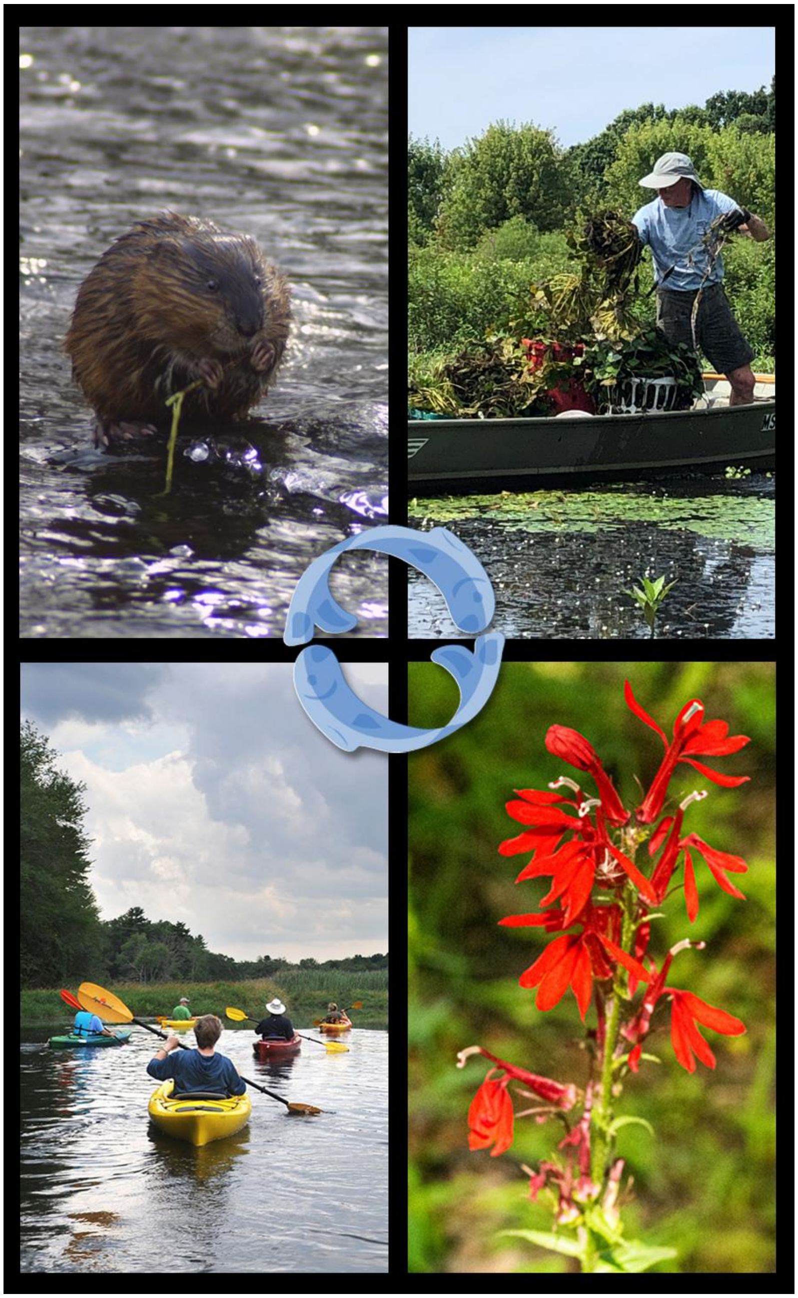
OARS

FOR THE ASSABET SUDBURY & CONCORD RIVERS



Water Quality Monitoring Program Final Report: 2018-2019 Field Seasons

March 2020

Acknowledgments

OARS wishes to thank our many dedicated volunteers for their work in the field and on our Board and advisory committees. We'd especially like to thank our 2018-19 water quality and bacteria volunteers: David Downing, Katherine Fay, Laura Fay, Lisa Fierce, Michael Flaum, Zoe Flanzer, Bill Froberg, Betsey Gardstein, Jack Hawkes, Kim Kastens, Lucy Kirshner, Adam Last, Sesha Manning, Audrey Maxwell, Michal Mueller, Charlotte O'Brien, Karin Paquin, Karen Pfautz, Len Rappoli, Pam Rockwell, Isaac Rockwell, David Rogers, Thomas Schneider, Rachel Shrives, Joseph Stein, Roger Stillwater, Blake Stone, Bill Wachur, Ann Wachur, Joanne Ward, Katherine Weeks, Summer Weidman, Fred Yen, Nancy Young.

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Cover pictures clockwise from top left: muskrat on Assabet (Dave Griffin); pulling water chestnut on Sudbury (Julia Khorana); cardinal flower (David Witherbee); paddling on Assabet in Hudson (Art Illman – Metro West Daily News).

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Abstract

This report covers the water quality and streamflow data collected between March 2018 and November 2019, summarizes the findings of a trends analysis between 1993 and 2019, presents aquatic plant biomass data collected in 2018 and 2019, and presents bacteria data collected in 2019 in our new bacteria monitoring program.

Water quality reports for 1999–2017 (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) and 2005 biomass sampling project (OAR, 2006a) are available on OARS' website (http://www.oars3rivers.org/river/waterquality/reports). Full data is 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, a 9-member Board of Directors, and 2 full-time and 6 part-time staff. Together with our volunteers and partners, OARS has made significant progress over the past 30 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 (which occurs when they are exposed on the river banks and/or at the end of the growing season) 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 2016 assessment (2016 Integrated List, approved 1/2/20), 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 (Category 5, "Waters Requiring a TMDL") for a variety of impairments, including *E. coli* in most sections of the Assabet and Concord Rivers (Mass DEP, 2019). A Total Maximum Daily Loading Study (TMDL) for total phosphorus on the Assabet River was completed in 2004. The most significant change in the 2016 Integrated List was the removal of total phosphorus as an impairment from three sections of the Concord River (MA82A-07, MA82A-08, and MA82A-09). OARS' data suggest that this change was reasonable.

The Sudbury River upstream of the Fruit Street bridge in Hopkinton/Westborough is listed as Category 2, "Attaining some uses; other uses not assessed," attaining uses for aesthetic, primary and secondary contact recreation. All 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, impaired for mercury in fish tissue; most sections are also listed for *E. coli*. Eleven of the tributaries in the basin are also listed as Category 5 Waters: Coles Brook (*E. coli*), Beaver Brook (*E. coli*), Eames Brook (aq. macroinvertebrate bioassessment, taste/odor, excess algal growth), Hop Brook in Marlborough/ Sudbury (total phosphorus, *E. coli*, dissolved oxygen, and noxious aquatic plants), Pantry Brook (fecal coliform), Elizabeth Brook (aq. macroinvertebrate bioassessment and *E. coli*), Nashoba Brook (*E. coli*, fisheries bioassessment), and River Meadow Brook (fecal coliform, *E. coli*). Mill Brook in Concord is listed as Category 4c Waters, "Impairment not caused by a pollutant." Other tributaries are listed as either Category 2 ("Attaining some uses; other uses not assessed") or Category 3 ("No Uses Assessed").

The findings of the *Assabet River Total Maximum Daily Load for Total Phosphorus* study (ENSR, 2001; Mass DEP, 2004) 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) throughout the year. While non-point sources (e.g., stormwater) contributed nutrients, they contributed significantly less than point sources over the growing season. 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. Mass DEP and EPA adopted a two-phased adaptive management plan to reduce phosphorus loads in the Assabet. In Phase I, lower total phosphorus discharge limits were required at the four major wastewater treatment plants (WWTPs). As a part of Phase I, 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 percent (Mass 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 meet a summer total phosphorus discharge limit of 0.1 mg/L and a winter limit of 1.0 mg/L. As of 2019, a new NPDES winter phosphorus discharge limit of 0.2 mg/L has been set for Hudson and Maynard. Hudson is already meeting this limit, but Maynard will need to implement operational changes to meet it (Figure 38).

A natural streamflow regime (i.e., range, duration, and timing of streamflows) throughout the year is critical to supporting fish and other aquatic life. Baseflow, the flow of groundwater into the streams, is particularly critical during the summer and is essential to diluting the effluent discharged to the river. 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 river and its tributaries must be preserved and, if possible, augmented. 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.

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

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 2019 was OARS' 28th consecutive summer collecting data at mainstem Assabet River sites, including the longest standing sites below each major wastewater treatment plant, its 18th year collecting data at tributary sites, its 16th year collecting data at mainstem Concord River sites, its 10th summer collecting Sudbury River data, its 15th year assessing aquatic plant biomass in the large impoundments of the Assabet River, its 2nd year collecting chloride data, and its 1st 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) (approved May 2016 to cover the 2016-2018 field seasons and renewed December 2018 to cover the 2019-2021 field seasons) and previous Quality Assurance Project Plans, and bacteria data, collected under OARS' *Quality Assurance Project Plan for OARS' Bacteria Monitoring Program* (OARS, 2019) (approved June 2019 to cover the 2019-2021 field seasons), 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, 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.

Table 1: Water Quality Sampling Sites 2018-2019

Waterbody	**Sites**	Town	OARS Site #	SARIS #	Lat/Long (d/m/s)	Sampling Dates			Gage reading /streamflow*
						June/Jul/ Aug	May/ Sept	Nov/ March	
Concord River	Rogers Street	Lowell	CND-009	46500	42°38' 11"/ -71°18' 05"	√	√	√	USGS Gage
Concord River	Lowell Street	Billerica	CND-045	46500	42°32' 05"/- 71°17' 58"	√			
Concord River	Route 225	Bedford	CND-110	46500	42°30' 33"/- 71°18' 48"	√			
Concord River	Lowell Rd. Bridge	Concord	CND-161	46500	42°27' 58"/ -71°21' 21"	√	√	√	
Assabet Lower	Route 2	Concord	ABT-026	46775	42°27' 56"/ -71°23' 28"	√	√	√	
Assabet Lower	Route 62 (Canoe access)	Acton	ABT-062	46775	42°26' 27"/ -71°25' 46"	√			
Assabet Lower	USGS Maynard Gage	Maynard	ABT-077	46775	42°25' 56"/ -71°26' 58"	√	√	√	USGS Gage
Assabet Upper	Route 62 (Gleasondale)	Stow	ABT-144	46775	42°24' 18"/ -71°31' 35"	√			
Assabet Upper	Robin Hill Road	Marlborough	ABT-237	46775	42°20' 44"/ -71°36' 50"	√			
Assabet Upper	Route 9	Westborough	ABT-301	46775	42°16' 59"/ -71°38' 18"	√	√	√	
Assabet Headwater	Mill Road	Westborough	ABT-312	46775	42°16' 26"/ -71°37' 56"	√	√	√	USGS Gage**
Assabet Impound	White Pond Road	Stow/Maynard	ABT-095	46775	42° 25' 23"/-71° 28' 29"	√*	√*		
Assabet Impound	Sudbury Road	Stow	ABT-134	46775	42° 24' 41"/-71° 30' 30"	√*	√*		
Assabet Impound	Cox Street	Hudson	ABT-162	46775	42° 23' 58"/-71° 32' 45"	√*	√*		
Sudbury River	Route 62 (Boat House)	Concord	SUD-005	47650	42°27' 30"/ -71°21' 58"	√	√	√	
Sudbury River	Sherman Bridge Road	Wayland	SUD-064	47650	42°23' 47" / -71°21' 52"	√	√		
Sudbury River	River Road	Wayland	SUD-086	47650	42° 21' 48"/ -71° 22'28"	√	√		
Sudbury River	Route 20	Wayland	SUD-096	47650	42° 22' 24"/ -71° 22' 56"	√	√		
Sudbury River	Sudbury Landing (Saxonville)	Framingham	SUD-144	47650	42° 19' 32.1"/-71° 23' 50"	√	√	√	USGS Gage
Danforth Brook	Route 85	Hudson	DAN-013	47275	42°23' 59"/ 71°33' 57"	√	√	√	OARS Gage
Elizabeth Brook	White Pond Road	Stow	ELZ-004	47125	42°25' 21"/ 71°28' 38"	√	√	√	
Hop Brook	Otis Street	Northborough	HOP-011	47600	42°17' 31"/ 71°39' 27"	√	√	√	OARS Gage
Hop Brook	Landham Road	Sudbury	HBS-016	47825	42° 21' 26"/-71° 24' 11"	√	√		
Nashoba Brook	Commonwealth Ave.	Concord	NSH-002	unnamed	42°27' 32"/ 71°23' 49"	√	√	√	OARS Gage
Nashoba Brook	Wheeler Lane	Acton	NSH-047	46875	42°30' 37"/ 71°24' 24"	√	√	√	USGS gage
North Brook	Pleasant St.	Berlin	NTH-009	47375	42°21' 16"/ 71°37' 36"	√	√	√	OARS Gage
River Meadow Brk.	Thorndike Street	Lowell	RVM-005	46525	42°37' 54"/- 71°18' 31"	√	√		

* 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 at 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 volunteers and staff.
√* indicates that site is only monitored for in-situ measurements – no water sample.

Figure 1: SuAsCo Watershed and 2018-2019 Water Quality Sampling Sites

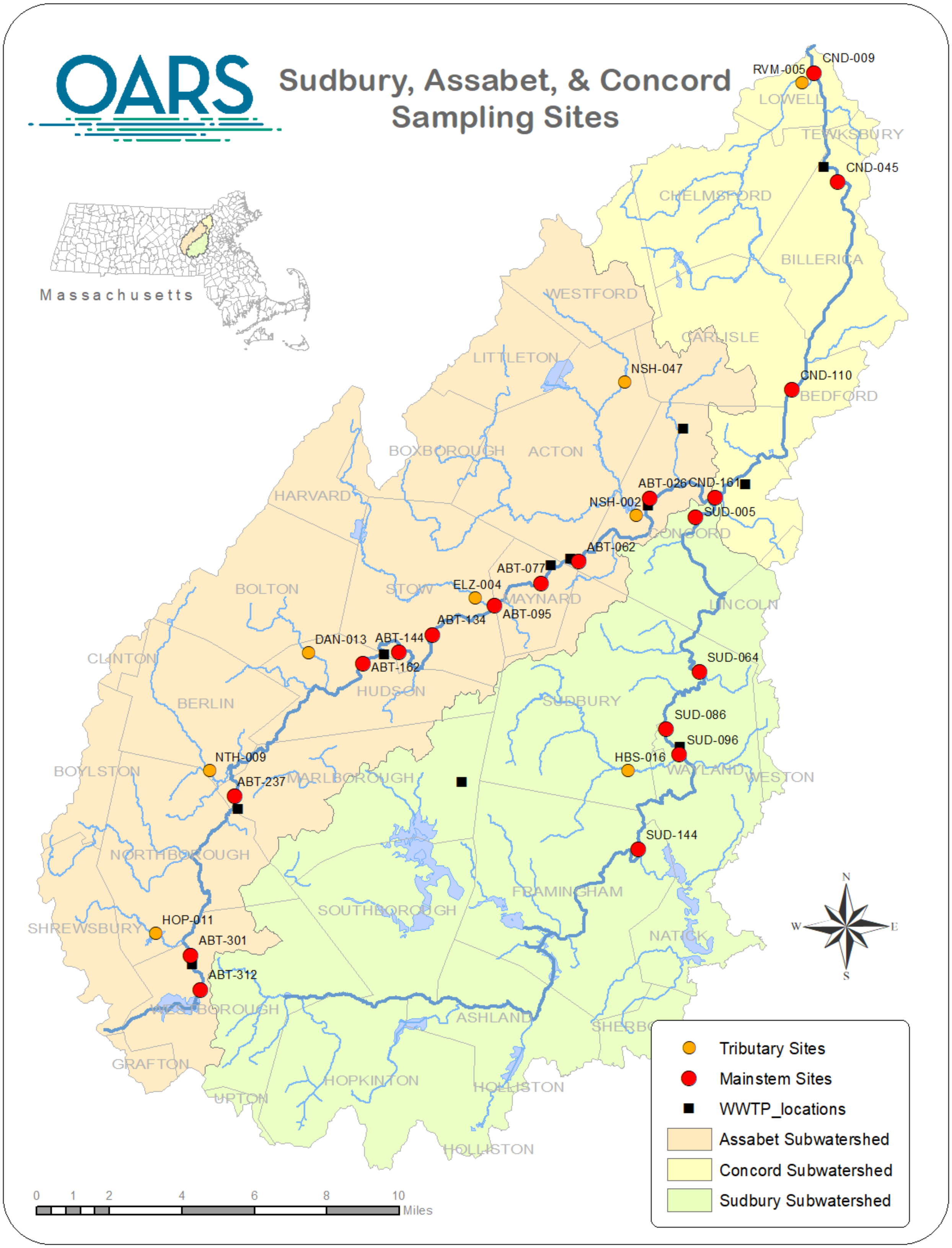


Table 2: Bacteria Sampling Sites 2019

Waterbody	**Sites**	Town	OARS Site #	SARIS #	Lat/Long (d/m/s)	Sampling May-Sep
Lower Assabet River	USGS Maynard Gage	Maynard	ABT-077	46775	42°25' 56"/ -71°26' 58"	√
Upper Assabet River	Cox Street	Hudson	ABT-162	46775	42° 23' 58"/-71° 32' 45"	√
Lower Concord River	Rogers Street	Lowell	CND-009	46500	42°38' 11"/ -71°18' 05"	√
Upper Concord River	Route 225	Bedford	CND-110	46500	42°30' 33"/- 71°18' 48"	√
Lower Sudbury River	Route 20	Wayland	SUD-096	47650	42° 22' 24"/ -71° 22' 56"	√
Upper Sudbury River	Route 135 bridge	Ashland	SUD-237	unnamed	42° 15' 31"/ -71° 27' 20"	√

Figure 2: SuAsCo Watershed and 2019 Bacteria Sampling Sites

Water Quality Sampling

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. In March, May, September, and November, only selected sites are sampled (due to funding limitations). 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 1:00pm. 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, and suspended solids samples were taken using bottles supplied by the state-certified laboratory 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 24 hours of collection and analyzed within their respective hold-times. Chlorophyll-*a* samples were delivered to the laboratory within 4 hours of sampling and analyzed within their hold-times. *In-situ* readings of temperature, dissolved oxygen, pH, and conductivity were taken using multi-function YSI 6-series meters (pre- and post-calibration 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 field blanks of distilled water were taken for 10% of samples. Table 3 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 3: Sampling and Analysis Methods

Parameter	Analysis Method #	Equipment Range/ Reporting Limits	Sampling Equipment	Laboratory
Temperature	---	-5 – 45 degrees C	YSI 6-series	---
pH	---	0 – 14 units	YSI 6-series	---
Dissolved oxygen	---	0 – 50 mg/L	YSI 6-series	---
Conductivity	---	0 – 1000 µS/cm	YSI 6-series	---
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
ortho-Phosphate	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	2 – 100 µg/L	bottle	Alpha Analytical

Water quality measurements were compared with the Massachusetts Water Quality Standards (Mass DEP, 2017). All segments of the Assabet are designated Class B/warm water fisheries. The Concord River from the confluence of the Assabet and Sudbury to the Billerica drinking water withdrawal is designated Class B warm water fishery/treated drinking water supply. From the Billerica withdrawal to Rogers Street in Lowell, the Concord is designated Class B warm water fishery, and the last segment (below OARS' last sampling site) from Rogers Street in Lowell to its confluence with the Merrimack is designated Class B (CSO)/warm water fishery. The Sudbury River from the outlet of Cedar Swamp Pond to Fruit Street, Hopkinton (not monitored as part of this project) is designated Class B/Outstanding Resource Water. From Fruit Street to the outlet of Saxonville Pond, Framingham, the Sudbury is designated Class B/warm water fishery. From the outlet of Saxonville Pond to its confluence with the Assabet, the Sudbury is designated Class B/aquatic life. All of the tributary streams assessed in this project are designated Class B waters. (For a list of SuAsCo stream segment designations, see Appendix I.)

The Mass Division of Fisheries and Wildlife lists 34 tributary streams in the basin as Coldwater Fisheries Resources (CFRs) (Mass DFW, 2017), and Mass DEP identifies 27 tributary streams as CFRs in its Sustainable Water Management Initiative viewer (http://maps.env.state.ma.us/flexviewers/SWMI_Viewer/index.html). Since these and other tributary streams support or have supported cold water fisheries (Schlotterbeck, 1954), it is useful to compare tributary dissolved oxygen and temperature measurements with cold water fisheries standards. For nutrient concentrations (where the Massachusetts standard is narrative) results were compared with EPA "Gold Book" total phosphorus criteria (US EPA, 1986) (Table 4) and with summertime data for Ecoregion XIV subregion 59 (US EPA, 2000) (Table 5).

