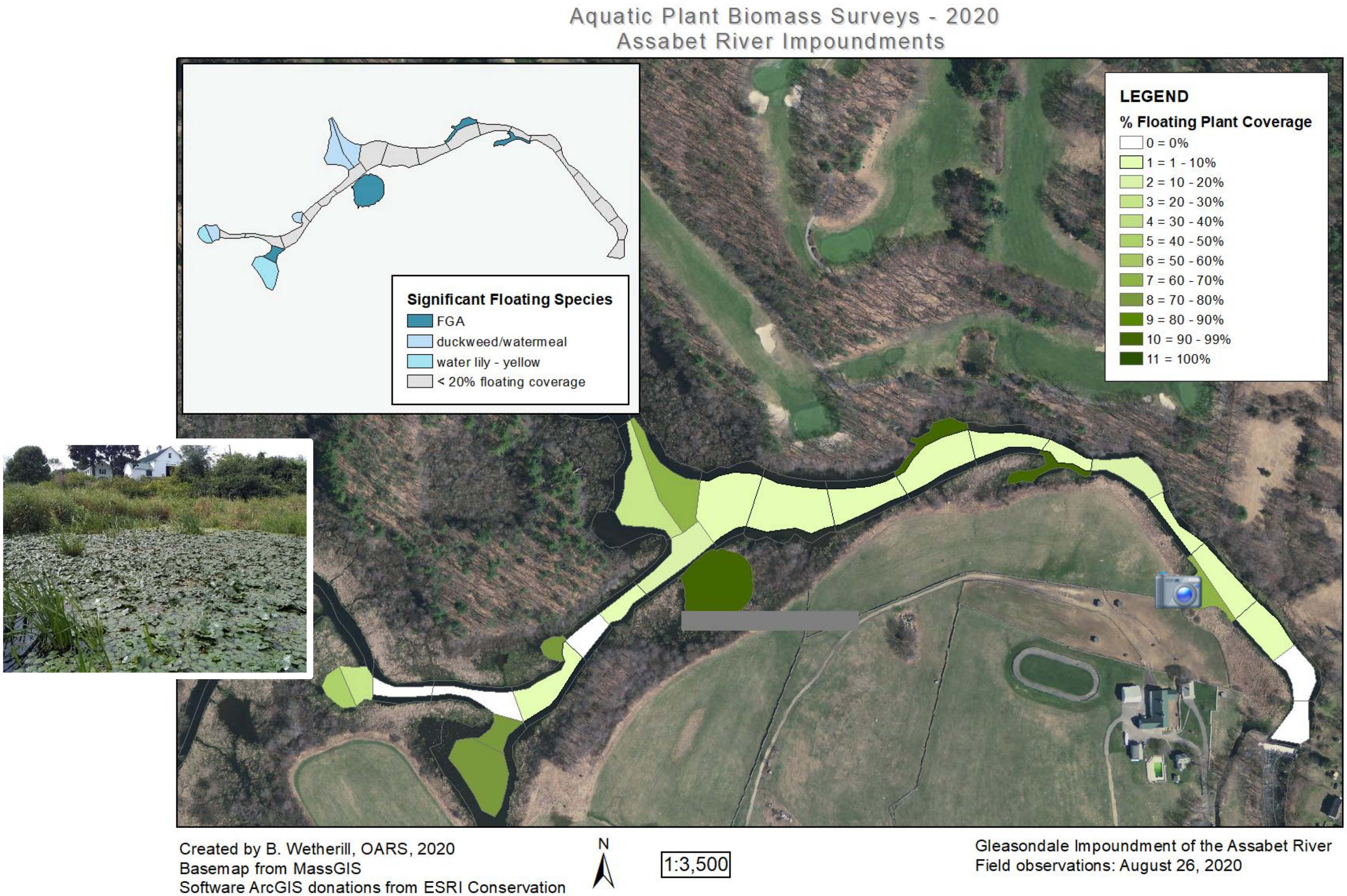
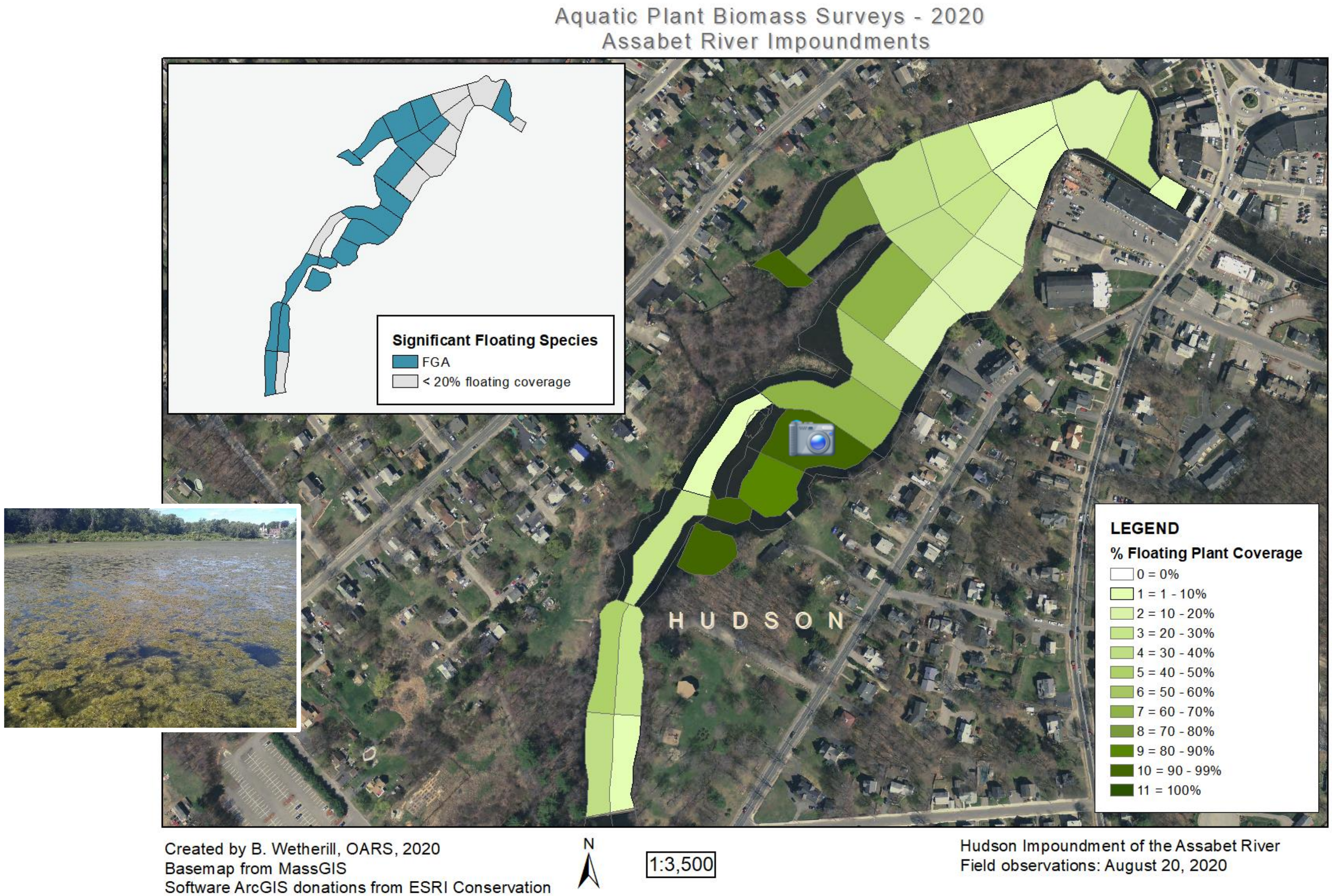