Table 4: Water Quality Standards and Guidance for Use Support (Mass DEP 2017)

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
pH	6.5 – 8.3 inland waters and Δ0.5 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	
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
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.	

Table 5: Reference Conditions for Ecoregion XIV (59) Streams (US EPA 2000)

Nutrient Parameter	Aggregate Nutrient Ecoregion XIV (subregion 59) Reference Conditions (25th percentile of June - September data)	Aggregate Nutrient Ecoregion XIV (subregion 59) Reference Conditions (50th percentile of June - September data)
Total Phosphorus	25 μg/L	50 μg/L
Ortho-phosphate	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

River Reaches and Tributaries

For data analysis, the water monitoring sites are divided into sections (waterbodies in Table 1): (1) the upper Assabet mainstem, (2) the lower Assabet mainstem, (3) the Concord River mainstem, (4) the Sudbury River mainstem, (4) the Assabet headwater and all tributary sites (except HBS-016), and (5) the Assabet River "impounded" sites. Because the headwaters site (ABT-312) is upstream of the first wastewater treatment plant discharge, it is reported separately from the other Assabet River mainstem sites and included with tributaries. Sites HOP-011 (Hop Brook), NTH-009 (North Brook), DAN-013 (Danforth Brook), ELZ-004 (Elizabeth Brook), NSH-047 (Nashoba Brook in Acton), and NSH-002 (Nashoba Brook) are all on tributaries to the Assabet River; RVM-005 (River Meadow Brook at Lowell) is on the largest tributary to the Concord River. HBS-016 (Hop Brook in Sudbury), a tributary to the Sudbury River, is reported separately from the other tributaries because it receives the discharge from the Marlborough Easterly wastewater treatment plant. Table 6 lists tributary and mainstem basin characteristics calculated using USGS's StreamStats program.

Table 6: StreamStats Drainage Basin Statistics

	Statistics at Mouth of Tributary[a]				
Headwater & Tributary Streams	Latitude/Longitude at Mouth	Drainage Area (sq.mi.)	Stratified Drift Area (sq.mi.)	% area stratified drift	Slope [b] (%)
Assabet at Maynard St., Westboro	42.2741/-71.6322	6.79	1.64	24.15	3.61
Cold Harbor Brook, Northboro	42.3238/-71.6413	6.86	1.97	28.72	5.01
Danforth/ Mill Brook, Hudson	42.3897/-71.5666	7.17	2.06	28.73	3.58
Elizabeth Brook, Stow	42.4217/-71.4776	19.09	6.93	36.30	3.73
Fort Meadow Brook, Hudson	42.3975/-71.5169	6.25	1.76	28.16	3.77
Hop Brook, Northboro/Shrewsbury	42.2887/-71.6449	7.87	2.09	26.56	3.57
Hop Brook, Sudbury	42.3627/-71.3733	22.0	13.4	61.14	2.44
Nashoba Brook, Concord	42.4592/-71.3942	48.05	19.05	39.65	2.29
North Brook, Berlin	42.3576/-71.6188	16.89	4.12	24.39	4.38
River Meadow Brook, Lowell	42.6318/-71.3087	26.32	16.18	61.47	1.91
Mainstem Rivers	Statistics near Mouth of River[a]				
Assabet River, Concord	42.4652/-71.3596	177.81	73.00	41.06	3.01
Sudbury River, Concord	42.4637/-71.3578	162	49.13	30.33	2.52
Concord River, Lowell	42.6351/-71.3015	400.0	197.97	49.49	2.63

[a] Calculated using USGS's StreamStats program (http://ststdmamrl.er.usgs.gov/streamstats/)
[b] Slope is the mean basin slope calculated from the slope of each grid cell in the designated sub-basin.

Long-term Trend Analysis 1992-Present

Summer (June, July, and August only) trends have been analyzed for most parameters. In general, these analyses are based on summaries for the river sections outlined above. 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 7 lists the long-term sites used and their sections.

The statistical significance of apparent trends was evaluated using a single-season Mann-Kendall test (Helsel et al., 2006) computed on flow-weighted concentration (using a locally weighted scatterplot smoothing - LOWESS). Flow data for the LOWESS smoothing was sourced from the USGS gage in Maynard for the Assabet River and Tributaries, from the USGS gage at Sudbury Landing (Saxonville) for the Sudbury, and from the USGS gage at Rogers Street for the Concord. Trends are deemed significant if the absolute value of the Kendall tau statistic is greater than 0.20 and the p value is less than 0.05.

Table 7: 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
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
	ABT-280					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-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
	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
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
	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
	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
	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
	CND-045																	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
	CND-161													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
	SUD-064																		X	X	X	X	X	X	X	X	X	X	X
	SUD-086																		X	X	X	X	X	X	X	X	X	X	X
	SUD-096																		X	X	X	X	X	X	X	X	X	X	X
	SUD-098																		X	X	X	X	X	X	X	X	X	X	X
	SUD-144																		X	X	X	X	X	X	X	X	X	X	X
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
Tributary Streams	HOP-011											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
	DAN-013											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
	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
	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
	NSH-002											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Hop Sudbury	HBS-016																		X	X	X	X	X	X	X	X	X	X	X

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

Bacteria Sampling Methods

Trained volunteers collected bacteria water samples at six sites throughout the watershed (Table 2 and Figure 2). OARS selected the six sites based on the Mass DEP 303d list of river segments impaired by bacteria (Mass DEP, 2017b) and current OARS water quality monitoring sites. Bacteria monitoring was conducted each Monday morning from June to September between 6:00am and 7:00am. *E. coli* samples were taken using sterile bottles supplied by the state certified laboratory 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 4 hours of collection and analyzed within 6 hours. 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 mid-depth where possible, by wading or using a pole. Duplicate field samples and field blanks of distilled water were taken for 10% of the samples. Table 8 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 8: 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

Bacteria measurements were compared with the standards defined by Mass DEP 314 CMR 4.00 (Mass DEP, 2017) outlined in Table 9. All of the sites are designated Class B Non-bathing.

Table 9: Fecal Indicator Bacteria Standards (Mass DEP 2017)

Parameter	Water Class	Designation	Geometric Mean	Single Sample
E. coli	Class A/B	Primary contact - Bathing	126 CFU/100mL (most recent 5 samples)	235 CFU/100mL
	Class A/B	Primary contact – Non bathing	126 CFU/100mL (previous 6 months)	235 CFU/100mL
	Class C	Secondary contact - boating	630 CFU/100mL (previous 6 months)	1260 CFU/100mL (10% of samples)

Precipitation and Streamflow

According to the Massachusetts Water Resources Commission, precipitation conditions were near or above normal for all months in 2018 and 2019 except the following two periods. In June to mid-July 2018 conditions were abnormally dry, but not drought (Mass DCR, 2018). In September to mid-October 2019 the Standardized Precipitation (SPI) and Keetch-Byram (KBDI) indexes both showed elevated severity drought conditions (Mass DCR, 2019).

Precipitation, and the associated increased stormwater runoff and streamflow changes, are correlated with concentrations of total suspended solids, total phosphorus, and nitrate/nitrites. 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 10). Samples collected on a rising hydrograph may include "first flush" runoff and the associated pollutants. Note that flow at the Sudbury River gage in Saxonville/Framingham is sometimes affected by dam manipulations upstream. Rainfall data were downloaded from the National Weather Service's Worcester Airport station (https://www.ncdc.noaa.gov/cdo-web/search). Sampling events that were preceded by more than 0.1 inches of rain (the standard definition of a "wet" weather sampling) are highlighted.

Table 10: Hydrographic and Precipitation Data 2018-2019

	Hydrograph at USGS gage			Precipitation (inches)	
Sampling Date	Assabet River at Maynard	Sudbury at Framingham	Concord at Lowell	Previous 2 calendar days (48 hrs)	Sampling day (incl. hrs. after sampling)
28-March, 2018	Flat	Rising	Falling	0	0
20-May, 2018	Flat	Rising	Flat	0.26	0.09
17-June, 2018	Falling	Rising	Flat	0.02	0
22-July, 2018	Falling	Flat	Flat	0	0.68
19-August, 2018	Flat	Flat	Falling	1.15	0.01
23-Sept, 2018	Falling	Falling	Falling	0.10	0
11-Nov, 2018	Rising	Flat	Flat	1.12	0
13-March, 2019	Flat	Flat	Rising	0	0
19-May, 2019	Falling	Falling	Falling	0.14	0.01
16-June, 2019	Falling	Falling	Falling	0	0.45
7-July, 2019	Rising	Falling	Flat	1.22	0
11-August, 2019	Falling	Falling	Flat	0	0
22-Sept, 2019	Falling	Falling	Falling	0	0
10-Nov, 2019	Falling	Falling	Falling	0	0

Figure 3: Daily rainfall with sampling dates (May-Sep 2018/2019)

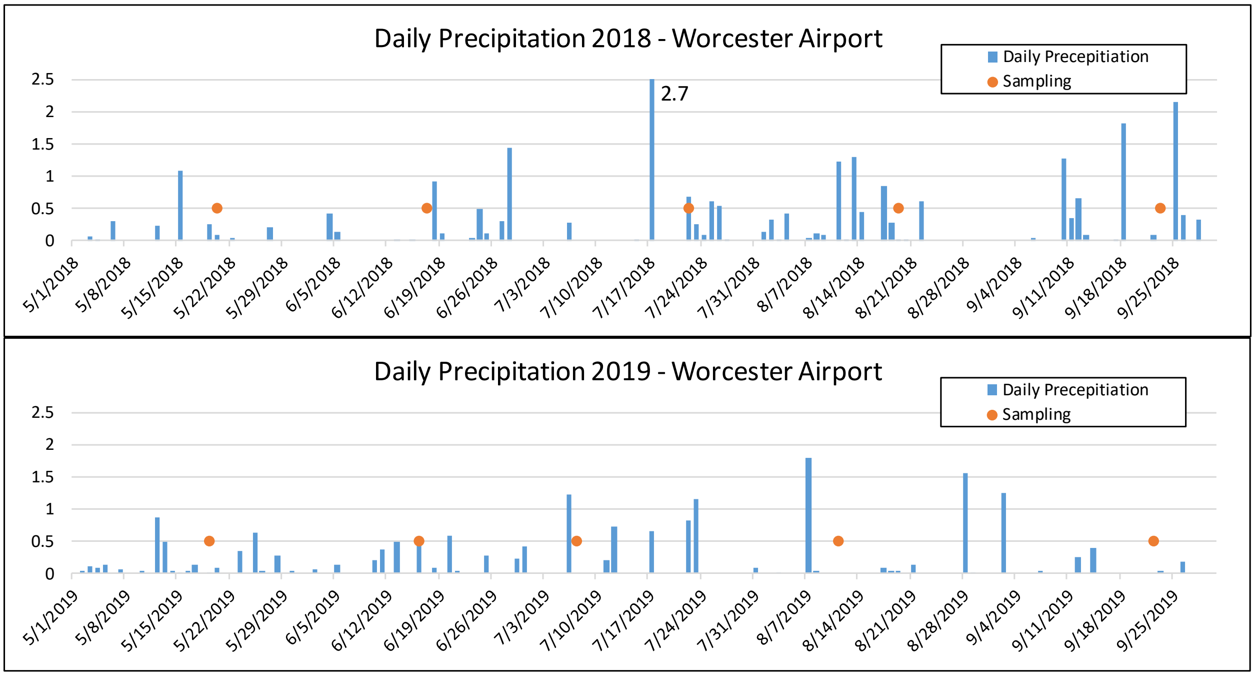


Figure 4 and Figure 5 show mean daily streamflow for May through September at the Assabet River and Sudbury River gages compared with the historic mean of the daily streamflow for the period of record. Hydrographs for the Concord River gage in Lowell and the Nashoba Brook gage in Acton are included in Appendix II. The Concord River is mainly a reflection of the combined flows of the Assabet and Sudbury, and Nashoba Brook is a lesser tributary. In 2018, the dry conditions in June caused all streamflow to fall well below averages through the end of June. For the rest of the season, flows fluctuated from low to high. Nashoba Brook and the Sudbury River, in particular, had many repeated short periods of very low flow. In 2019, all of the rivers generally maintained near or above average flows, supported by the high groundwater levels, except during the drought conditions in September. Figure 6 shows year-on-year average summer streamflow for the Assabet and Sudbury since 1992.

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 13.46 cfs to the river from May through September 2018 and 15.29 cfs from May through September 2019 (EPA, 2020). This compares with the average flows for this period at the Assabet River gage of 150 cfs, but minimum gage flow was 24 cfs in 2018 and 21 cfs in 2019. Since the WWTP flows are fairly stable, there are times when they may represent > 50% of total flow.

Monthly streamflow was also recorded at five tributary monitoring sites and near the Assabet River headwaters, above the first wastewater discharge.

Figure 4: Mean Daily Streamflow, Assabet River, 2018-2019

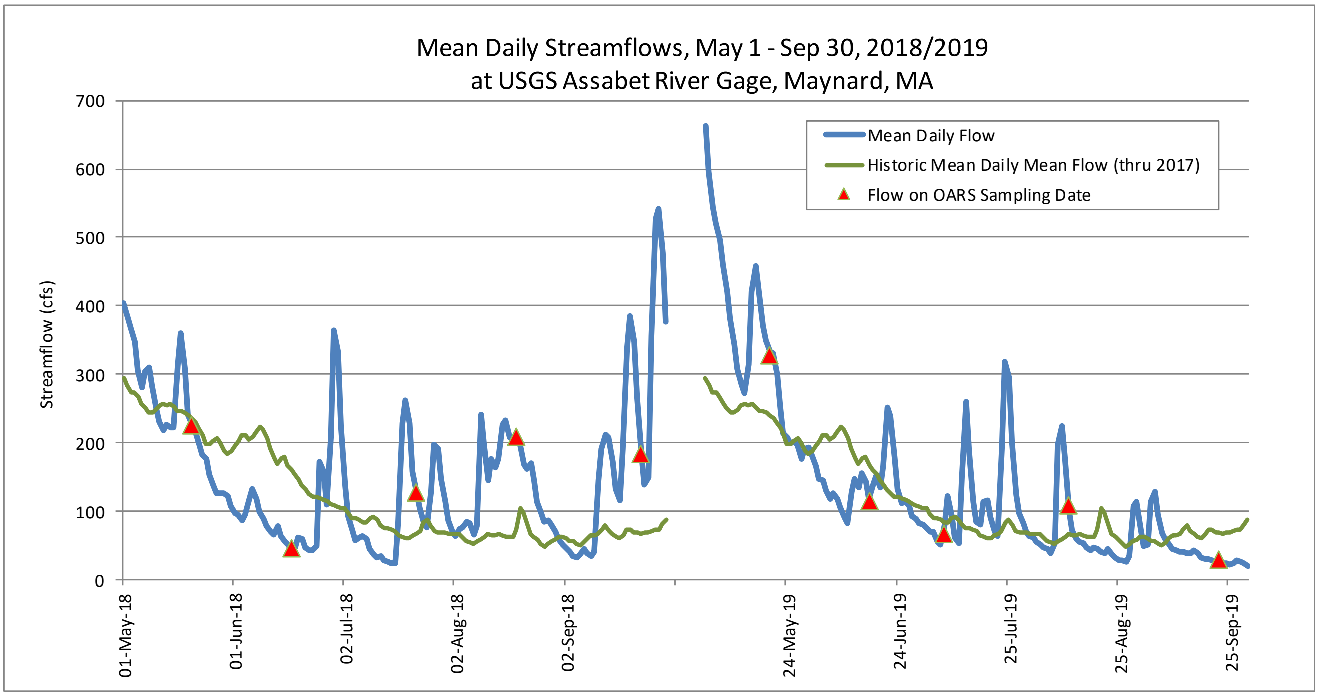


Figure 5: Mean Daily Streamflow, Sudbury River, 2018-2019

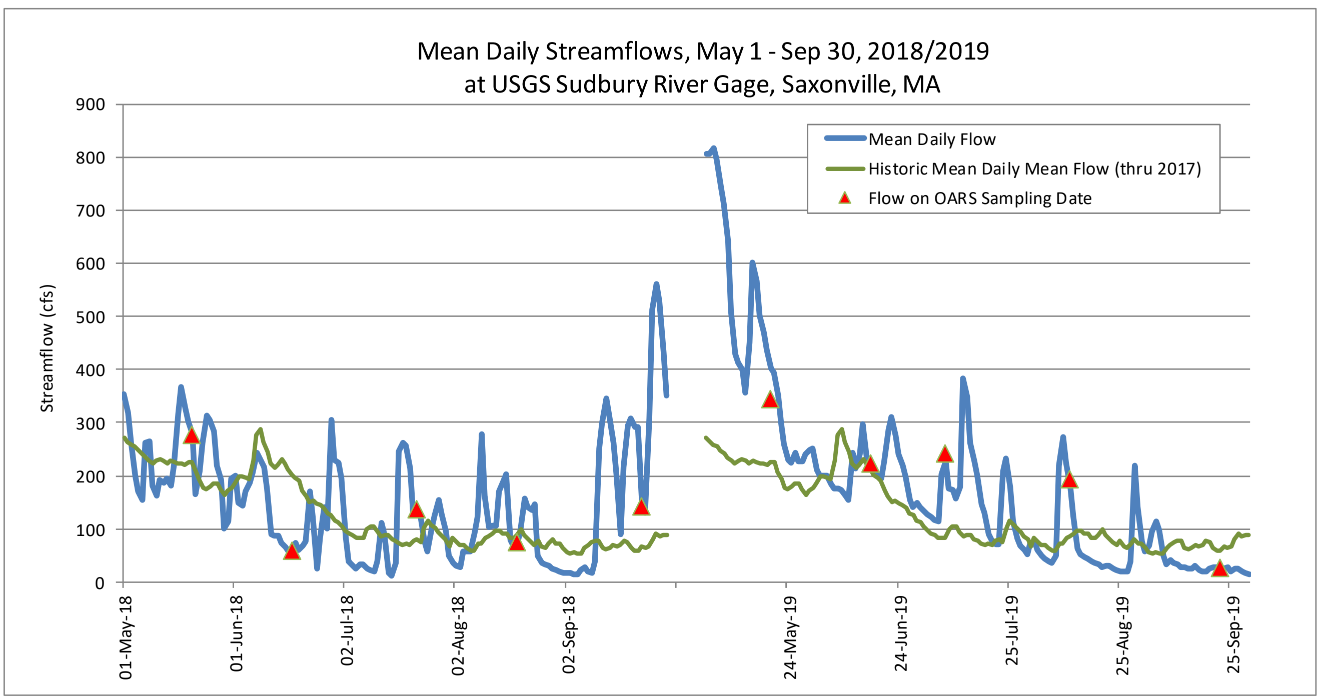


Figure 6: Average summer streamflow (June/July/August)

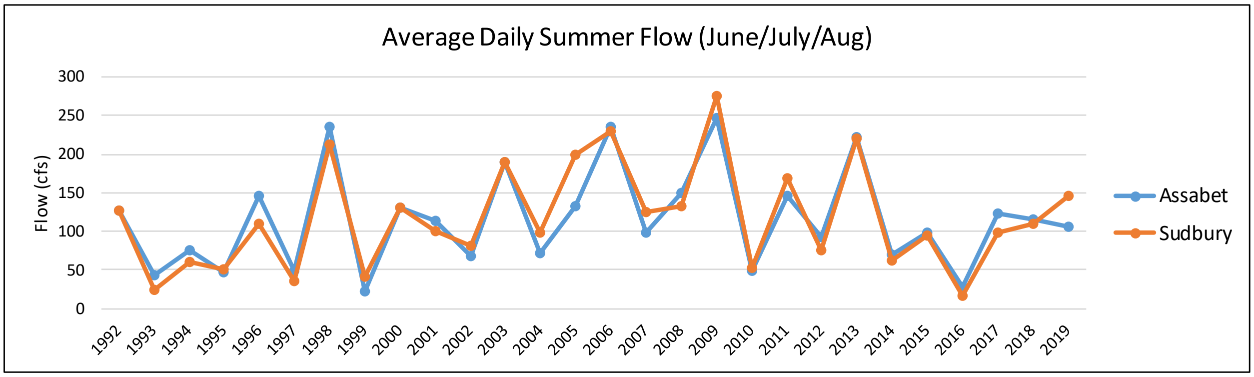
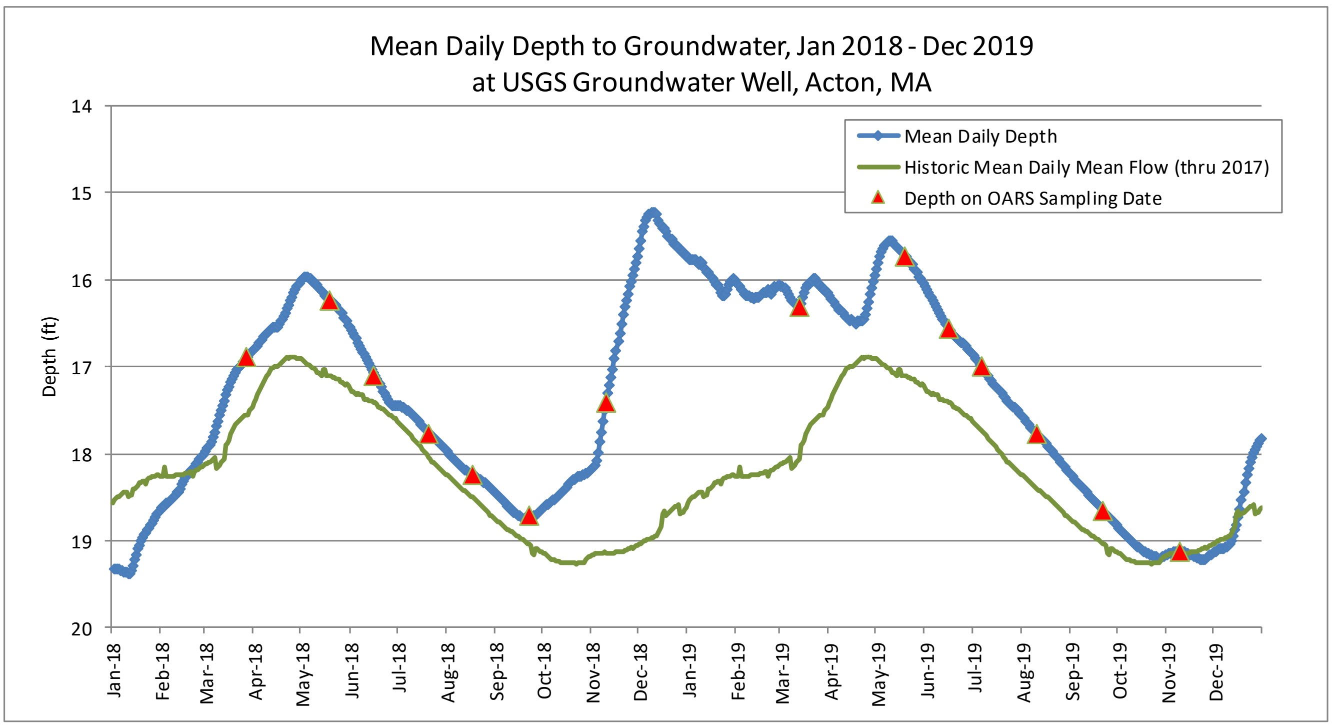


Figure 7 shows groundwater levels in 2018 and 2019 compared with historic mean levels from the USGS monitoring well in Acton (USGS 422812071244401 MA-ACW 158 ACTON, MA). Groundwater levels were above average for most of this period, with exceptionally high levels in the first half of 2019. Changes in groundwater levels reflect precipitation and evapo-transpiration rates and, in turn, affect baseflow to the streams.

Figure 7: Groundwater Levels (USGS Monitoring Well Acton, MA)



Water Quality Results

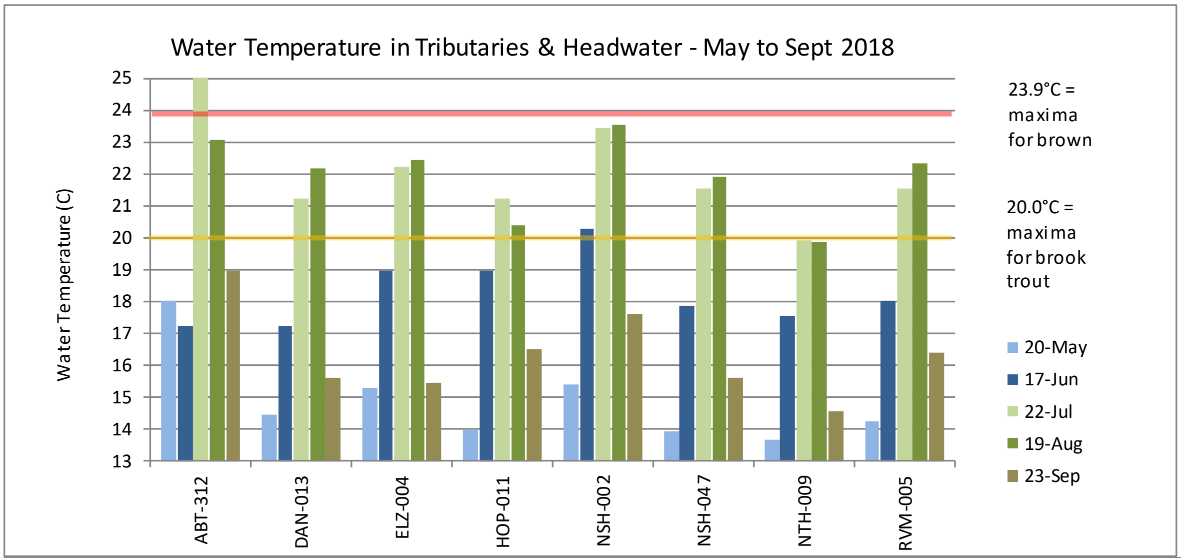
Reach and tributary statistics are summarized in tabular form in Appendix III. Individual parameters are discussed here. Note that for most analyses, we are switching from reporting median statistics to mean statistics, because most of the statistics are only summarizing 3 or 4 sites. Mean statistics can be more informative given the small number of data points. In previous years we reported median statistics.

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 2018 and 2019. In July of 2019, two sites on the Concord (CND-045 and CND-110) came close to this threshold with temperatures above 27°C. 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 (20.0°C). The recommended single-reading maxima for brook trout is 20.0°C and for brown trout is 23.9°C. Most sites exceeded 20°C in July and August of both years (Figure 8). In 2018, only ABT-312 exceeded the 23.9°C threshold, but in 2019 ABT-312, ELZ-004, and NSH-002 all exceeded it.

Year-on-year comparisons of temperature data show very little statistical change in water temperatures for the period of record (Figure 9). Trend lines are level for most sections except the Headwater & Tributaries and Concord sections. The Headwater & Tributaries section seems to show an upward trend in water temperatures since 2002 of about 0.05°C per year. An analysis by site also shows that this upward trend does seem to be present for this time period for most of the sites in this category (Figure 10). However, looking at a longer time period for the one Headwater & Tributary site that we have data back to 1992 shows less of an upward trend – only 0.007°C per year (Figure 11) and a Mann-Kendall flow-weighted statistical analysis returns no significant trend for either Headwaters & Tributaries or Concord (Table 11).

Figure 8: Temperatures in Tributaries and Headwater



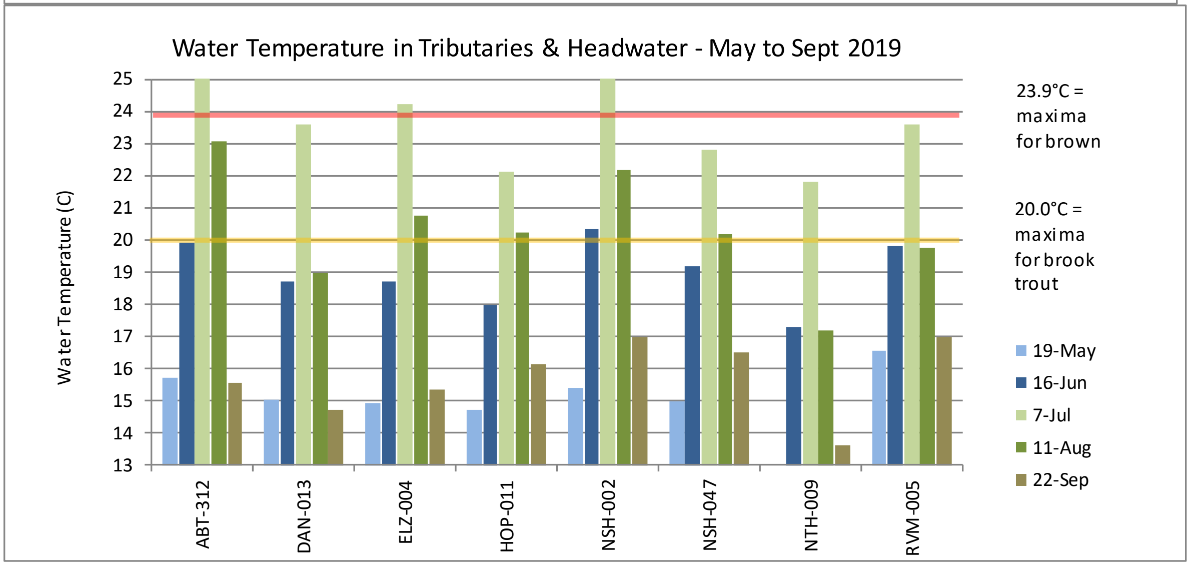


Figure 9: Year-on-year mean summer water temperature by section (June/July/August)

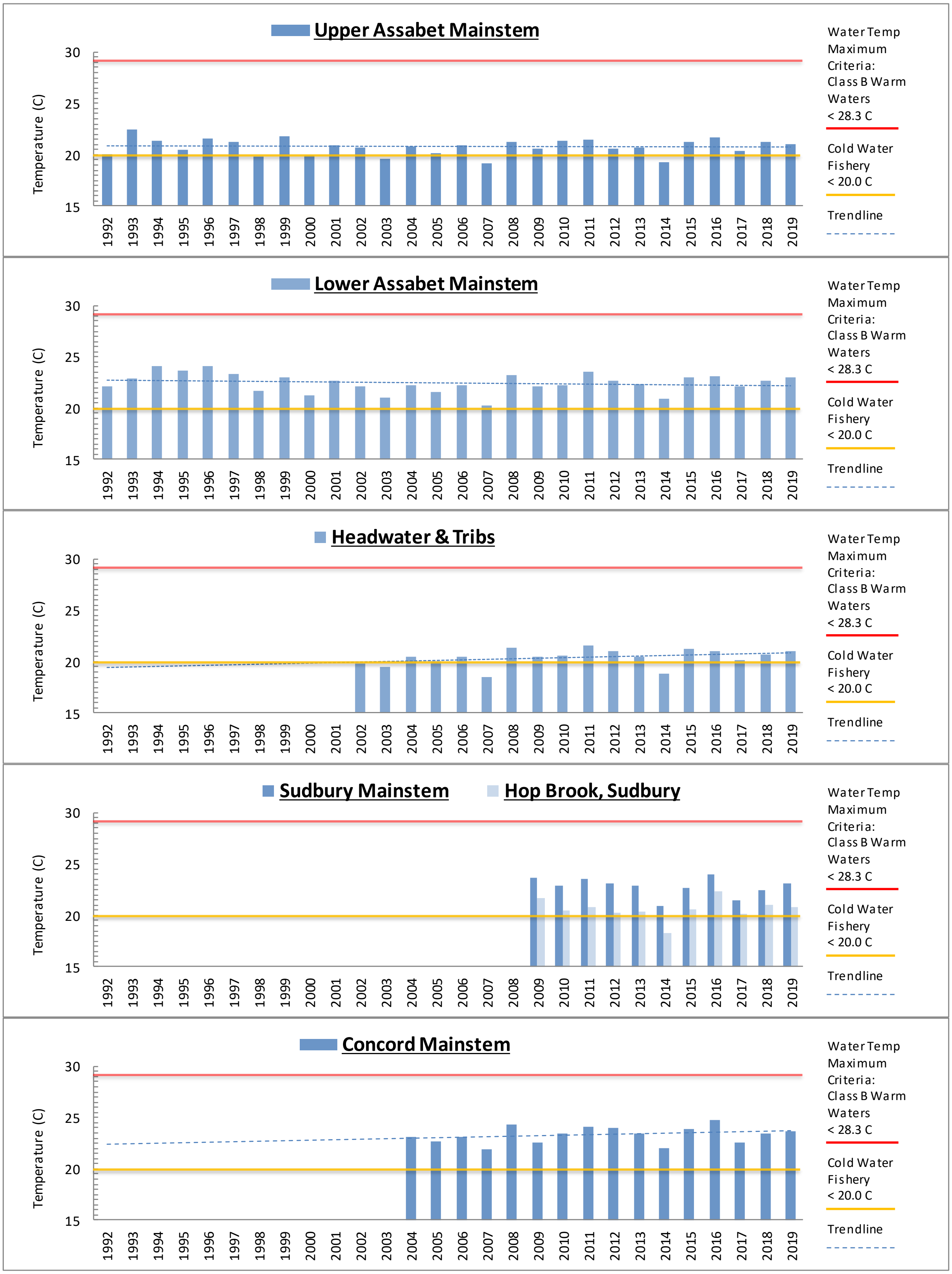


Figure 10: Year-on-year mean summer water temperatures for selected Head & Trib. Sites

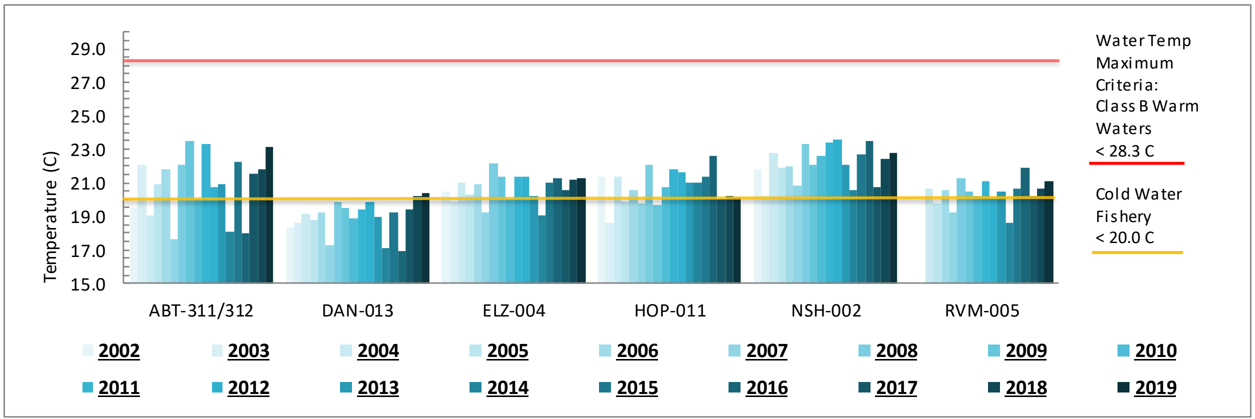


Figure 11: Year-on-year mean summer water temperatures for Assabet Headwater

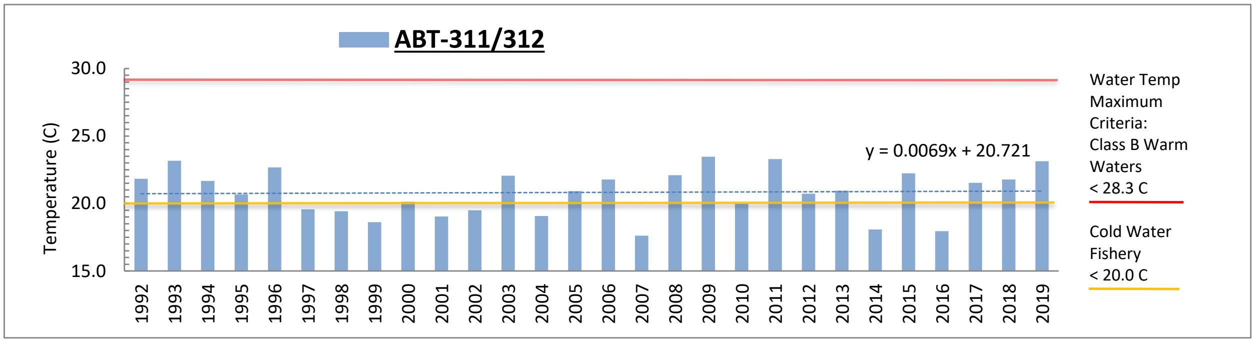


Table 11: Mann-Kendall trend analysis for water temperature

Mann-Kendall test		flow-weighted
	Head&Tribs	**Concord**
years	2002-2019	2004-2019
tau	0.076	0.076
p	0.4204	0.4500
trend	NST	NST

pH

In 2018 and 2019, all measurements met the Class B standards for pH, with readings ranging from 6.57 to 7.97. ABT-062 (Rt. 62 canoe access downstream of the Maynard WWTP) was a consistent outlier, with the highest values each year (7.81 in 2018 and 7.97 in 2019) (Figure 12). In general, the Assabet consistently had higher pH values than the other rivers (Figure 13).

Year-on-year analysis of summer pH shows a visible upward trend in pH for the Assabet and tributaries (Figure 14). Mann-Kendall analysis confirms this as a statistically significant upward trend (Table 12). This seems to be driven by high pH values between 2012 and 2018. In 2019, pH was lower in all sections except the Sudbury. There are not enough data yet for the Concord and Sudbury to see any trends.