Figure 69: Total Floating Biomass - Hudson



Summary

This report presents the water quality, streamflow, bacteria, and aquatic plant biomass data OARS collected on the Assabet, Sudbury, and Concord Rivers and tributary streams in 2020 and 2021. It also summarizes and evaluates trends in the data that have become evident for the period of record. Following are the high-level findings for each parameter. The details for each are laid out in the body of the report.

The two years that this report focuses on were noteworthy in their different **Precipitation** patterns. The year 2020 was very dry, with precipitation, flows, and groundwater all well below average, but 2021 was exactly the opposite, with precipitation, flows, and groundwater all well above average. This factor had a major effect on almost all of the parameters monitored.

Water Temperature is an important characteristic for aquatic life that is particularly important to watch with concerns of global warming. In 2020, water temperatures in the Lower Assabet, Sudbury, and Concord reached concerning levels approaching the Class B standard and the tributaries were generally above the Cold Water standard. The trend analysis shows a possible upward trend in the Assabet headwaters and River Meadow Brook, but it is not yet statistically significant.

Conductivity levels are very high in the Upper Assabet and some tributaries. Levels were reduced in 2021, due to precipitation dilution, but ABT-301, HOP-011, and RVM-005 consistently have very high conductivity levels – well above the EPA range for mixed fisheries. Additionally, our long-term data show a clear and statistically significant upward trend in conductivity for all sections of our rivers. Conductivity in New England is believed to be primarily an indicator of road salt pollution, so this is of concern.

pH readings in 2020 and 2021 were clearly affected by the amount of precipitation which serves to dilute the pH-raising effects of WWTP discharges. Levels were elevated in 2020 due to the drought and very low in 2021 due to the large amounts of rainwater. Trend analysis shows a clear upward trend in pH in the Assabet sections, which may be a positive sign of reduced eutrophication and lower levels of aquatic respiration, driven by long-term phosphorus reductions.

Dissolved Oxygen trends continue to show a positive upward trend in the Assabet sites, supporting the WWTP improvements that have been made there. However, DO in the Lower Sudbury is trending down, with no known cause. The Hop Brook in Sudbury consistently has very low DO levels, but its trend shows improvements. Elizabeth Brook is worth watching, because it has consistently had very low levels ever since we started monitoring.

Total Phosphorus is the primary indicator that we watched as improvements were being made to the wastewater treatment plants on the Assabet. Trend analysis shows the dramatic reduction in TP through 2012, when the final upgrades were implemented. Since 2012, TP levels have been stable, though we have noticed a slight uptick in the last three years. The treatment plants are meeting their NPDES discharge permit limits, but our rivers are hovering at or above the threshold and we still have consistently high TP levels in Hop Brook downstream of the Marlborough Easterly WWTP. The years 2020 and 2021 were unusual in terms of precipitation and TP was affected by both extremes –

concentration in dry weather and land runoff in wet weather. Analysis of TP load highlights the major role of wet weather events on the amount of phosphorus passing through the river system.

Orthophosphate represents the bioavailable portion of Total Phosphorus. As a percentage of TP, it is trending down in the Assabet, which is a good indicator for WWTP performance. However, other data show that stormwater can deliver especially high percentages of orthophosphate. This would mean that tackling stormwater can have a big impact on bioavailable phosphorus.

Nitrate levels are very high downstream of all WWTPs, and trends show that river concentrations and loads are increasing over time. The WWTPs are the primary source of nitrate in the rivers, and nitrate discharges are currently not regulated. This is primarily a concern for tidal estuaries downstream of our rivers, but it may be something we need to watch more closely. A decreasing trend has been documented in a few headwaters and tributaries, but the cause has not been identified.

Ammonia can be an indicator of industrial spills, municipal wastewater discharges, waste decomposition, and natural nitrogen fixation. It can be toxic to aquatic life, but the levels recorded in our rivers have consistently been well below any toxicity threshold values. A few sites show sporadic ammonia hits that may be worth watching, these are Maynard WWTP, Hop Brook in Sudbury, River Meadow Brook, and Nashoba Brook.

Total Suspended Solids have consistently been highest in the Concord River, probably driven by dam turbulence and motorized boating. In 2020, many headwater and tributary sites experienced high TSS levels in connection with the low flows and probably human disturbance of sediments. Load analysis of all years highlights the role of heavy flows in carrying suspended solids downstream.

Chlorophyll *a* is a measure of planktonic algae in the water and can be an indicator of eutrophication. High nutrient levels could result in algal blooms. We are only measuring chlorophyll *a* in the Sudbury River. Measurements in 2020 and 2021 at the Lower Sudbury sites tended to average above the EPA Ecoregion XIV reference conditions. The good news is that our year-on-year data show a fairly strong downward trend for all sites combined.

Chloride can be an indicator of road salts in the water and sediments. It is very closely correlated with conductivity, which we have confirmed through three years of sampling. Based on this correlation, we are able to model long-term chloride trends, and our data show strong increasing modeled chloride concentrations in all of our rivers, especially in River Meadow Brook and the Upper Assabet. This increasing trend is a serious threat to the ecological health of all of our waterways.