Figure 12: pH by site Upper and Lower Assabet

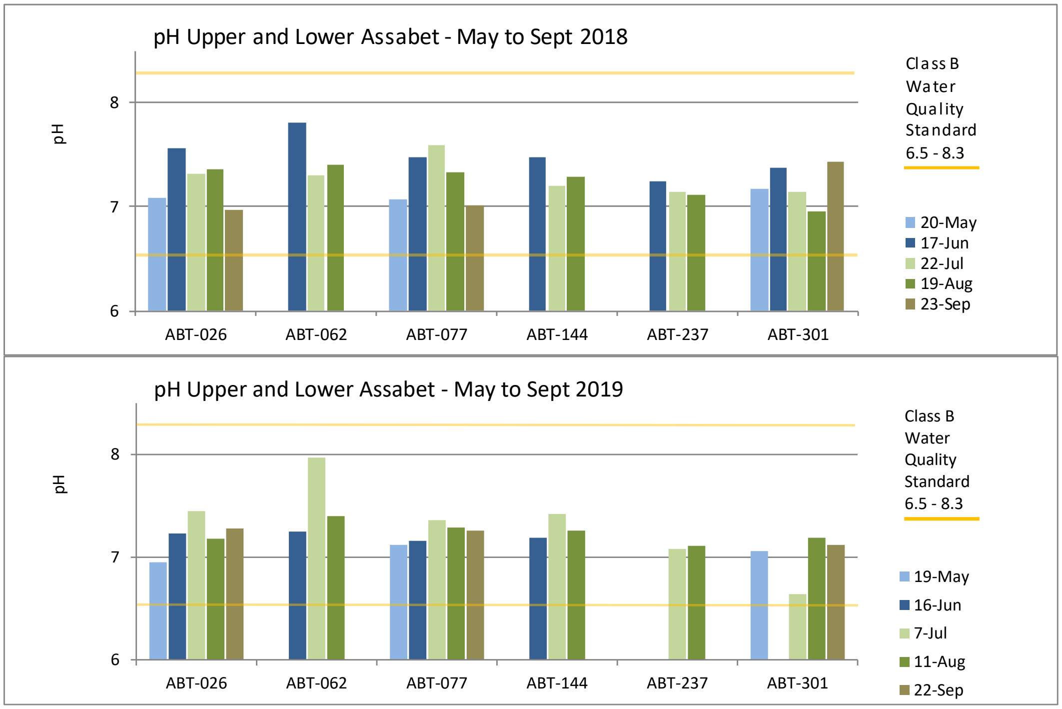


Figure 13: Mean pH by Section 2018/2019

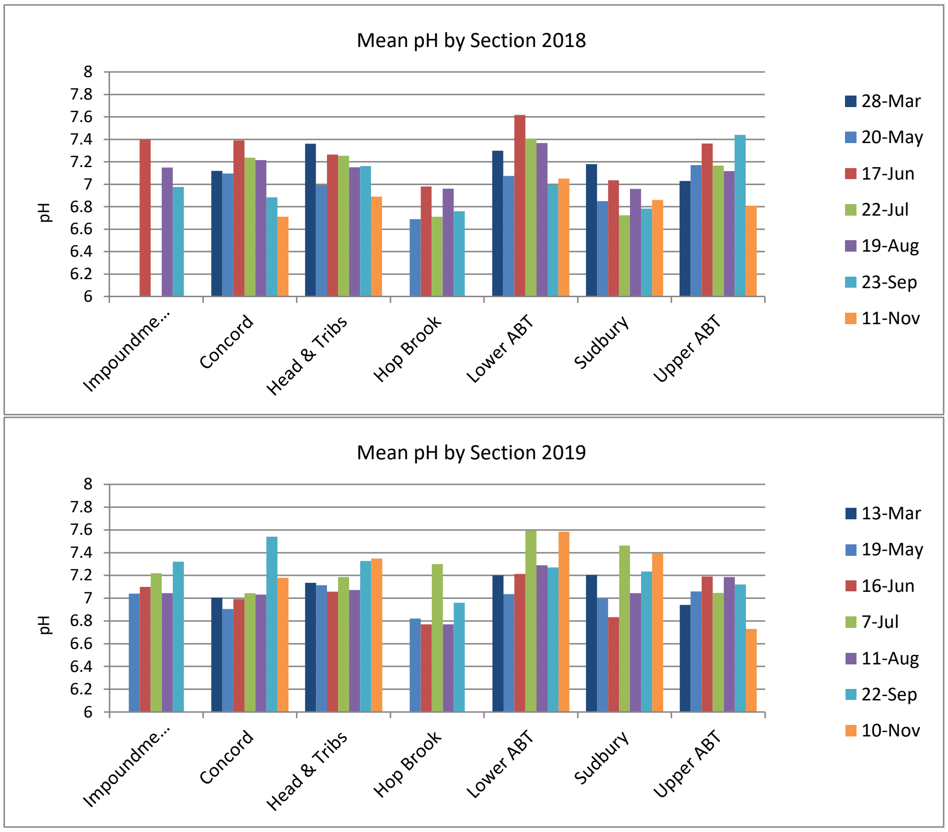


Figure 14: Year-on-year mean summer pH by section (June/July/August)

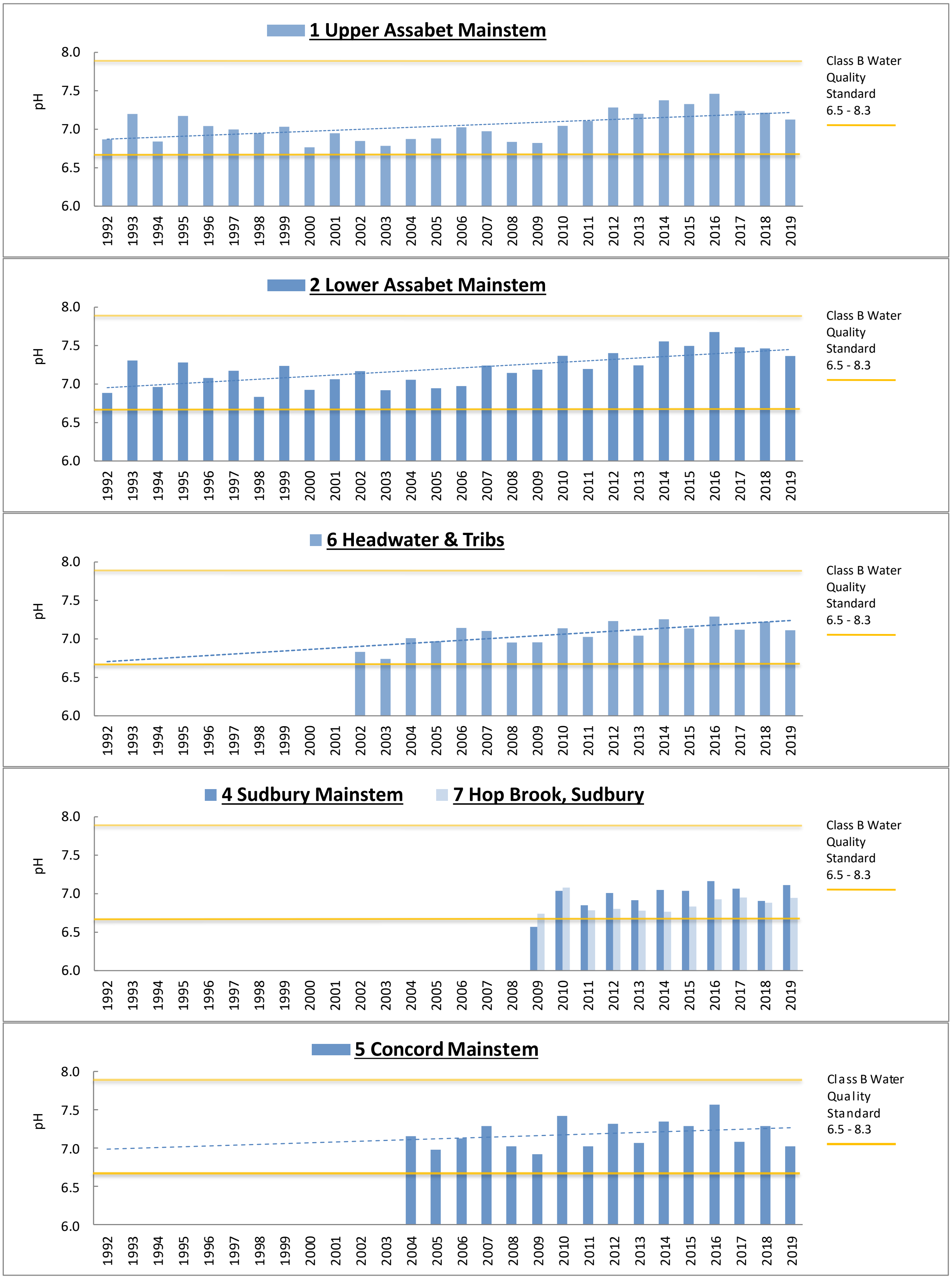


Table 12: Mann-Kendall trend analysis of pH

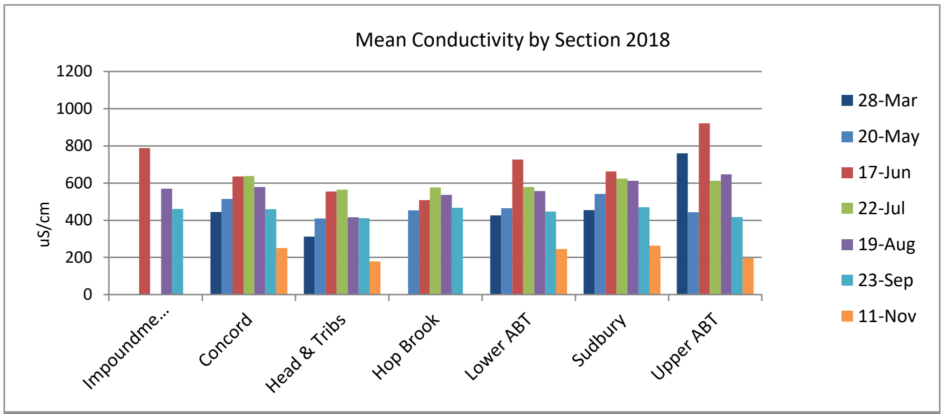
Mann-Kendall test		flow-weighted	
	Upper ABT	**Lower ABT**	**Head&Tribs**
years	1992-2019	1992-2019	2002-2019
tau	0.304	0.448	0.451
p	0.0000	0.0000	0.0000
trend	**upward**	**upward**	**upward**

Conductivity

Conductivity is an indirect indicator of pollutants such as effluent, non-point source runoff (especially road salts), and erosion. EPA studies of inland fresh waters (http://water.epa.gov/type/rsl/monitoring/vms59.cfm) indicate that streams supporting good mixed fisheries have a range between 150 and 500 µS/cm. The range of mainstem conductivity readings was 243 - 915 µS/cm in 2018 and 354 - 900 µS/cm in 2019, with the exception being ABT-301, which is just downstream of the Westborough water treatment plant, with values hitting 1005 µS/cm in 2018 and 1622 µS/cm in 2019. In 2019, ABT-301 exceeded 1000 µS/cm in 3 out of 7 sampling events. Among the tributary streams, the conductivity range was 103 – 1534 µS/cm for the two years. The lowest readings were in the North Brook and Danforth Brook. River Meadow Brook and the Assabet Hop Brook consistently had the highest readings, exceeding 1000 µS/cm multiple times.

Year-on-year analysis of conductivity levels shows an upward trend for the period of record for all sections, with peak conductivity levels in 2016 (Figure 18). A Mann-Kendall trend analysis confirms statistically significant trends for the Assabet, tributaries, and Concord (Table 13). A detailed analysis of the three sites with the highest conductivity levels shows the same upward trend (Figure 17). Even excluding the high 2016 levels, there is still a strong upward trend. This upward trend is concerning and deserves more study.

Figure 15: Mean conductivity by section (2018/2019)



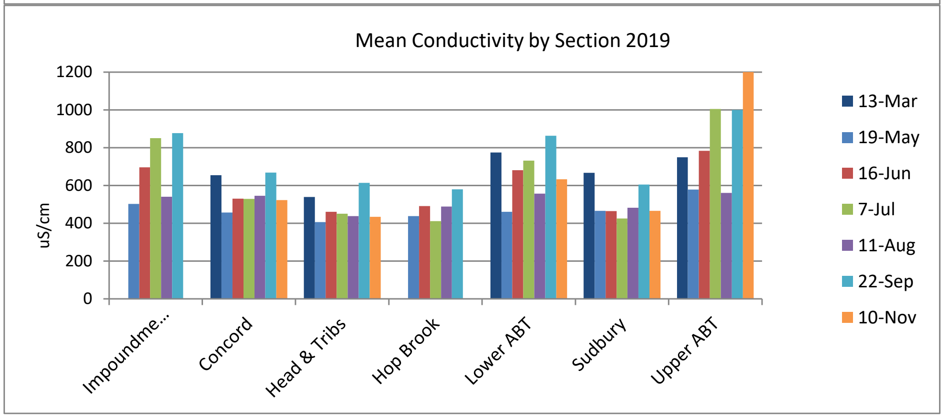


Figure 16: Tributary conductivity by site

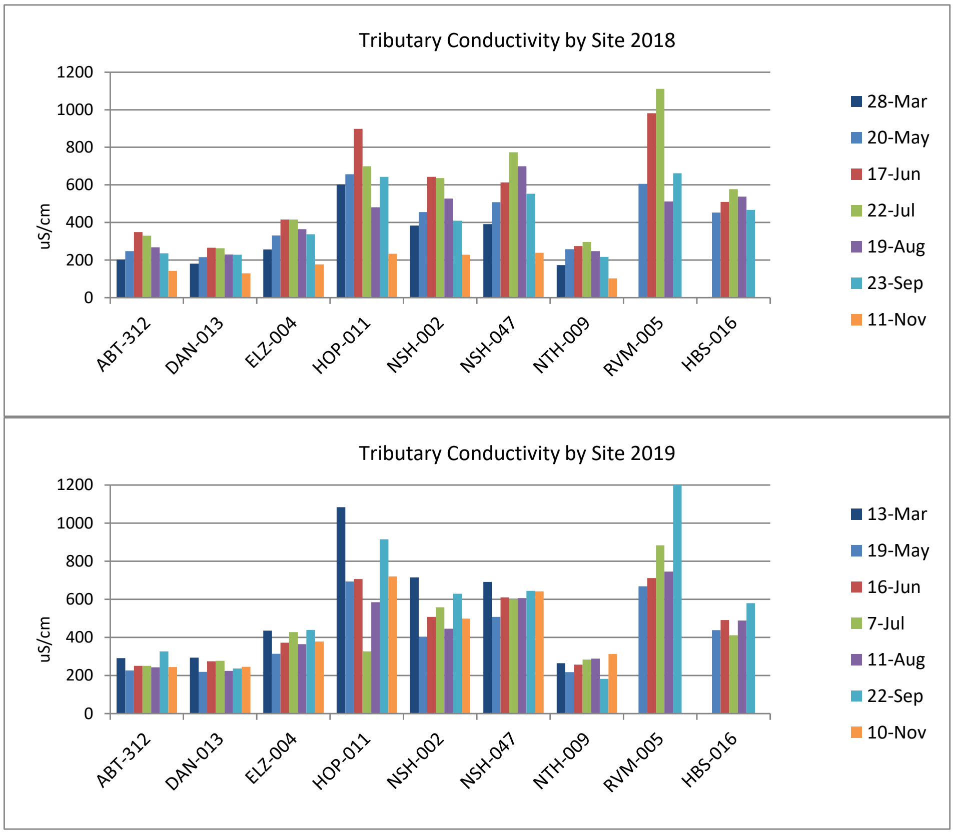


Figure 17: Year-on-year mean summer conductivity for selected sites (June/July/August)

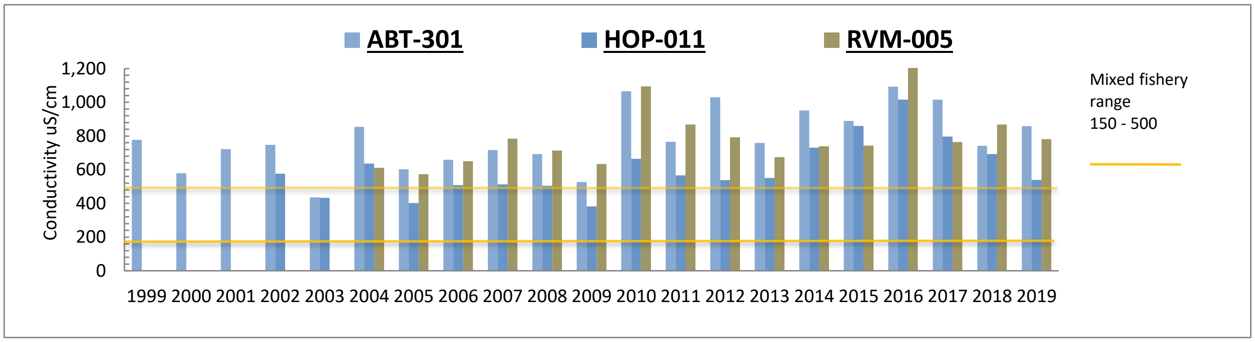


Table 13: Mann-Kendall trend analysis for conductivity

Mann-Kendall test		flow-weighted		
	Upper ABT	Lower ABT	Head&Tribs	Concord
years	1998-2019	1998-2019	2002-2019	2004-2019
tau	0.445	0.437	0.490	0.440
p	0.0000	0.0000	0.0000	0.0000
trend	upward	upward	upward	upward

Figure 18: Year-on-year mean summer conductivity by section (June/July/August)

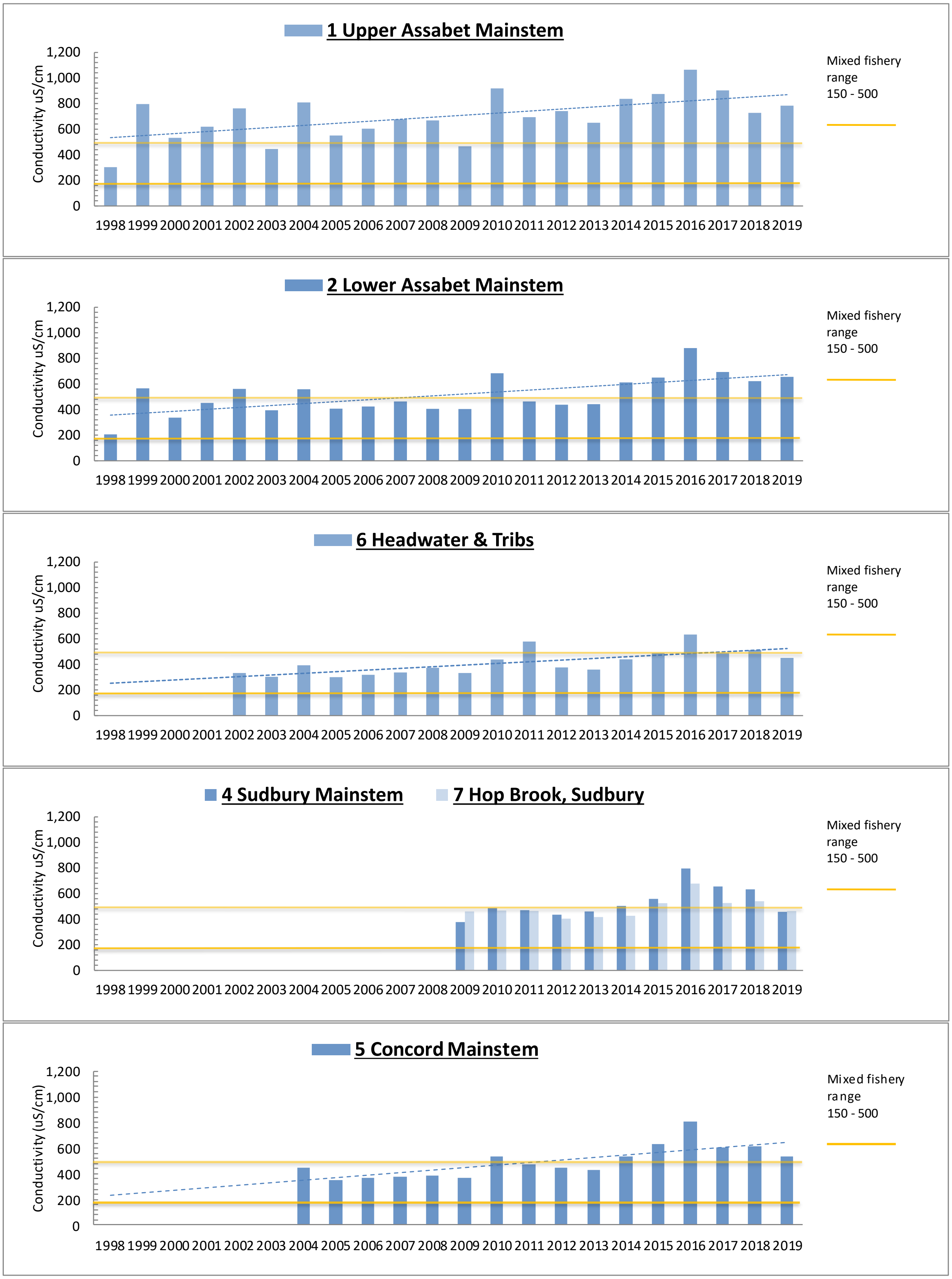
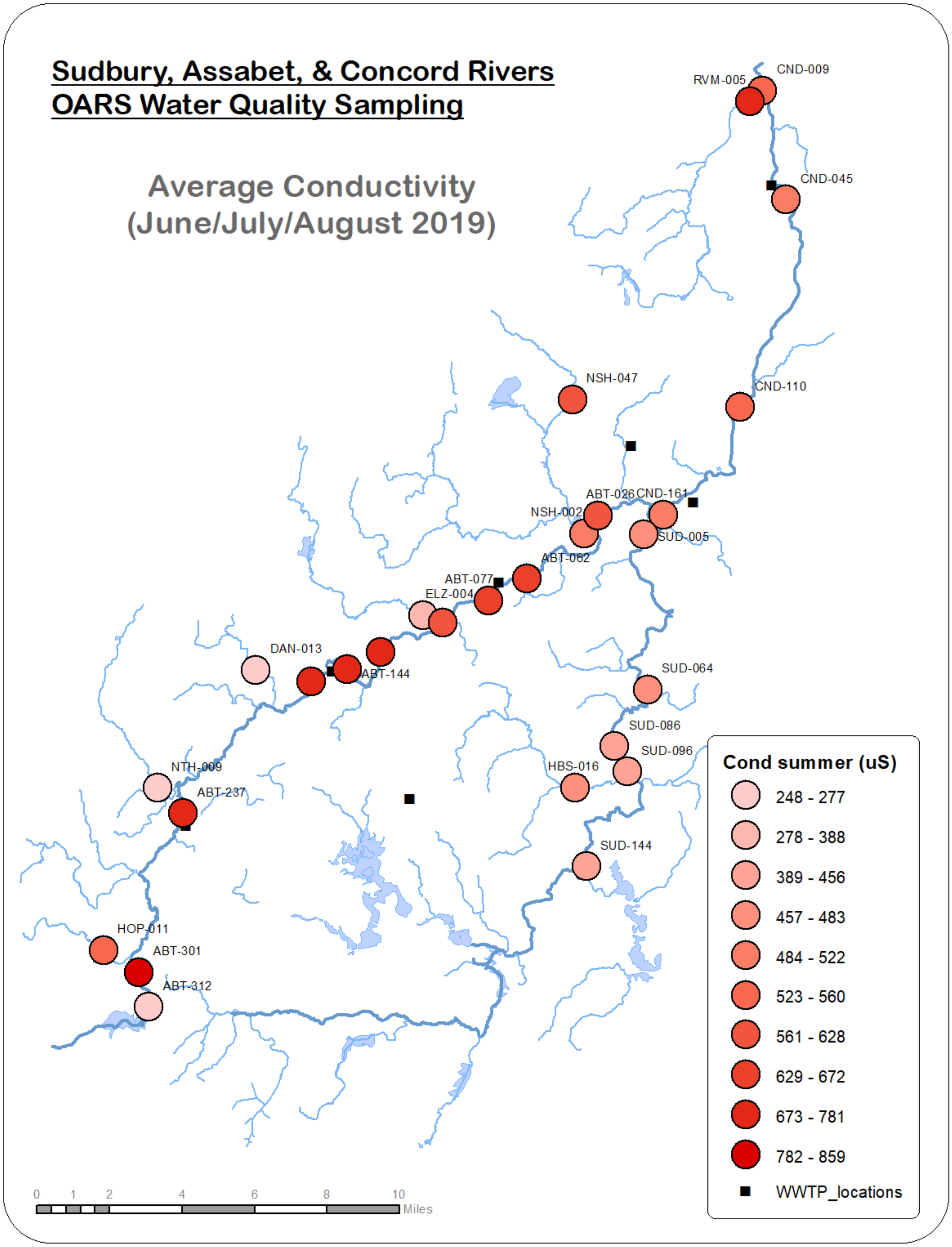