The **Water Quality Index** is a summary metric that combines many of the parameters listed above. It is used as a primary component of our River Report Card. For most river sections, except the Upper Assabet, the index has been primarily driven by phosphorus concentrations, with a slight decline in recent years due to phosphorus average concentration upticks. For the Upper Assabet, it has been primarily impacted by the very high nitrate concentrations from WWTPs, and it fluctuated dramatically in 2020 and 2021 due to drought and rainwater dilution.

E. coli bacteria are an indicator of health safety of the river for recreational users. OARS started monitoring the river for bacteria in 2019. Bacteria levels in all three years have generally followed a similar pattern. Maynard, Ashland, and Lowell consistently have concerning levels of bacteria, hovering near or above the MA DEP swimming threshold. Interestingly, Maynard's results do not show an influence of precipitation, possibly indicating sanitary sewer contamination. Hudson fluctuates at or below the swimming threshold. Sudbury and Bedford consistently show very low levels of contamination, so we have decided to move those two sites to two new locations next year to expand our knowledge of the river conditions.

Biomass has been surveyed at three impoundments in the Assabet since 2005 to track progress toward the goal of reducing nuisance biomass. The data have not shown a reduction in biomass over this time period, but they do show a fairly strong negative correlation between biomass and rainfall, especially for duckweed. Trend analysis shows the Hudson impoundment increasing in biomass over time, and analysis of the plant species surveyed shows that Hudson is dominated by a single species (FGA). All indications are that the Hudson impoundment is moving toward extreme eutrophication, and we are considering whether this is related to the high nitrate concentrations in the Upper Assabet.

References

ACOE, 2010, "Assabet River, Massachusetts Sediment and Dam Removal Feasibility Study", Department of the Army, New England District, U.S. Army Corps of Engineers, Concord, MA.

American Public Health Association, 1995, "Standard Methods for the Examination of Water and Wastewater, 19th Edition", American Public Health Association, American Water Works Association, Water Pollution Control Federation, Washington D.C.

CDM, 2008, "Assabet River Sediment and Dam Removal Study, Modeling Report", prepared for U.S. Army Corps of Engineers, June 2008.

Daley, M.L, Potter, J.D., McDowell, W.H., 2009, "Salinization of urbanizing New Hampshire streams and groundwater: effects of road salt and hydrologic variability", Freshwater Science, 28-4, 2009.

Ellis, M.M., 1944, "Water Purity Standards for Fresh-Water Fishes", Special Scientific Report #2, U.S. Department of Interior, Fish and Wildlife Service.

ENSR, 2001, "SuAsCo Watershed Assabet River TMDL Study: Phase One – Assessment Final Report", ENSR International, Document # 9000-259-100.

EPA, 1983, "Methods for Chemical Analysis of Water and Wastes", U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory, Cincinnati. EPA-600/4-87-017.

EPA, 1986. "Quality Criteria for Water 1986". EPA 440/5-86-001. U.S. Environmental Protection Agency, Office of Water Regulations and Standards, Washington, D.C., May 1986.

EPA, 1999, "1999 Update of Ambient Water Quality Criteria for Ammonia", EPA-822-R-99-014, U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

EPA, 2000, "Ambient Water Quality Criteria Recommendations: Rivers and Streams in Nutrient Ecoregion XIV", EPA 822-B-00-022, United States Environmental Protection Agency: Office of Water, Office of Science and Technology, Health and Ecological Criteria Division. Washington, D.C.

EPA, 2002, "National Recommended Water Quality Criteria: 2002", EPA 822-R-02-047, U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

EPA, 2013, "Aquatic Life Ambient Water Quality Criteria for Ammonia – Freshwater 2013", EPA-822-R-13-001, U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

EPA, 2007, "Guidelines Establishing Test Procedures for the Analysis of Pollutants Under the Clean Water Act; National Primary Drinking Water Regulations; and National Secondary Drinking Water Regulations; Analysis and Sampling Procedures; Final Rule", in Federal Register / Vol. 72, No. 47 / Monday, March 12, 2007 / Rules and Regulations, Pp. 11200 – 11249.

EPA, 2022, Discharge Monitoring Report (DMR) Pollutant Loading Tool. https://echo.epa.gov/trends/loading-tool/get-data/custom-search/ . Data accessed: March 9, 2022.

Evans, D.M., Villamagna, A.M., Green, M.B. et al., 2018, "Origins of stream salinization in an upland New England watershed", Environ Monitoring and Assessment 190, 523, 2018.

Helsel, D.R., D.K. Mueller, and J.R. Slack, 2006, "Computer program for the Kendall family of trend tests: U.S. Geological Survey Scientific Investigations Report", 2005–5275, 4 p.

Kelly, W., 1999, "A Guide to Aquatic Plants in Massachusetts", New England Aquarium, Boston, MA, and Massachusetts Department of Environmental Management, Lakes and Ponds Program, Boston, MA.

Kelting, D.L., Laxson, C.L., Yerger, C.Y., 2012, "Regional analysis of the effect of paved roads on sodium and chloride in lakes", Water Research, Volume 46, Issue 8, 2012.

MA DCR, 2020, "September 2020 Hydrologic Conditions in Massachusetts", MA Water Resources Commission.

MA DCR, 2021, "September 2021 Hydrologic Conditions in Massachusetts", MA Water Resources Commission.

MA DEP, 2004, "Assabet River Total Maximum Daily Load for Total Phosphorus", Report Number: MA82B-01-2004-01, Control Number CN 201.0.

MA DEP, 2012, "Sustainable Watershed Initiative Technical Resources", https://www.mass.gov/guides/sustainable-water-management-initiative-swmi-technical-resources .

MA DEP, 2013, 3.14 CMR 4.00 Massachusetts Surface Water Quality Standards. Massachusetts Department of Environmental Protection, Division of Water Pollution Control, December 2013.

MA DEP, 2021, "Final Massachusetts Integrated List of Waters for the Clean Water Act 2018/2020 Reporting Cycle", Massachusetts Department of Environmental Protection, Division of Watershed Management, Watershed Planning Program, November 2021, CN: 505.1.

MA DFW, 2017, Massachusetts Division of Fisheries and Wildlife, Coldwater Fish Resources List, https://www.mass.gov/info-details/coldwater-fish-resources .

OAR, 2009a, "Quality Assurance Project Plan for StreamWatch: OAR's Water Quality and Quantity Monitoring Program" (approved 7/20/09).

OAR, 2009b, "Quality Assurance Project Plan for OAR's Lower Sudbury River Water Quality Monitoring Program" (approved 8/14/09).

OAR, 2000b, "Water Quality Monitoring Program Final Report 1999", Organization for the Assabet River, Concord, MA.

OAR, 2001, "Water Quality Monitoring Program Final Report Summer 2000", Organization for the Assabet River, Concord, MA.

OAR, 2002, "Water Quality Monitoring Program Final Report Summer 2001", Organization for the Assabet River, Concord, MA.

OAR, 2003, "Water Quality Monitoring Program Final Report Summer 2002", Organization for the Assabet River, Concord, MA.

OAR, 2004, "Water Quality Monitoring Program Final Report – May to October 2003", Organization for the Assabet River, Concord, MA.

OAR, 2005, "Water Quality Monitoring Program Final Report – May to October 2004", Organization for the Assabet River, Concord, MA.

OAR, 2006a, "Aquatic Plant Biomass Assessment of the Large Impoundments of the Assabet River in Eastern Massachusetts – August 2005", Organization for the Assabet River, Concord, MA.

OAR, 2006b, "Water Quality Monitoring Program Final Report – May to October 2005", Organization for the Assabet River, Concord, MA.

OAR, 2007, "StreamWatch and Water Quality Monitoring Program Final Report – May to September 2006", Organization for the Assabet River, Concord, MA.

OAR, 2010, "StreamWatch and Water Quality Monitoring Program Final Report – 2007 & 2008", Organization for the Assabet River, Concord, MA.

OARS, 2011, "Water Quality Monitoring Program Final Report – 2009 & 2010", OARS, Concord, MA.

OARS, 2012, "Water Quality Monitoring Program Final Report – 2011 Field Season", OARS, Concord, MA.

OARS, 2014, "Water Quality Monitoring Program Final Report – 2012-2013 Field Seasons", OARS, Concord, MA.

OARS, 2015, "Water Quality Monitoring Program Final Report – 2014 Field Season", OARS, Concord, MA.

OARS, 2016, "Water Quality Monitoring Program Final Report – 2015 Field Season", OARS, Concord, MA.

OARS, 2017, "Water Quality Monitoring Program Final Report – 2016 Field Season", OARS, Concord, MA.

OARS, 2018, "Water Quality Monitoring Program Final Report – 2017 Field Season", OARS, Concord, MA.

OARS, 2020, "Water Quality Monitoring Program Final Report – 2018-2019 Field Seasons", OARS, Concord, MA.

OARS, 2018b, "Quality Assurance Project Plan for OARS' Water Quality and Quantity Monitoring Program. Approval Period: 2019-2021", OARS, Concord, MA. Amended August 6, 2019.

OARS, 2019, "Quality Assurance Project Plan for OARS' Bacteria Monitoring Program. Approval Period: 2019-2021", OARS, Concord, MA. Amended July 28, 2020.

Selbig, W.R., 2016, "Evaluation of leaf removal as a means to reduce nutrient concentrations and loads in urban stormwater", *Science of the Total Environment*, Vol. 571, Pg. 124-133.

Schlotterbeck, L.C., 1954, “A Fisheries Investigation of the Merrimack and Ipswich River Drainages”, Federal Aid to Fisheries Project F-1-R-3, Massachusetts Division of Fisheries and Game.

Zimmerman, M.J., Y. Qian, and T. Yong Q., 2011, “Monitoring to assess progress toward meeting the Assabet River, Massachusetts, phosphorus total maximum daily load—Aquatic macrophyte biomass and sediment-phosphorus flux”, U.S. Geological Survey Scientific Investigations Report 2011–5179, 77 p.

Zuidema, S., Wollheim, W.M., Mineau, M.M., Green, M.B. and Stewart, R.J., 2018, “Controls of Chloride Loading and Impairment at the River Network Scale in New England”, J. Environ. Qual., 47: 839-847.

Glossary of Terms

adaptive management: the process by which new information about a watershed is incorporated into the watershed management plan. Ideally, adaptive management is a combination of research, monitoring, and practical management that allows "learn by doing." It is a useful tool because of the uncertainty about how ecosystems function and how management affects ecosystems.

ammonia (NH_3): a form of nitrogen available for uptake by plants and microorganisms. Sources include fertilizer, home cleaning products, food processing, and the breakdown of organic nitrogen in sediments and untreated sewage. While ammonia can be readily utilized by plants, high concentrations of ammonia are directly toxic to aquatic life. A secondary effect of increased ammonia occurs when bacteria oxidize the NH_3 to NO_3, a process called nitrification, consuming four atoms of oxygen for every atom of nitrogen converted. This process can dramatically lower dissolved oxygen in the water.

baseflow: the flow of water from aquifers into the streambed. In natural systems in New England baseflow makes up most of the river flow during the summer.

channel flow status: an estimation of the amount of the streambed that is covered with water. Method from the EPA Rapid Bioassessment Protocol.

Class B: Massachusetts Class B, sometimes referred to as “fishable, swimmable,” is one of the state’s designations of “appropriate water uses to be achieved and protected” under the federal Clean Water Act. (MA DEP, 2013)

conductivity: the ability of the water to conduct an electrical charge. Conductivity is a rough indicator of the presence of pollutants such as: wastewater from wastewater treatment plants or septic systems; non-point source runoff (especially road salts); and soil erosion. Reported in micro Siemens per centimeter (µS/cm), conductivity is measured by applying a constant voltage to one nickel electrode and measuring the voltage drop across 1 cm of water. The flow of electrical current through the water is proportional to the concentration of dissolved ions in the water - the more ions, the more conductive the water and the higher the “conductivity.” Since conductivity in water is also temperature dependent, the results are often reported as “specific conductance,” which is the raw conductivity measurement adjusted to 25° C.

dissolved oxygen: the presence of oxygen gas molecules (O_2) in the water, reported as percent saturation (% sat) or in milligrams per liter (mg/L). The concentration of dissolved oxygen (DO) in the water column provides a direct indication of the water’s ability to support aquatic life like fish and macroinvertebrates. Dissolved oxygen is removed from the water by aquatic plants when they respire (both day and night) and by bacterial decomposition of organic matter. Dissolved oxygen is added to the water by plants through photosynthesis (daytime only). The lowest dissolved oxygen concentrations of the day occur in the early morning after nighttime respiration and before daytime photosynthesis. Both extreme (low or high) DO concentrations and large changes in DO concentrations over the day (diurnal variation) are damaging to the habitat.