Figure 19: Map of 2019 average summer conductivity



Chloride

We started sampling for chloride in 2018 to measure the effect of road-salt application on the rivers. We sample in March (road-salt application season) and August (off-season) to capture peak and off-peak times (Figure 20). Chloride has generally proven to be higher in March, but there are exceptions. The North Brook (NTH-009) had higher chloride levels in August in both 2018 and 2019, and Nashoba Brook (NSH-002) had higher levels in August 2018 (Figure 21). 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 (US EPA, 2002). None of our rivers have exceeded the continuous criterion of 230 mg/L during the summer months, but several sites have exceeded it in the winter months. ABT-301 in the Upper Assabet just below the WWTP exceeded in 2018, and Hop Brook Northborough exceeds it every year. These are both sites that have also exhibited consistently high conductivity levels. The fact that August chloride levels correlate well with March levels by site supports the hypothesis that road-salt is retained in soils and percolates out slowly over the summer. Lower flows and evaporation could explain high concentrations in August, but this would not explain why the sites with higher March levels also have higher August levels.

A comparison of chloride and conductivity shows an almost perfect relationship between the two, but it is interesting to see that the March 2018 signature was significantly different than all of the other sampling events, with the possible exception of November 2018 (Figure 22).

Figure 20: Mean Chloride by Section (2018/2019)

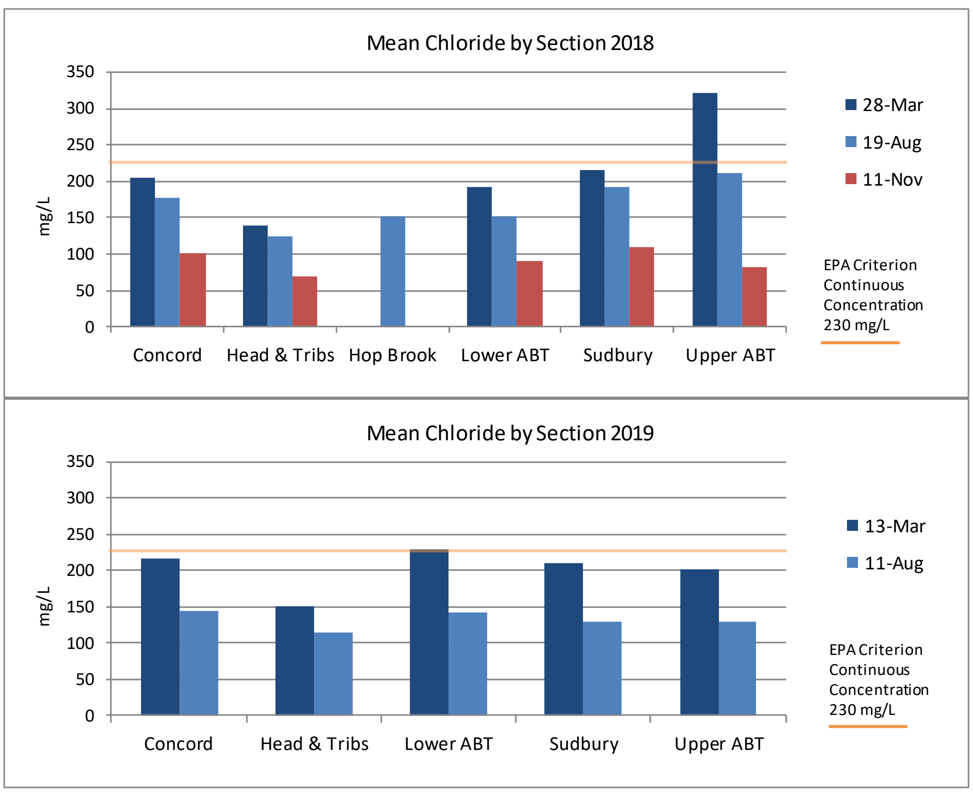


Figure 21: Chloride for Headwater and Tributary Sites (2018/2019)

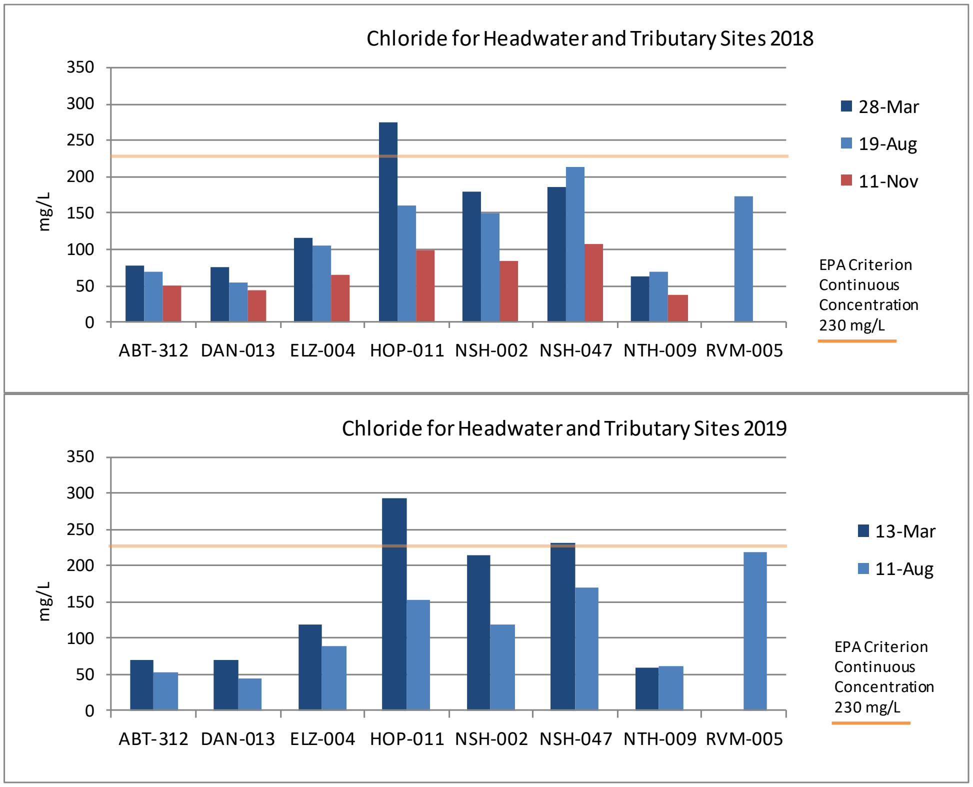
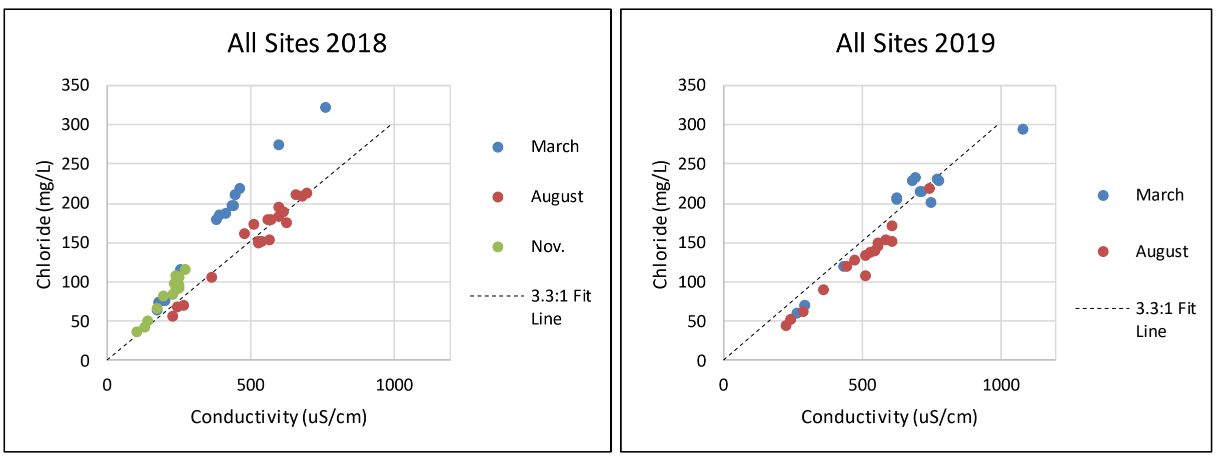


Figure 22: Chloride vs. Conductivity (2018/2019)



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. For 2018 and 2019, dissolved oxygen measurements in the Assabet and Concord Rivers met Water Quality Standards (>5.0 mg/L for Class B), except for 1 site in August 2018 and 4 sites in July 2019 (Table 14).

The Sudbury mainstem sites generally did not meet the Class B standards but did meet Class B Aquatic Life standards (>3.0 mg/L for Class B Aquatic Life for mainstem Sudbury sites), except for Sudbury at Sherman Bridge (SUD-064), which was generally below 3 mg/L (Table 14). Elizabeth Brook (ELZ-004) and Hop Brook Sudbury (HBS-016) also were consistently below the Class B standard. The low DO concentrations for the Sudbury are also shown in the graphs in Figure 23. Note that low DO measurements may not constitute a violation of WQS if caused by natural conditions.

Year-on-year analysis of dissolved oxygen shows a significant improvement in dissolved oxygen levels in the Assabet River in 2000 (Figure 24). This was likely a direct benefit of the phosphorus reductions in the Assabet from the WWTP improvements in 2000. OARS switched from measuring DO with the HACH titration method to YSI meters in 1998. Further improvements were made to the WWTPs in 2012, but the effect on DO levels was less pronounced. A Mann-Kendall trend analysis shows a significant upward flow-weighted trend for the period of record from 1992 to today but no significant trend for the period after the 2000 WWTP improvements, and no trend for any other river segments (Figure 25).

In situ readings (temperature, dissolved oxygen, conductivity, and pH) at the "impounded" sites (ABT-162, ABT-134, and ABT-095) show a consistent difference between impounded and non-impounded (free-flowing) sites (Table 15 and Table 16). Average temperature and DO levels were lower at the impounded sites in 2018 and 2019 by 2-10%. This difference was not seen in 2017 (possibly due to the switch from median to mean).

Table 14: Dissolved Oxygen concentrations by site 2018 and 2019 (mg/L)

2018	20-May	17-Jun	22-Jul	19-Aug	23-Sep
ABT-026	8.92	7.53	6.89	6.55	8.47
ABT-062		9.35	8.42	8.46	
ABT-077	9.51	7.74	7.35	7.84	8.47
ABT-095		9.06		5.21	7.56
ABT-134		10.43		5.37	7.65
ABT-144		9.18	8.02	7.88	
ABT-162		7.56		7.2	8.68
ABT-237		7.29	7.13	7.36	
ABT-301	9.21	8.16	7.07	7.08	9.19
ABT-312	9.7	6.38	7.83	7.62	9.45
CND-009	8.51	10.05	7.83	7.34	8.59
CND-045		9.58	8.56	7.68	
CND-110		9.04	7.23	5.31	
CND-161	5.59	7.05	5.9	4.38	6.23
DAN-013	9.88	8.76	7.22	8.24	9.32
ELZ-004	6.93	4.43	3.75	4.44	7.16
HBS-016	3.74	3.89	1.33	0.94	3.72
HOP-011	10.34	7.14	7.39	6.75	8.75
NSH-002	8.4	9.18	7.19	4.96	7.99
NSH-047	7.58	7.5	6.75	6.7	8.09
NTH-009	10.01	7.89	8.2	8.67	9.87
RVM-005	9.49	10.28	8.1	8.09	9.47
SUD-005	5.73	7.38	5.24	3.28	3.35
SUD-064	3.1	5.46	3.13	1.79	2.76
SUD-086	4.62	6.04	4.28	2.07	3.93
SUD-096	5.7	5.94	4.64	2.37	4.82
SUD-144	9.72	8.9	7.59	7.57	9.27

2019	19-May	16-Jun	7-Jul	11-Aug	22-Sep
ABT-026	10.25	8.22	6.45	6.98	7.22
ABT-062		9.12	8.11	8.24	
ABT-077	10.13	8.59	5.83	8.19	8.6
ABT-095	9.09	9.35	2.27	7.4	7.54
ABT-134	9.18	7.95	4.26	7.32	10.07
ABT-144		9.03	6.06	14.79	
ABT-162	9.78	8.43	5.1	9.19	6.74
ABT-237		7.57	6.14	6.97	
ABT-301	9.92	7.69	5.56	7.15	7.11
ABT-312	10.28	7.84	7.05	7.72	9.04
CND-009	9.73	8.19	7.46	7.51	9.6
CND-045		8.13	7.01	7.79	
CND-110		6.04	4.86	6.23	
CND-161	8.93	5.25	4.34	5.48	8.57
DAN-013	10.06	8.89	8.18	9.07	8.37
ELZ-004	8.09	5.58	3.81	7.13	4.8
HBS-016	4.19	2.77	1.32	1.74	5.84
HOP-011	11.72	8.83	5.68	7.61	9.76
NSH-002	10.07	8.48	7.19	6.39	1.85
NSH-047	8.91	7.21	5.98	6.7	8.35
NTH-009	10.69	8.52	7.67	8.69	9.91
RVM-005	9.51	8.57	7.11	8.33	9.6
SUD-005	7.29	4.73	3.43	4.64	9.13
SUD-064	7.52	2.14	1.82	2.02	6.69
SUD-086	7.53	3.76	3.03	3.24	6.59
SUD-096	7.73	4.61	3.17	3.45	7.75
SUD-144	8.84	9.69	7.86	8.22	8.39

*Shaded entries indicate readings not meeting stream standards.

Figure 23: Mean Dissolved Oxygen by section (2018/2019)

Figure 24: Year-on-year mean summer Dissolved Oxygen by section (June/July/August)

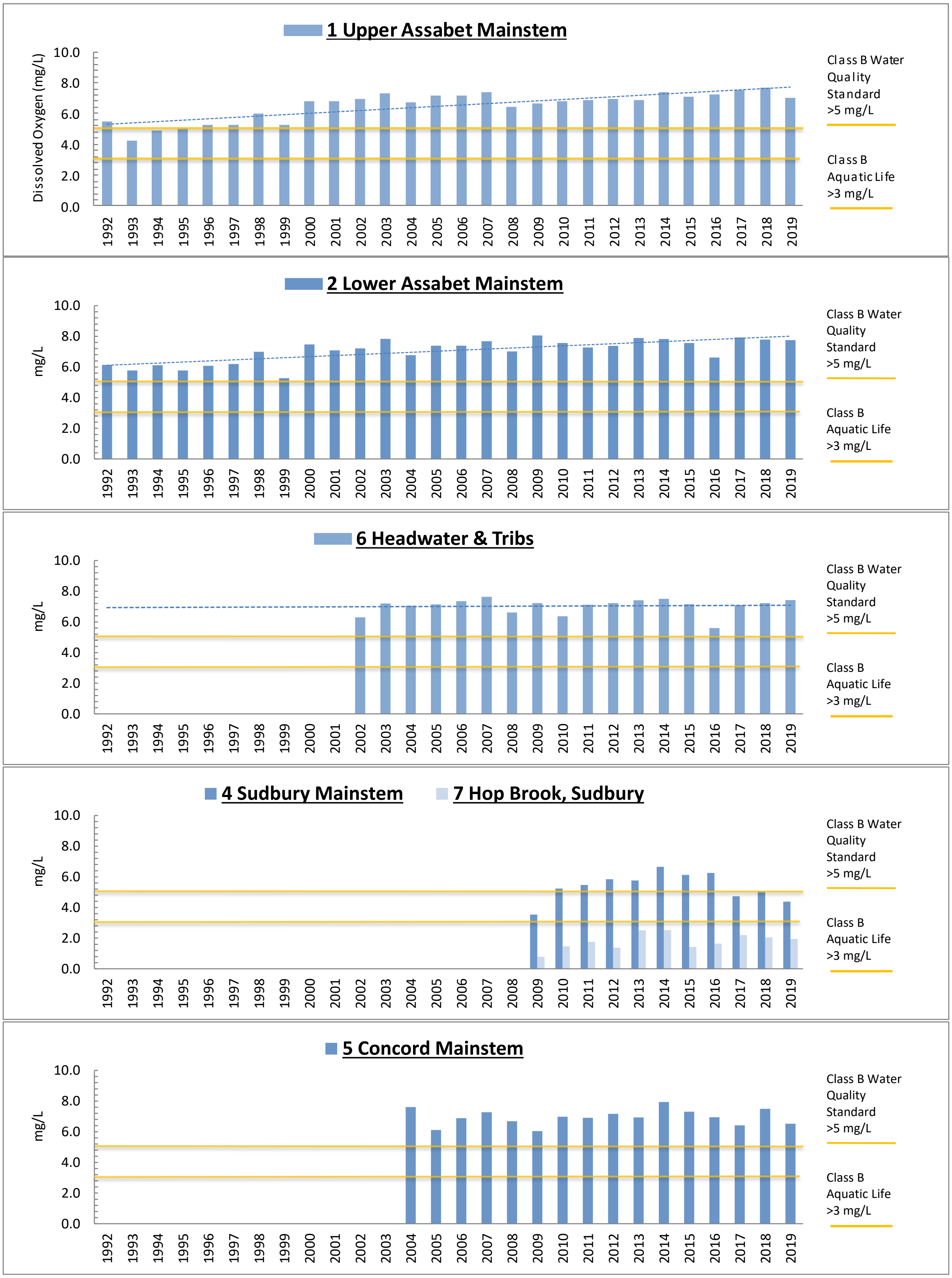


Figure 25: Mann-Kendall trend test results for Dissolved Oxygen

Mann-Kendall test	flow-weighted							
	Upper ABT	**Lower ABT**	**Upper ABT**	**Lower ABT**	**Head&Tribs**	**Sudbury**	**Hob Brook**	**Concord**
years	1992-2019	1992-2019	2000-2019	2000-2019	2002-2019	2009-2019	2009-2019	2004-2019
tau	0.445	0.422	0.095	0.131	0.027	-0.048	0.094	0.057
p	0.0000	0.0000	0.2868	0.1407	0.7768	0.7212	0.4754	0.5755
trend	**upward**	**upward**	NST	NST	NST	NST	NST	NST

Table 15: Comparison between Impounded and Lower Assabet Site Readings 2018

Comparison of Mean Readings from Impounded vs. Lower Assabet Sites (May – Sept, 2018)					
Section / Statistic	Temp (C)	Dissolved Oxygen %	Dissolved Oxygen (mg/L)	Cond (µS/cm)	pH (S.U.)
Impounded Sites	20.4	84.3	7.64	606	7.2
Lower Assabet Sites	20.9	90.8	8.12	571	7.3
Relative Percent Difference	2.3%	7.4%	6.1%	6.1%	2.2%

Table 16: Comparison between Impounded and Lower Assabet Site Readings 2019

Comparison of Mean Readings from Impounded vs. Lower Assabet Sites (May – Sept, 2019)					
Section / Statistic	Temp (C)	Dissolved Oxygen %	Dissolved Oxygen (mg/L)	Cond (µS/cm)	pH (S.U.)
Impounded Sites	19.9	82.6	7.58	694	7.1
Lower Assabet Sites	21.0	90.8	8.15	658	7.3
Relative Percent Difference	5.4%	9.5%	7.2%	5.3%	2.8%

Phosphorus

In 2018, mean Total Phosphorus (TP) concentrations were below the EPA "Gold Book" recommendation (0.05 mg/L) for all river sections, except Hop Brook Sudbury (HBS-016), which is affected by Marlborough Easterly WWTP, and for all dates, except November, which exceeded the 0.05 mg/L recommended concentration for all sections (Figure 26). In 2019, mean TP concentrations exceeded the recommended concentration much more often (Figure 26). All sections exceeded the recommended concentration multiple times, with Hop Brook Sudbury well above and the Upper Assabet significantly above (driven by ABT-301, which is just below the Westborough WWTP). The November elevated levels may be attributed to phosphorus released from decomposing leaf litter (Selbig, 2016). The March, June, and August elevated levels in 2019 are harder to explain. None of these sampling dates had any significant rain events and river flow was not unusually low. Both June and August were during a falling hydrograph about two days after peak flow. A detailed study of TP by site is shown in Figure 27, but, except for ABT-301, nothing stands out as a clear outlier.