Ecoregion: An area over which the climate is sufficiently uniform to permit development of similar ecosystems on sites that have similar properties. According to EPA, the ecoregions are “designed to serve as a spatial framework for the research, assessment, management, and monitoring of ecosystems and ecosystem components."

eutrophic: abundant in nutrients and having high rates of productivity frequently resulting in oxygen depletion below the surface layer.

eutrophication and cultural eutrophication: Eutrophication is the enrichment of bodies of fresh water by inorganic plant nutrients (e.g. nitrate, phosphate). It may occur naturally but can also be the result of human activity (cultural eutrophication from fertilizer runoff and sewage discharge) and is particularly evident in slow-moving rivers and shallow lakes.

geomean: Geometric mean is an average calculated using the product of a set of numbers instead of the sum (as in an arithmetic mean). The geomean is the *n*th root of the product of *n* numbers. It is generally used for data that is exponential in character.

Gold Book: EPA's 1986 publication of recommended water quality standards. (EPA, 1986)

hydrograph: A graph showing stage, flow, velocity, or other property of water with respect to time. More hydrographic definitions: http://water.usgs.gov/wsc/glossary.html#TOC

impoundment: A body of water contained by a barrier such as a dam along the course of a stream or river.

mainstem: The main channel of a river, as opposed to the streams and smaller rivers that feed into it.

mesotrophic: having a nutrient loading resulting in moderate productivity.

nitrogen: a major nutrient supporting plant growth. Nitrogen is measured in its various forms as **nitrate (NO_3)**, **nitrite (NO_2)**, **ammonia (NH_3)**, **ammonium (NH_4)**, and **organic nitrogen**. **Total Kjeldahl nitrogen (TKN**) is a measurement that includes organic nitrogen, ammonia, and ammonium, and roughly represents nitrogen that is not immediately bioavailable. **Total nitrogen** is calculated as the sum of TKN and nitrates. **Available nitrogen**, calculated as the sum of nitrate and ammonia/ammonium, gives a measure of the nitrogen readily available for absorption by plants. Although most aquatic plant growth in rivers is limited by the availability of phosphorus, increased nitrogen availability can also lead to algal blooms.

oligotrophic: having a small supply of nutrients, low production of organic matter, low rates of decomposition, and high dissolved oxygen in the lower layers of the water column.

phosphorus: Plants need nutrients to grow; in particular, they need a balance of phosphorus (P) and nitrogen (N). Phosphorus is measured as **total phosphorus** (TP) and **orthophosphate** (ortho-P). Orthophosphate is soluble inorganic phosphate, the form required by plants. In most fresh waters, the concentration of phosphorus available to plants is low enough that the plants cannot grow at their maximum rate, making phosphorus the limiting nutrient (i.e. the most important nutrient for controlling plant growth).

pH: the negative log of the hydrogen ion concentration in water, a measure of the acidity of water. pH is measured on a logarithmic scale from 1 to 14, with 1 being very acidic, 7 being neutral, and 14 being very basic. Extreme pH levels, in either direction, can be toxic to fish and other aquatic life and play a role in the behavior of other pollutants such as heavy metals in the environment. Changes in pH can be the result of acid rain/snow, chemicals entering the waterways, or algal blooms.

sediment phosphorus flux: the exchange of phosphorus between the sediment layer and the overlying water column. Whether the sediments are a nutrient sink or source depends on the composition of the sediments and the condition of the overlying water column. Particularly, under anoxic conditions, phosphorus tends to be released from the sediments.

stage and streamflow measure the amount of water in the river. Stage is the height of the water above the riverbed, and is read at staff gages on the mainstem river and at sites on six tributaries. Streamflow (also called discharge) is the volume of water passing a given point in the river (reported in cubic feet per second, “cfs”).

stage-discharge rating (aka “rating curve”): the relationship between stage (water height) and discharge (streamflow). The rating curve is determined empirically by making a series of streamflow measurements at different stages and analyzing the graphed results.

temperature affects the ecosystem in a number of ways. Many organisms, especially cold water fish, are sensitive to high temperatures. The solubility of oxygen is lower in warmer water, decreasing dissolved oxygen concentrations. Algae, weeds, and pathogenic microorganisms can all grow faster in warmer water.

TMDL: Total Maximum Daily Loading, defined under the federal Clean Water Act, is a calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards, and an allocation of that load among the various sources of that pollutant.

total suspended solids (TSS): the amount of silt, clay, organic material, and algae in the water. Sources include erosion and the solids in effluent. Once in the water column, suspended solids are transported downstream and settle gradually, along with decaying plant matter, to form thick organic-rich sediments in the slower sections of the river.

tributary: A stream or river whose water flows into a larger stream, river, or lake.

Appendix I Mainstem Reach and Tributary Statistics

2020 Statistics – Mean values (calculated on ½ detection level where sample is Below Detection Limit)

	Reach	# Sites	Temp (°C)	DO % Sat	DO Conc (mg/L)	Cond (µS/cm)	pH	TSS (mg/L)	TP (mg/L)	ortho-P (mg/L)	NO_3-N (mg/L)	NH_3-N (mg/L)	Cl- (mg/L)	Chl (µg/L)
March 15, 2020	Concord	2	7.9	96	11.4	560	7.2	6.0	0.030	0.005	0.63	0.05	146	
	Headwater & Tribs	7	6.3	96	11.8	443	7.2	1.1	0.023	0.006	0.27	0.06	112	
	Lower Assabet	2	6.7	99	12.1	554	7.4	2.5	0.045	0.020	1.45	0.05	138	
	Upper Assabet	1	8.6	98	11.5	613	7.3	2.0	0.110	0.090	3.60	0.05	112	
	Lower Sudbury	2	7.8	93	11.1	566	7.3	4.0	0.020	0.005	0.41	0.05	164	
May 17, 2020	Concord	2	17.3	92	8.8	502	6.6	6.0	0.050	0.008	0.17	0.05		
	Headwater & Tribs	9	16.4	83	8.1	419	7.1	3.2	0.068	0.006	0.13	0.05		
	Lower Assabet	2	18.1	94	8.9	492	7.2	5.0	0.085	0.005	0.71	0.05		
	Upper Assabet	1	15.8	90	8.9	443	7.3	3.0	0.900	0.005	2.80	0.05		
	Lower Sudbury	5	16.9	78	7.6	498	6.9	2.6	0.048	0.007	0.08	0.05		
June 14, 2020	Concord	4	22.1	86	7.6	623	7.3	13.5	0.108	0.013	0.48	0.05		
	Headwater & Tribs	10	19.1	77	7.2	565	7.2	28.2	0.160	0.028	0.36	0.12		8.5
	Lower Assabet	3	21.2	93	8.4	664	7.6	2.0	0.077	0.017	1.43	0.05		
	Upper Assabet	3	19.3	95	8.8	1122	7.5	2.3	0.083	0.020	4.97	0.05		
	Lower Sudbury	5	21.5	40	3.5	581	6.8	3.0	0.126	0.020	0.10	0.09		5.5
July 12, 2020	Concord	4	27.4	83	6.5	597	7.2	12.3	0.033	0.015	0.22	0.05		
	Headwater & Tribs	10	24.8	64	5.3	619	7.0	9.8	0.052	0.027	0.22	0.10		2.0
	Lower Assabet	3	26.5	81	6.5	680	7.5	1.7	0.020	0.008	0.99	0.05		
	Upper Assabet	3	24.7	83	6.9	1618	7.4	2.2	0.033	0.020	6.33	0.05		
	Lower Sudbury	5	26.5	47	3.8	619	6.9	7.4	0.056	0.030	0.09	0.15		10.6

2020 Statistics – Mean values (calculated on ½ detection level where sample is Below Detection Limit)

	Reach	# Sites	Temp (°C)	DO % Sat	DO Conc (mg/L)	Cond (µS/cm)	pH	TSS (mg/L)	TP (mg/L)	ortho-P (mg/L)	NO_3-N (mg/L)	NH_3-N (mg/L)	Cl- (mg/L)	Chl (µg/L)
August 16, 2020	Concord	4	24.1	80	6.8	848	7.3	3.5	0.070	0.008	0.56	0.05	251	
	Headwater & Tribs	10	20.4	61	5.5	687	7.1	24.2	0.178	0.029	0.27	0.07	211	3.4
	Lower Assabet	3	22.7	82	7.1	1232	7.5	2.2	0.110	0.007	1.47	0.05	352	
	Upper Assabet	3	21.9	78	6.8	1542	7.5	2.3	0.077	0.022	9.87	0.05	438	
	Lower Sudbury	5	23.0	53	4.6	709	7.1	9.6	0.114	0.028	0.08	0.10	172	13.4
September 13, 2020	Concord	2	20.3	81	7.3	809	7.3	3.5	0.045	0.005	1.39	0.05		
	Headwater & Tribs	9	16.1	70	6.9	563	7.1	4.3	0.052	0.013	0.23	0.06		
	Lower Assabet	2	18.5	79	7.5	900	7.4	1.5	0.035	0.005	1.90	0.05		
	Upper Assabet	1	20.5	121	10.8	1796	7.5	2.0	0.040	0.020	16.60	0.05		
	Lower Sudbury	4	19.6	70	6.4	656	7.2	7.4	0.058	0.010	0.11	0.06		
November 8, 2020	Concord	2	9.2	98	11.5	723	7.1	4.5	0.030	0.020	0.66	0.09		
	Headwater & Tribs	7	9.4	85	9.7	531	6.9	1.0	0.041	0.010	0.18	0.05		
	Lower Assabet	2	10.0	92	10.4	734	7.1	3.0	0.030	0.010	1.24	0.05		
	Upper Assabet	1	14.3	98	10.0	1396	7.3	0.5	0.130	0.130	12.20	0.05		
	Lower Sudbury	2	9.7	90	10.3	710	7.0	3.8	0.025	0.013	0.21	0.05		

Blank = not sampled/not recorded/censored

2021 Statistics – Mean values (calculated on ½ detection level where sample is Below Detection Limit)

	Reach	# Sites	Temp (°C)	DO % Sat	DO Conc (mg/L)	Cond (µS/cm)	pH	TSS (mg/L)	TP (mg/L)	ortho-P (mg/L)	NO_3-N (mg/L)	NH_3-N (mg/L)	Cl- (mg/L)	Chl (µg/L)
March 21, 2021	Concord	1	5.7	105	13.2	545	7.3	2.0	0.030	0.005	0.71	0.05		
	Headwater & Tribs	8	4.7	95	12.2	484	7.0	0.8	0.025	0.006	0.31	0.06		
	Lower Assabet	2	5.5	99	12.7	558	7.3	2.0	0.035	0.005	1.31	0.05		
	Upper Assabet	1	7.1	104	12.6	962	7.2	2.0	0.060	0.020	4.16	0.05		
	Lower Sudbury	2	5.5	99	12.6	578	7.2	1.5	0.020	0.005	0.35	0.05		
May 16, 2021	Concord	1	17.3	83	8.0	514	6.6	6.0	0.060	0.010	0.34	0.05		
	Headwater & Tribs	9	16.2	82	8.1	494	6.8	2.7	0.056	0.012	0.17	0.06		
	Lower Assabet	2	16.9	92	9.1	538	7.2	4.5	0.060	0.008	0.77	0.08		
	Upper Assabet	1	16.5	90	8.8	664	6.9	2.0	0.030	0.010	3.70	0.05		
	Lower Sudbury	5	17.5	83	7.9	550	7.0	3.4	0.044	0.007	0.07	0.05		
June 13, 2021	Concord	3	22.7	74	6.3	547	6.9	4.7	0.100	0.037	0.36	0.05		
	Headwater & Tribs	11	18.9	77	7.1	543	7.0	2.5	0.099	0.043	6.04	0.08		1.0
	Lower Assabet	3	21.5	90	8.0	605	7.1	3.0	0.117	0.030	1.00	0.10		
	Upper Assabet	3	18.8	90	8.3	700	7.3	2.2	0.073	0.027	2.36	0.05		
	Lower Sudbury	5	21.5	36	3.1	555	6.6	2.1	0.082	0.028	0.03			3.5
	Upper Sudbury	1	19.8	79	7.2	398	6.9	1.0	0.070	0.020	0.22			
July 11, 2021	Concord	3	20.4	76	6.8	345	6.7	6.3	0.110	0.030	0.29	0.05		
	Headwater & Tribs	11	18.7	70	6.5	357	6.4	3.4	0.081	0.020	8.34	0.06		1.0
	Lower Assabet	3	19.5	88	8.0	271	6.5	7.3	0.120	0.033	0.21	0.05		
	Upper Assabet	3	19.9	76	6.9	329	6.4	3.3	0.073	0.017	0.31	0.05		
	Lower Sudbury	5	20.8	41	4.9	400	6.6	4.6	0.092	0.012	0.03			5.1
	Upper Sudbury	1	19.6	98	9.0	357	6.8	5.0	0.090	0.010	0.03			