Analysis of ortho-phosphate shows that bio-available phosphates represent on average between 40 and 50% of TP (Figure 28). Proportions are even lower in November sampling – 17% in

2018 and 32% in 2019. A boxplot analysis is included comparing 2018 and 2019 to show that proportions of TP are statistically similar even though it looks like 2019 had lower percentages.

Year-on-year analysis of TP (Figure 31 and Figure 32) shows the improvements delivered by the Assabet WWTP upgrades in 2000 and 2012. For the Assabet, the downward trend prior to 2013 is obvious, so trends for the Assabet and downstream were only analyzed from 2013 onward for this report. The test statistics from the Mann-Kendall test are shown next to the boxplot trend analyses (Figure 32). They showed no significant trends for any river sections for the periods analyzed. It should be noted that as recently as 2017, the data seemed to show a weak downward trend in TP for the Sudbury River and Hop Brook. The last two years have nullified that trend. The 2017 report also noted a weak decreasing trend in ortho-phosphate for Hop Brook and the Tributaries. This updated analysis shows no significant trend for Hop Brook, but still shows a significant flow-weighted downward trend in ortho-phosphate for the Headwaters and Tributaries (Figure 29).

The year-on-year analysis also shows that there is still a TP issue downstream of the Marlborough Easterly WWTP. Hop Brook Sudbury has continuously shown mean summer TP concentrations well above the EPA Gold Book recommended level. Figure 33 shows the dramatic reduction in TP discharge from Marlborough Easterly as a result of the 2015 plant improvements, and current discharge amounts from Marlborough East are very low compared to other WWTPs (Figure 38). A comparison of TP concentrations in Hop Brook and in the Easterly WWTP effluent shows the effluent near the Gold Book recommended level but Hop Brook consistently much higher than the Gold Book level in June/July/August (Figure 34). The sampling event in July 2018 (the only month when levels were not high) was 6 days after a very large rainfall event that flushed the streams. It appears there is another source of phosphorus in Hop Brook, including perhaps phosphorus stored in the sediments that gets released to the water column in the summer. CDM identified just such a mechanism in the Assabet (CDM, 2008, pg. 5-4).

The year-on-year analysis shows higher TP levels in 2019, which are particularly visible in the Upper Assabet (Figure 31, Figure 32). We believe that these higher 2019 values reflect reality, but we are unable to explain them and we have experienced quality control issues with TP that force us to qualify these data. The reason we believe these data are real is that the largest deviation from the norm is in the Upper Assabet, specifically downstream of the Westborough and Marlborough Westerly WWTPs (see Figure 32 to compare Upper Assabet to other river sections and see Figure 35 and Figure 36 for Upper Assabet details by month and site). However, the reason we qualified the data is that the TP analysis has been prone to QC checks that do not meet our Data Quality Objectives (Appendix IV). We are taking steps to identify and eliminate the cause of this discrepancy. A review of monthly discharges from Westborough WWTP did not show any abnormal discharge amounts in 2019 (Figure 37).

Figure 26: Mean Total Phosphorus by section (2018/2019)

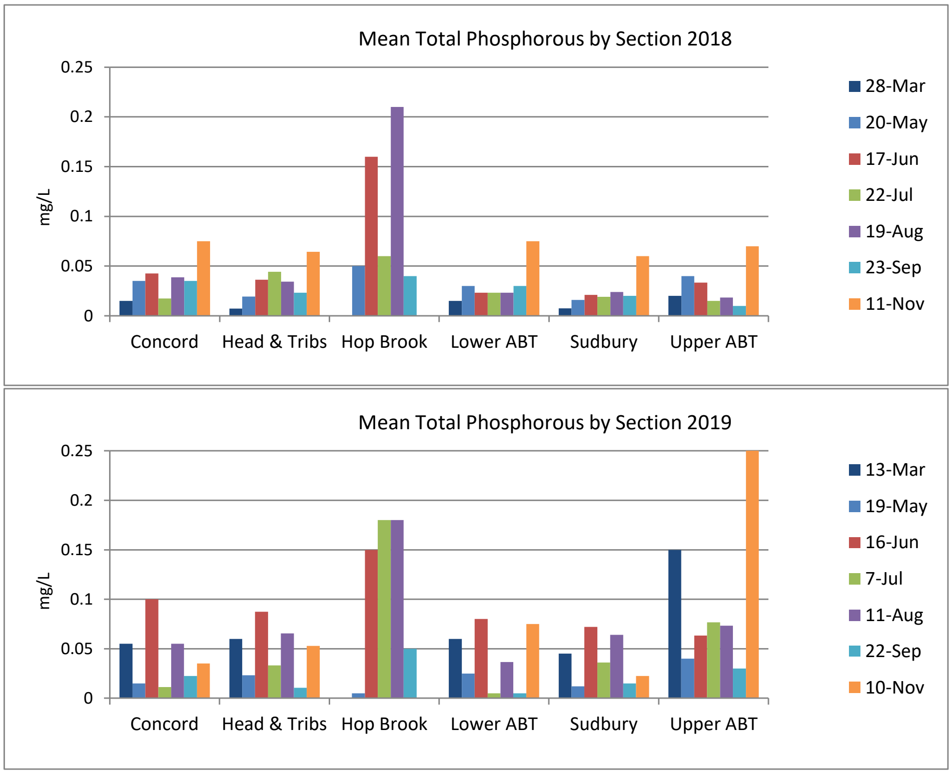


Figure 27: Total Phosphorus for selected sites (2019)

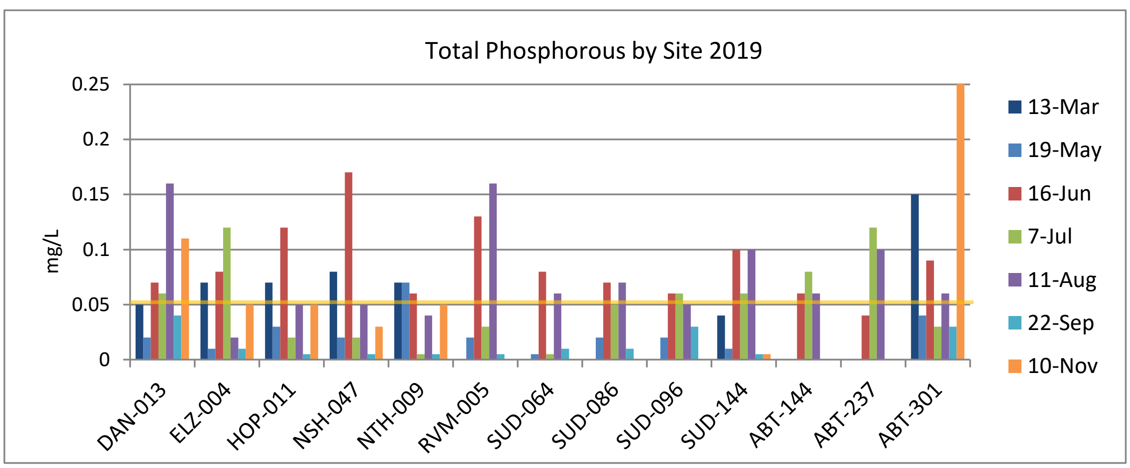


Figure 28: Mean ortho-phosphate by section (2018/2019)

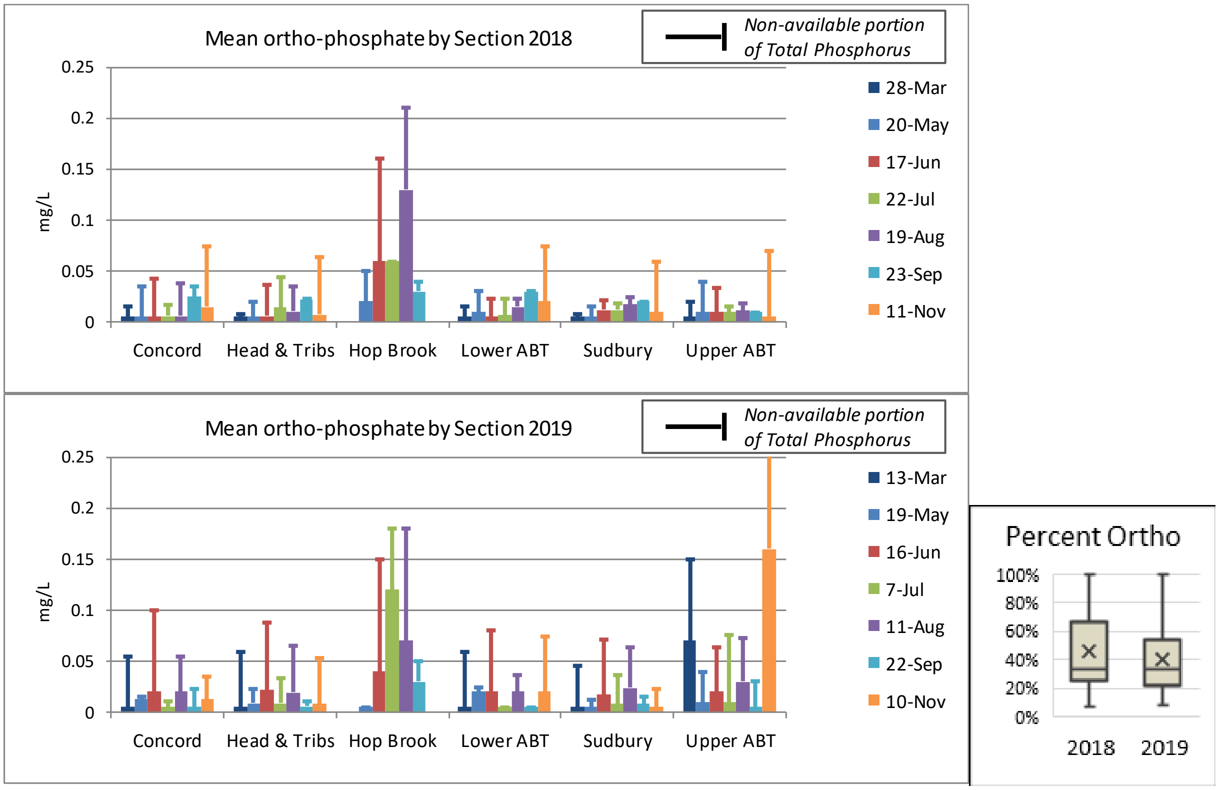
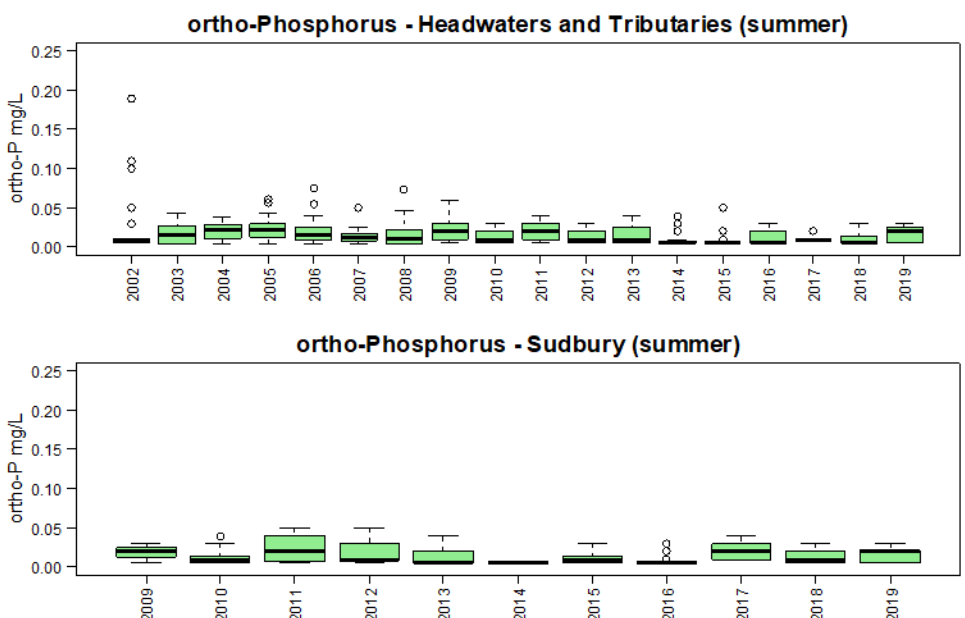


Figure 29: Year-on-year boxplot analyses of ortho-phosphate (June/July/August)



Mann-Kendall test	
Head&Tribs	2002-2019
flow-weighted	
tau	-0.322
p	0.0006
trend	**downward**

Mann-Kendall test	
Sudbury	2009-2019
flow-weighted	
tau	-0.032
p	0.8166
trend	NST
Hob Brook	2009-2019
tau	-0.200
p	0.1249
trend	NST

Figure 30: Map of 2019 average summer Total Phosphorus

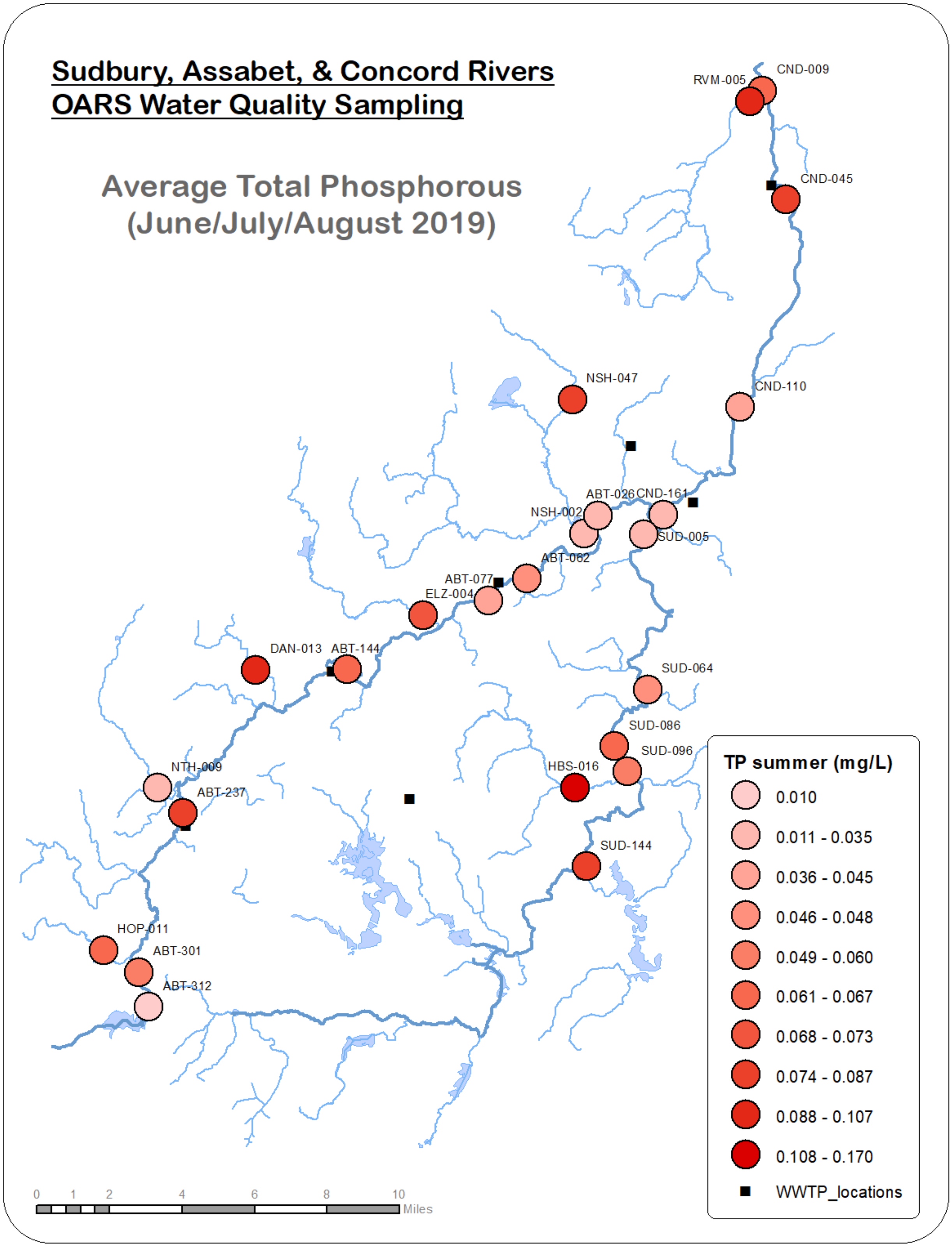


Figure 31: Year-on-year mean summer Total Phosphorus by section (June/July/August)