2021 Statistics – Mean values (calculated on ½ detection level where sample is Below Detection Limit)

	Reach	# Sites	Temp (°C)	DO % Sat	DO Conc (mg/L)	Cond (µS/cm)	pH	TSS (mg/L)	TP (mg/L)	ortho-P (mg/L)	NO_3-N (mg/L)	NH_3-N (mg/L)	Cl- (mg/L)	Chl (µg/L)
August 15, 2021	Concord	3	26.9	73	5.8	514	6.9	5.0	0.077	0.030	0.51	0.05		
	Headwater & Tribs	11	23.3	67	5.8	564	7.0	3.8	0.086	0.027	11.20	0.07		4.4
	Lower Assabet	3	26.0	86	7.0	605	7.4	2.2	0.057	0.013	0.98	0.09		
	Upper Assabet	3	23.3	81	6.9	868	7.3	4.3	0.040	0.008	2.48	0.05		
	Lower Sudbury	5	26.2	37	3.0	521	6.7	5.6	0.094	0.040	0.05			10.6
	Upper Sudbury	1	24.1	86	7.2	515	7.0	1.0	0.070	0.020	0.30			
September 12, 2021	Concord	1	20.5	87	7.8	385	6.7	6.0	0.060	0.030	0.25			
	Headwater & Tribs	9	18.3	66	6.2	388	6.8	2.4	0.043	0.021		0.07		
	Lower Assabet	2	19.6	92	8.4	424	7.0	4.5	0.050	0.030	0.57	0.05		
	Upper Assabet	1	20.2	82	7.4	394	6.7	2.0	0.020	0.005		0.05		
	Lower Sudbury	5	20.7	44	4.0	389	6.6	3.0	0.044	0.020	0.03			
November 14, 2021	Concord	1	8.6	94	11.0	282	7.0	3.0	0.040	0.020	0.38			
	Headwater & Tribs	9	7.4	88	10.5	301	6.9	1.2	0.030	0.008		0.05		
	Lower Assabet	2	8.3	94	11.0	385.00	7.0	1.50	0.040	0.010	0.64	0.05		
	Upper Assabet	1	8.8	104	12.1	424.00	6.9	1.00	0.090	0.050		0.05		
	Lower Sudbury	2	9.0	86	10.0	402.00	7.0	3.50	0.035	0.005	0.13			

Blank = not sampled/not recorded/censored

Appendix II Data Quality Notes

OARS' data quality objectives and data qualifiers are listed below. Full QC details are available in OARS' Quality Control Report on request.

Data Quality Objectives

Parameter	Field Duplicate	Lab Duplicate	Field/Lab Blanks	Accuracy
Air temp	< 10% RPD	na	na	± 2 °C
Water Temp	< 10% RPD	< 10% RPD	na	± 1 °C
pH	± 0.5 S.U.	± 0.5 S.U.	na	± 0.2 S.U. at pH 7.00
DO	< 10% RPD or < 20% RPD if <4.0mg/L	< 20% RPD	na	± 5% at 100% DO sat
Conductivity	< 20% RPD or <30% RPD if <250mS/cm	< 20% RPD	na	± 50 mS at 0 and 1000 mS/cm
TSS	< 30% RPD or ± 1mg/L if ≤ 3mg/L	< 20% RPD	BDL	NA
TP	< 20% RPD or ± 0.01 mg/L if <0.05 mg/L	< 20% RPD	BDL	85-115% recovery of lab spike
ortho – P	< 20% RPD or ± 0.01 mg/L if <0.05 mg/L	< 20% RPD	BDL	85-115% recovery of lab spike
NO3	< 30% RPD	< 20% RPD	BDL	85-115% recovery of lab spike
NH3	< 30% RPD	< 20% RPD	BDL	85-115% recovery of lab spike
Chloride	< 30% RPD	< 20% RPD	BDL	85-115% recovery of lab spike
Chl-a	< 20% RPD or ± 2mg/L if <15mg/L	< 20% RPD	BDL	NA
Gage height	< 10% RPD	na	na	± 0.01 ft
Flow	na	na	na	± 15 % of rating curve

Data Qualifiers

Data qualifiers	Description
NA	not sampled
P	provisional data (QA/QC not yet performed)
Q	data met most but not all QA/QC requirements
NR	data censored and not reported

Qualified or censored data for 2020 and 2021 include:

Date	Parameter	Qualified/ Censored	Sites	Problem / Action
3/15/20	pH	Q	Upper Assabet	Sensor was very slow
5/17/20	Conductivity	Q	Lower Assabet and Sudbury	Contaminated calibration fluid. Adjusted all values up by ~100 uS/cm.
5/17/20	TP & NH3	Q	NSH-047	Sediment in samples and field duplicate RPD not met. Used values from duplicates.

6/14/20	Temperature	Q	Lower Assabet	Sensor low by 1.4 C, so adjusted all sites up.
6/14/20	DO	Q	Lower Assabet	Sensor calibration check outside RPD objective.
6/14/20	TP	Q	Lower Assabet	One field duplicate missed RPD objective.
6/14/20	In-situ	Q, NR	SUD-144, SUD-064, SUD-086, HBS-016	Sampler had trouble with sensor. Qualified some parameters and censored others.
6/14/20	TSS	Q	HBS-016	Sample had too much organic matter.
6/14/20	DO	Q	Upper Assabet	Sensor gave message "Will produce inaccurate results", but data looked good.
6/22/20	Chlorophyll	Q	All sites	Field and lab duplicates both exceeded RPD, but values similarly low.
7/12/20	TSS	Q	Sudbury	One field duplicate missed RPD objective.
8/16/20	TP	Q	All sites	Two field duplicates missed RPD objective.
8/17/20	Chlorophyll	Q	All sites	Field duplicate missed RPD objective, but values similarly high.
9/13/20	TP	Q	Lower Assabet	One field duplicate missed RPD objective.
9/13/20	DO	Q	ABT-301	Sensor readings still going up after 15 minutes, but value considered valid.
5/16/21	DO	Q	Concord	Sensor consistently low by 6-10%.
6/13/21	TP	Q	All sites	All field duplicates missed RPD objective.
8/15/21	TP	Q	Middle Assabet	One field duplicated missed RPD objective.
9/12/21	pH	Q	Upper Assabet	Sensor consistently low by 0.3 units. Adjusted all up.
11/14/21	DO, pH, Cond, Temp	Q	ABT-301, HOP-011, SUD-293	Some values recorded in logger did not match field sheet. Used logger values.
11/14/21	Gage height	Q	SUD-293	Gage was not accessible. Value recorded from fuzzy photograph.