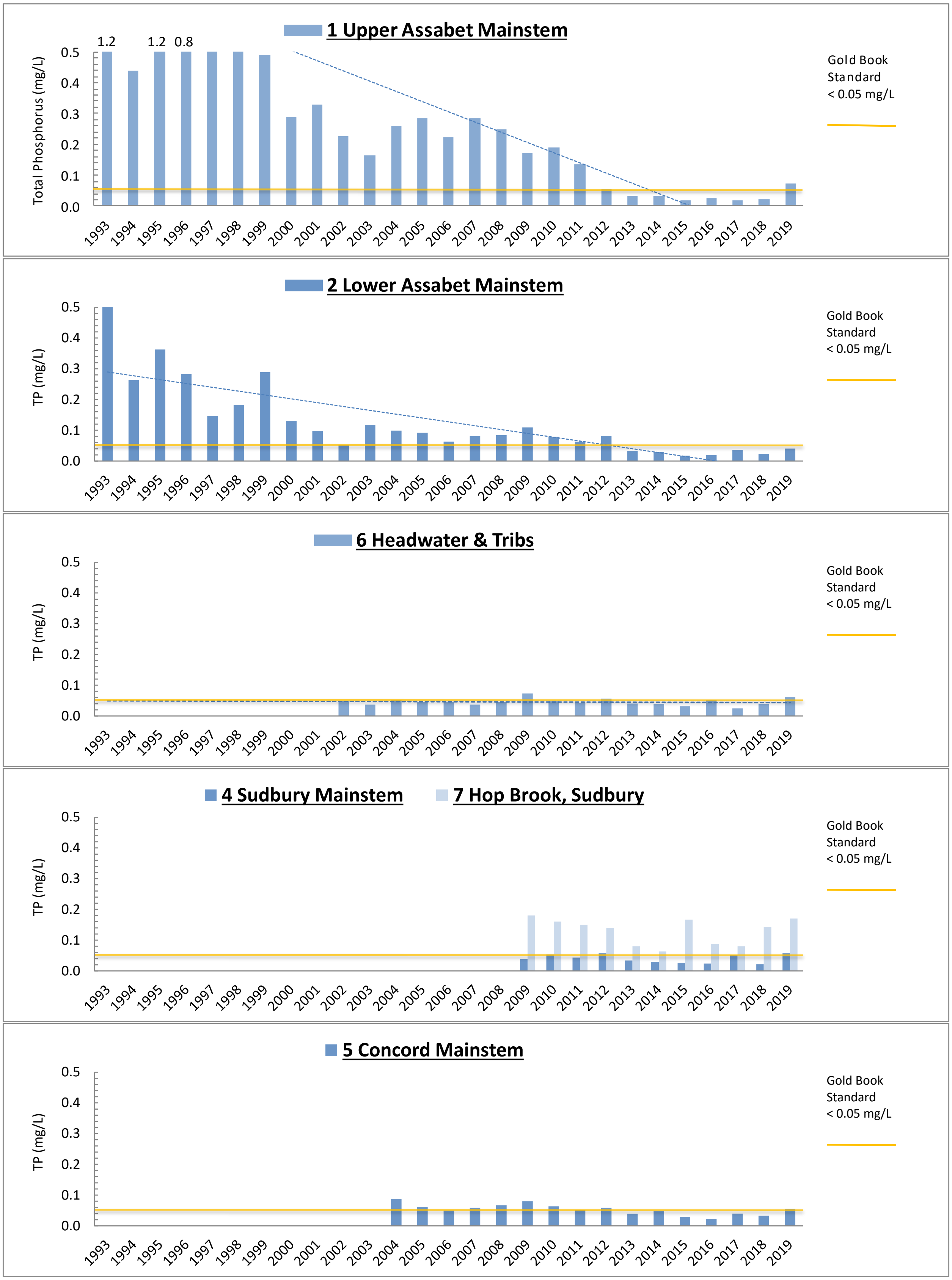
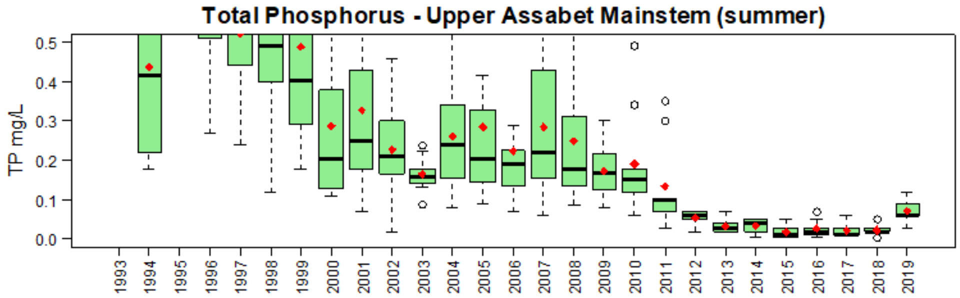
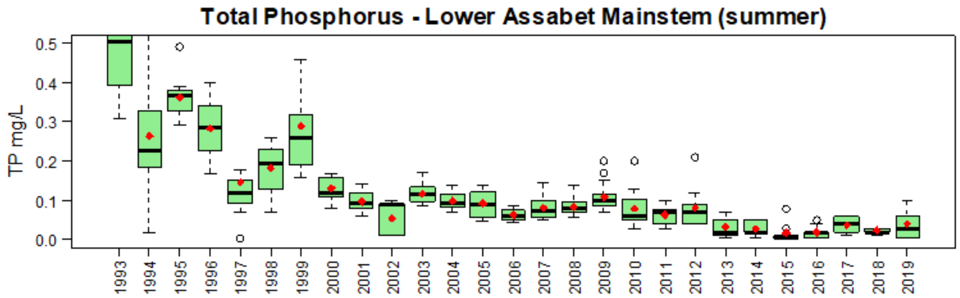


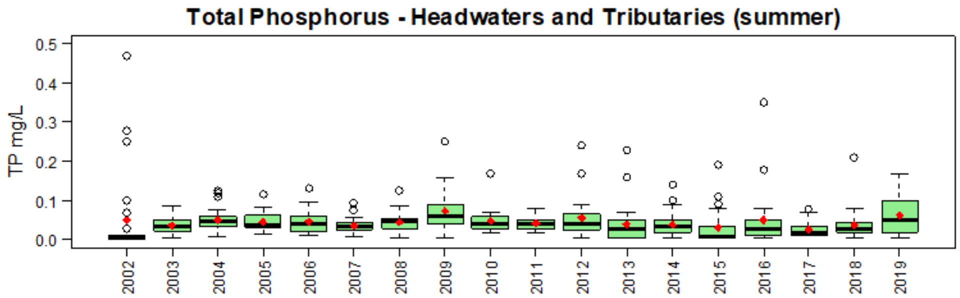
Figure 32: Year-on-year boxplot analyses of Total Phosphorus (June/July/August)



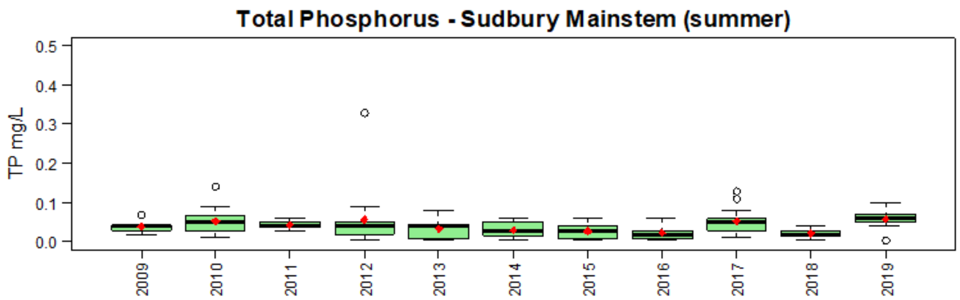
Mann-Kendall test	
Upper ABT	2013-2019
flow-weighted	
tau	0.165
p	0.2966
trend	NST



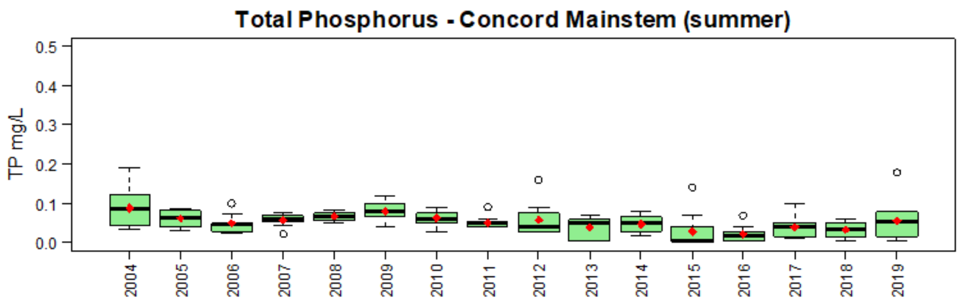
Mann-Kendall test	
Lower ABT	2013-2019
flow-weighted	
tau	0.017
p	0.9326
trend	NST



Mann-Kendall test	
Head&Tribs	2002-2019
flow-weighted	
tau	-0.142
p	0.1318
trend	NST



Mann-Kendall test	
Sudbury	2009-2019
flow-weighted	
tau	-0.099
p	0.4537
trend	NST
Hob Brook	2009-2019
tau	-0.108
p	0.4118
trend	NST



Mann-Kendall test	
Concord	2013-2019
flow-weighted	
tau	-0.108
p	0.4118
trend	NST

Figure 33: Marlborough Easterly WWTP TP discharge (2013-2019)

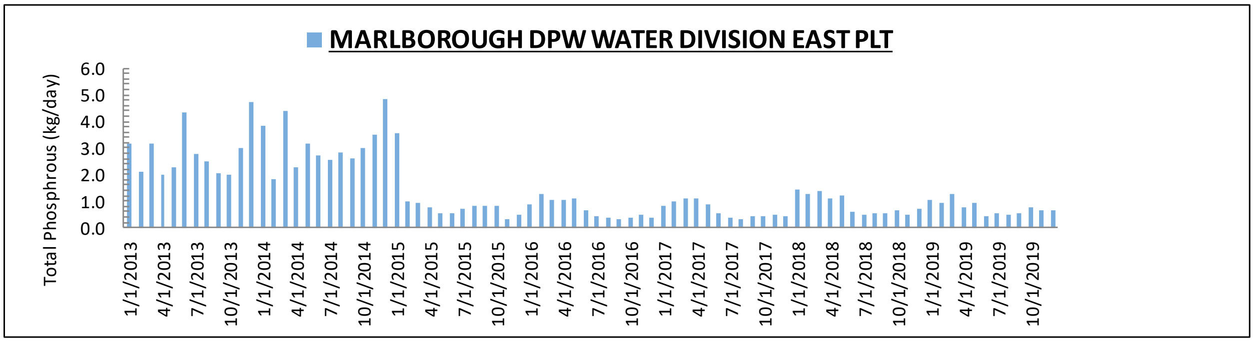


Figure 34: Hop Brook Sudbury vs. WWTP TP concentrations

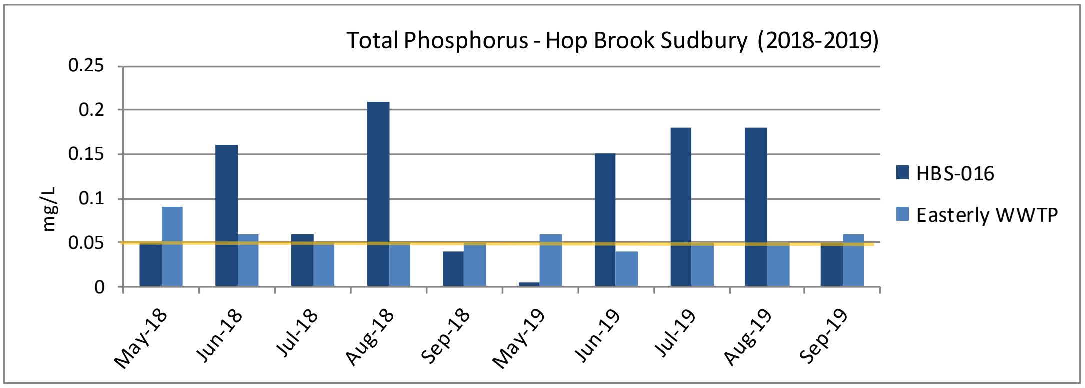


Figure 35: Total Phosphorus Upper Assabet by month

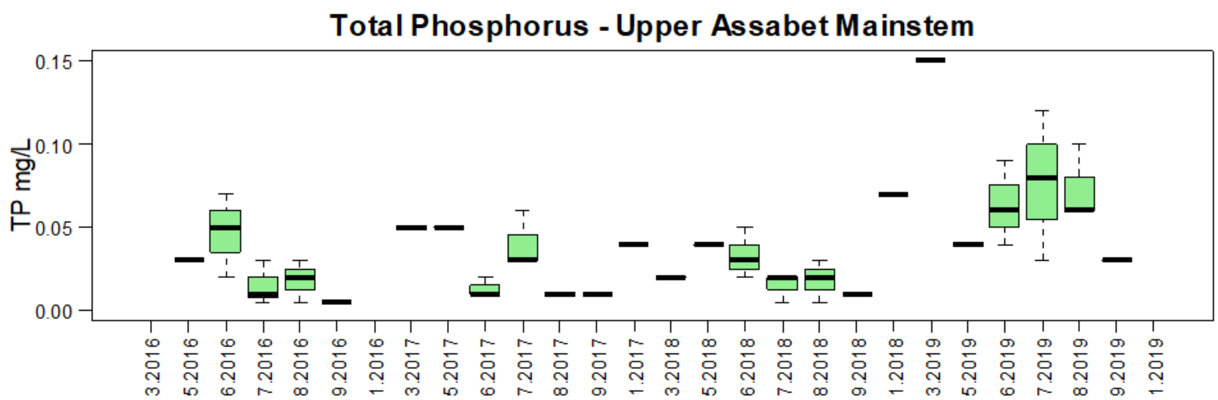
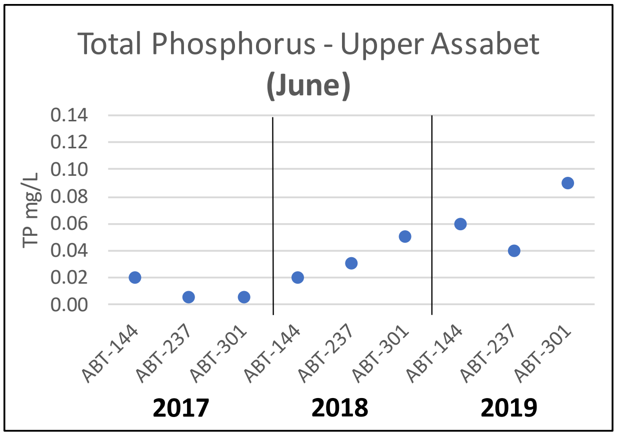


Figure 36: Total Phosphorus for specific Upper Assabet sites by month



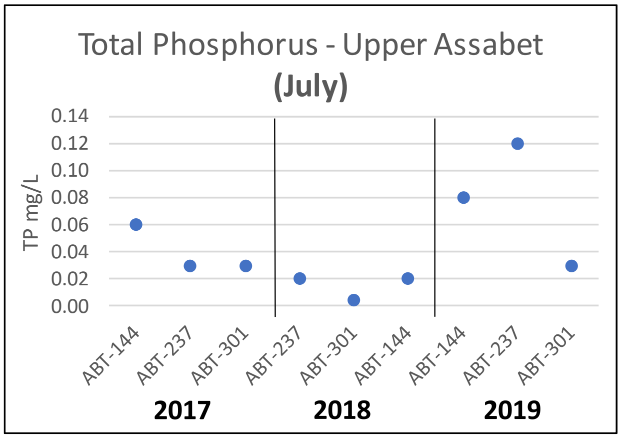


Figure 37: Westborough WWTP TP discharges by month

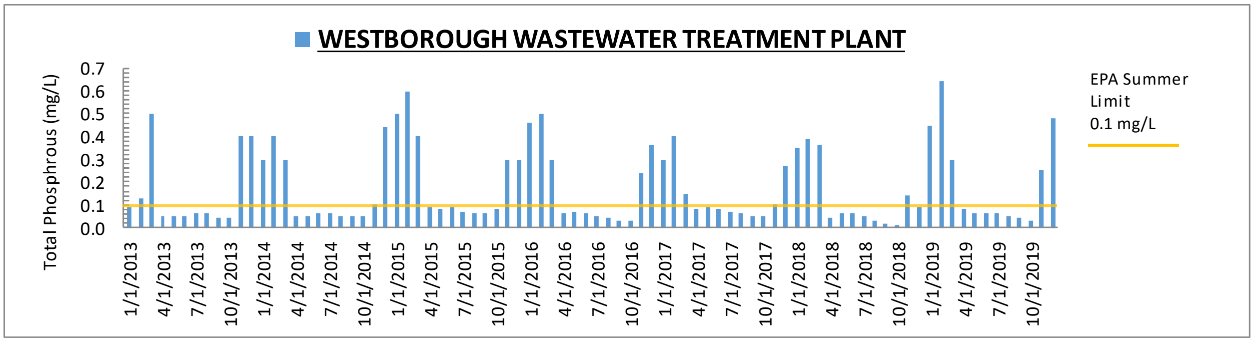


Figure 38: WWTP Average Daily TP Discharge (2019)

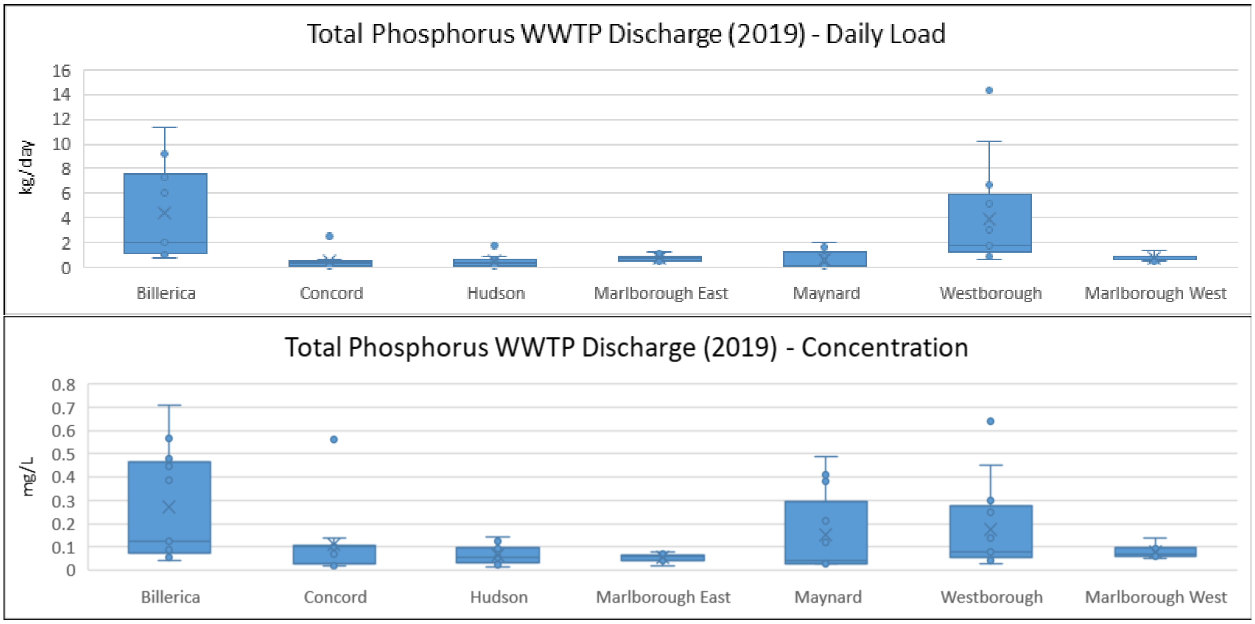
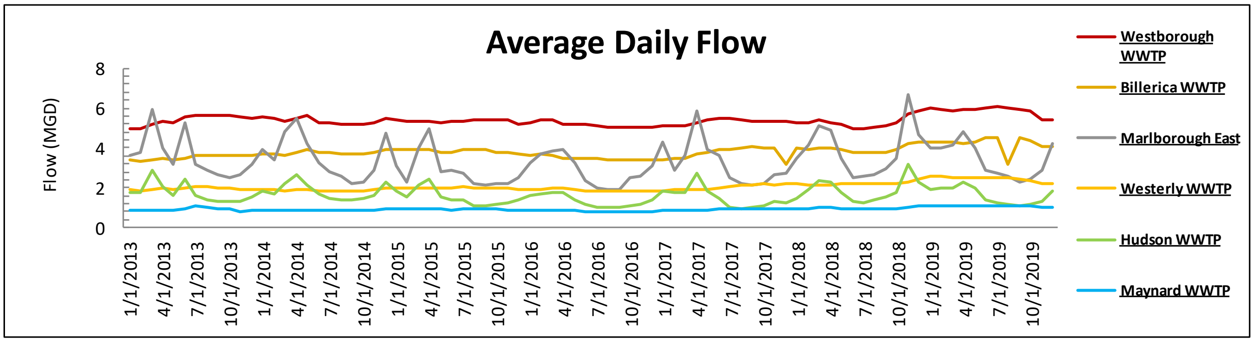


Figure 39: WWTP Discharge Flow (daily - 2013-2019)



Nitrate

Mean nitrate-N (NO_3) concentrations in 2018 and 2019 were generally in the range of the Ecoregion reference condition (for NO_2+NO_3 as N) of 0.34 mg/L in the Sudbury, Concord, and Tributaries, but all of the Assabet Mainstem sites exceeded this reference level by 2X or more (Figure 40). These high NO_3 levels in the Assabet seem to be linked to outflow from the Westborough Wastewater Treatment Plant. ABT-301, which is just downstream of the Westborough WWTP, had much higher NO_3 levels than any of the other sites, and NO_3 levels clearly decline the farther sampling sites are downstream from Westborough WWTP (Figure 41).

Year-on-year analysis of NO_3 reiterates the consistently high NO_3 levels in the Assabet but does not show any reliable trends for any of the mainstem sections (Figure 42). A downward trend is noticeable for headwaters and tributaries, and the Mann-Kendall test confirms this with a p-value <0.00005 (Table 17). A detailed review of the headwater and tributary sites shows that this downward trend is evident on all of the sites with continuous data (Figure 43). The weakly increasing trend in the upper and lower Assabet that was reported in the 2017 report is no longer statistically significant.