Note that in 2020 and 2021 we qualified 21-25% of our TP measurements because field duplicate RPD values exceeded the Data Quality Objective. (This is down from 45% in 2019.) It is important to note that we take a particularly stringent QC approach by qualifying all sites sampled by a sampling team if one field duplicate fails. Since identifying this issue in 2019, we have been conducting a study of TP QC. A write-up of the study is included in the 2021 QC Report. In 2021, we took two actions to address the issue: (1) the lab agreed to reduce holding times from 28 days to 15 days, (2) we adjusted our sampling process to avoid heavy particulate matter. However, there was only a slight improvement in results. We are continuing to study this issue jointly with MA DEP. Based on data from other sampling programs, it seems that this is a common dynamic with Total Phosphorus. We have agreed with MA DEP to adjust our Data Quality Objective starting in 2022 to allow for 30% RPD if TP is greater than 0.05 mg/L.

Appendix III Water Quality Data

(contact OARS for full data set)

Appendix IV Aquatic Plant Biomass Survey Data 2005 - 2021

Section	Year	Class 0 Area (m^2) No floating biomass	Class 1 Area (m^2) 1-25% cover	Class 2 Area (m^2) 26-50% cover	Class 3 Area (m^2) 51-75% cover	Class 4 Area (m^2) 76-99% cover	Class 5 Area (m^2) 100% cover
Hudson Impoundment	2005	13595	20779	5782	1764	1655	623
	2006	26376	13221	0	2122	1764	714
	2007	0	21643	8635	13296	623	0
	2008	1954	41621	623	0	0	0
	2009	10676	24900	8621	0	0	0
	2010	7475	22760	0	4038	714	9210
	2011	nr	nr	nr	nr	nr	nr
	2012	3807	11207	18918	4340	1764	4161
	2013	6091	1780	11557	5776	5128	13866
	2014	2582	13686	13625	1764	3204	9336
	2015	0	7871	9299	3918	13691	9418
	2016	3005	11618	10256	4878	1708	12732
	2017	0	22060	16926	1764	0	3447
	2018	623	20526	17802	5247	0	0
	2019	0	22215	16034	1764	3469	714
	2020	0	14895	12379	8781	3982	4161
	2021	0	11583	19884	5210	7521	0
Ben Smith Impoundment	2005	nr	nr	nr	nr	nr	nr
	2006	nr	nr	nr	nr	nr	nr
	2007	5364	45609	11985	3732	4204	16431
	2008	15773	68668	715	0	2167	0
	2009	48373	24687	4096	4605	5564	0
	2010	13628	42568	7981	10460	8314	4373
	2011	22162	61505	0	3657	0	0
	2012	14769	20069	14608	15488	14098	8292
	2013	25480	51180	7828	0	0	2835
	2014	7475	56407	22726	0	0	715
	2015	24425	44325	11964	0	6610	0
	2016	0	52585	21321	7052	6366	0
	2017	0	51185	25782	715	3776	5865
	2018	13847	50146	23331	0	0	0
	2019	23643	44693	11252	7736	0	0
	2020	0	52826	22111	9536	0	2852
	2021	32574	54750	0	0	0	0
Gleasondale Impoundment	2005	17488	0	2056	0	539	6062
	2006	11364	3967	1594	0	3667	5554
	2007	0	15481	3918	2907	3839	0
	2008	1775	20295	2307	614	851	304
	2009	nr	nr	nr	nr	nr	nr
	2010	nr	nr	nr	nr	nr	nr
	2011	nr	nr	nr	nr	nr	nr

Section	Year	Class 0 Area (m^2) No floating biomass	Class 1 Area (m^2) 1-25% cover	Class 2 Area (m^2) 26-50% cover	Class 3 Area (m^2) 51-75% cover	Class 4 Area (m^2) 76-99% cover	Class 5 Area (m^2) 100% cover
	2012	18909	3346	1611	0	509	1770
	2013	8913	6714	1873	2307	1360	4980
	2014	6708	11928	1171	3522	0	2817
	2015	6935	6630	4066	4362	0	2278
	2016	5206	11629	3008	851	2488	2963
	2017	1705	10913	4919	2846	3233	2530
	2018	6482	7088	5974	0	2215	4386
	2019	7199	11585	2120	3784	918	539
	2020	2906	15027	1911	2463	2716	1123
	2021	5516	13572	1153	1911	3993	0

* Biomass was not assessed in 2011 in Hudson or in 2009/2010/2011 in Gleasondale. In Ben Smith in 2005/2006, the assessment did not include sections upstream of the White Pond Rd. bridge.

* Conversion Factors (based on mean OARS field measurements and trend line): Class 0 = 0 g/m^2; Class 1 = 427 g/m^2; Class 2 = 1,186 g/m^2; Class 3 = 2,000 g/m^2; Class 4 = 2,855 g/m^2; Class 5 = 3,782 g/m^2. Area * class conversion factor /1,000 = total wet weight in kilograms.

Appendix V Coldwater Fishery Resources

Massachusetts Division of Fisheries and Wildlife List of Coldwater Fishery Resources in the Concord (SuAsCo) basin (MA DFW, 2017). *Note that MA DEP identifies 27 tributary streams as CFRs in its Sustainable Water Management Initiative viewer (MA DEP, 2012).*

Stream Name	SARIS #
Cranberry Brook	8247885
Danforth Brook	8247275
Flagg Brook	8247225
Great Brook	8247175
Hayward Brook	8248000
Hog Brook	8247325
Hop Brook (1)	8247600
Hop Brook (2)	8247825
Howard Brook	8247525
Jackstraw Brook	8248475
Landham (Allowance) Brook	8247900
Nagog Brook	8246900
North Brook	8247375
Piccadilly Brook	8248450
Pine Brook	8247950
Rawson Hill Brook	8247575
Run Brook	8247875
Second Division Brook	8247075
Sheepsfall Brook	8247250
UNT to A-1 Site (1) (Nourse Brook)	8247627
UNT to A-1 Site (2)	8247628
UNT to Assabet River	8247260
UNT to Cranberry Brook	8247886
UNT to Great Brook	8247180
UNT to Hog Brook (Fosgate Brook)	8247327
UNT to Hop Brook	8247879
UNT to Hop Brook (2, 1; Trout Brook)	8247830
UNT to Hop Brook (2, 3)	8247855
NT to Nashoba Brook	8246876
UNT to North Brook	8247435
UNT to Pine Brook	8247965
UNT to Second Division Brook	8247076
UNT (Nourse Brook)	8248530
Wrack Meadow Brook	8247440