Figure 40: Mean Nitrate by section (2018/2019)

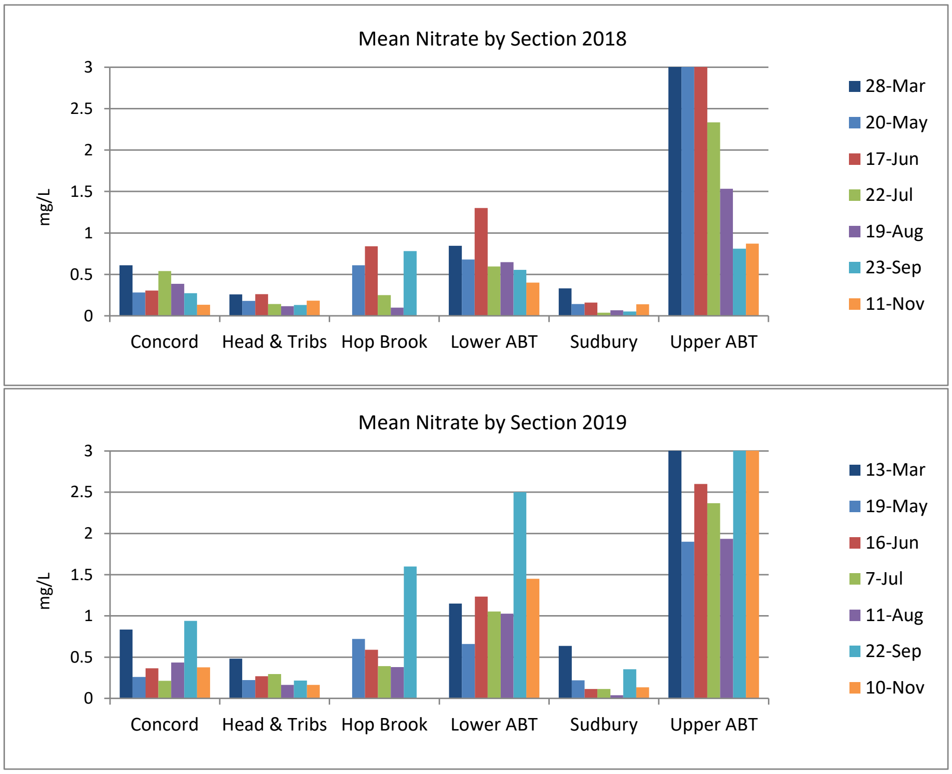


Figure 41: Nitrate concentrations for Assabet Mainstem sites (2018/2019)

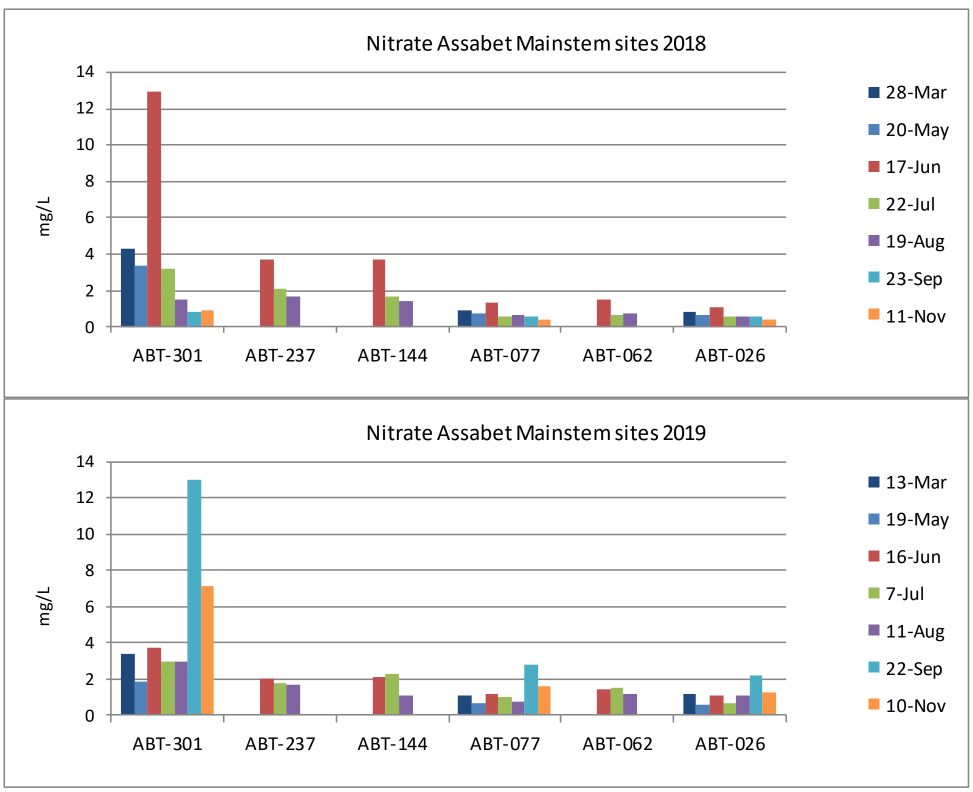


Figure 42: Year-on-year mean summer Nitrate by section (June/July/August)

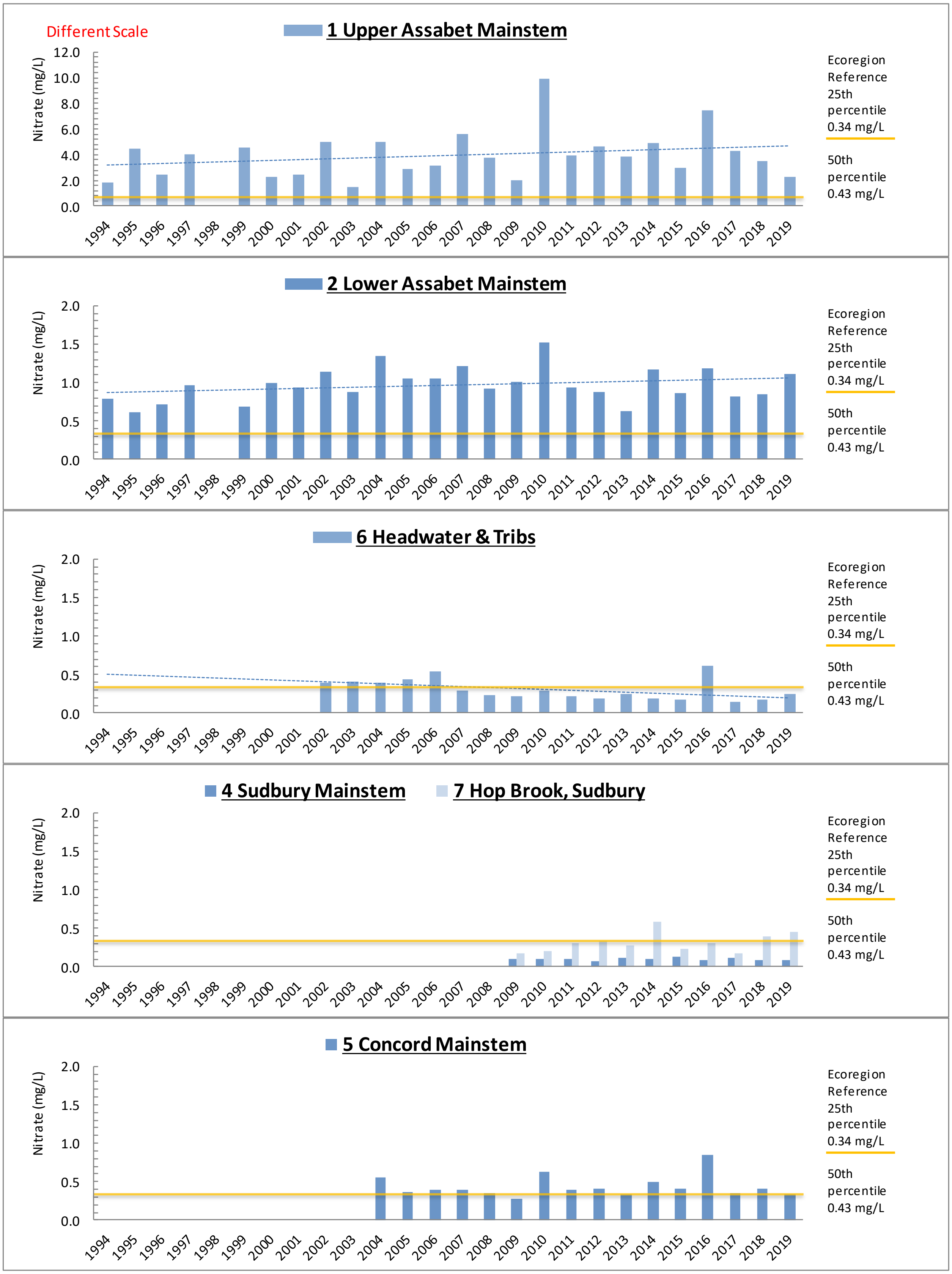
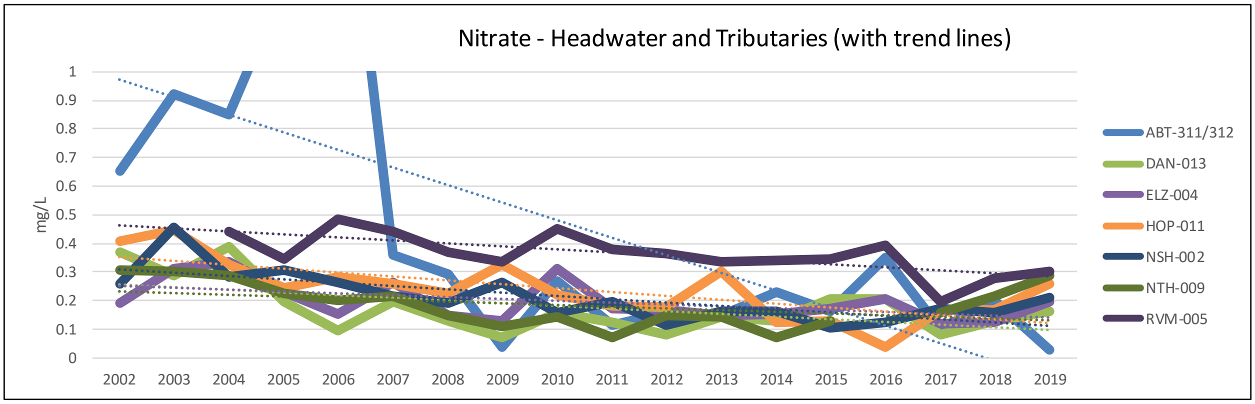


Table 17: Mann-Kendall trend test results for NO3

Mann-Kendall test	flow-weighted					
	Upper ABT	Lower ABT	Head&Tribs	Sudbury	Hob Brook	Concord
years	1999-2019	1999-2019	2002-2019	2009-2019	2009-2019	2004-2019
tau	0.165	0.031	-0.427	-0.113	0.051	0.046
p	0.0562	0.7219	0.0000	0.3918	0.7079	0.6503
trend	NST	NST	downward	NST	NST	NST

Figure 43: Year-on-year summer Nitrate for Headwater and Tributary sites (with trend lines)



*For NTH-009, the 2016 mean value of 3.14 was removed from this graph because it was an extreme outlier.

Total Suspended Solids

Mean total suspended solids (TSS) concentrations by section are shown in Figure 44. Hop Brook Sudbury had many sampling events in both 2018 and 2019 with very high TSS levels. This has not been the case all years. Most previous years Hop Brook's TSS levels were equal to or less than Sudbury averages (Figure 46). A review of TSS discharges from the Marlborough Easterly WWTP (on Hop Brook) does show slightly elevated TSS discharges in early 2018 and 2019. It is possible that this is related, but it doesn't seem like the levels are high enough to explain our extremely high results in Hop Brook. High TSS values in the Sudbury in 2018 and 2019 were all at sites downstream of the Hop Brook confluence. In the Concord, the higher TSS levels were consistent across all sites. The outlying high value in June 2019 was measured at the confluence of the Sudbury and Assabet (CND-161).

Year-on-year analysis of TSS does not show any noticeable trends (Figure 46). The higher than normal TSS in the Assabet in 1999 and 2000 is probably a reflection of the water quality prior to the WWTP upgrades in 2000. The annual data confirms that the Concord consistently has higher TSS levels than the other rivers.

Figure 44: Mean TSS by section (2018/2019)

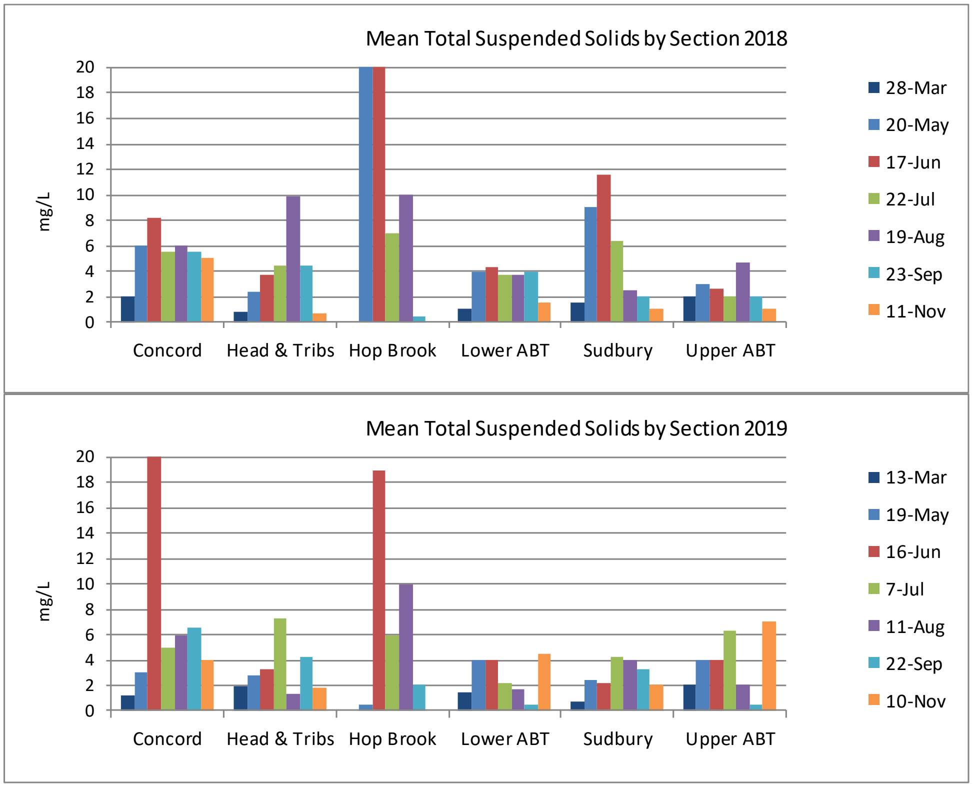


Figure 45: Marlborough Easterly WWTP TSS discharge (2013-2019)

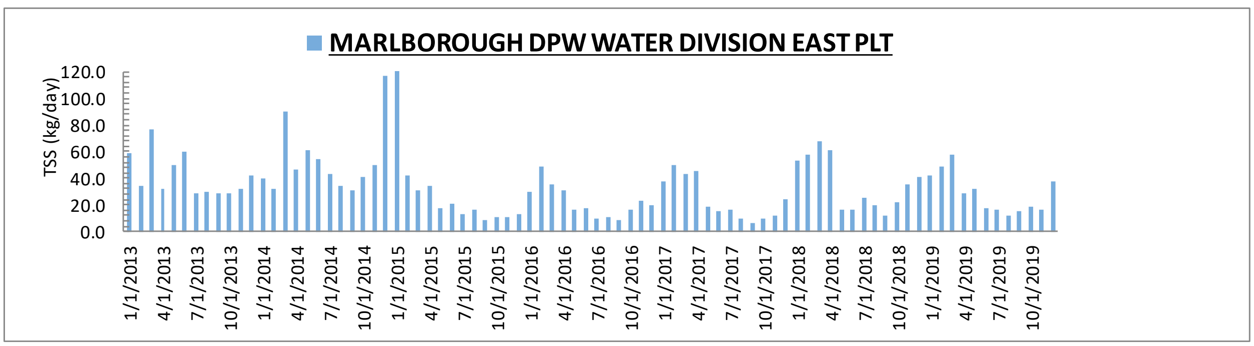
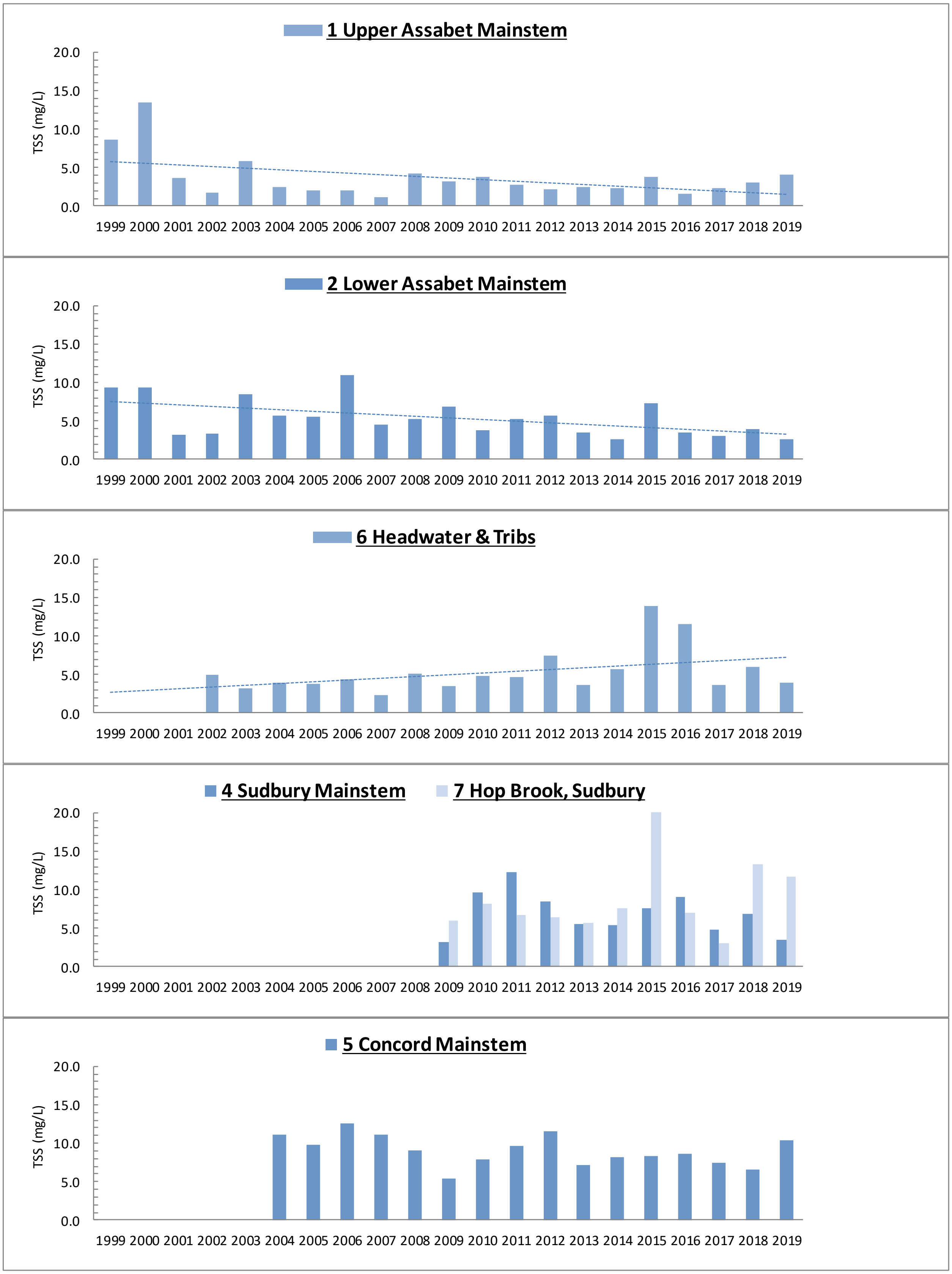


Figure 46: Year-on-year mean summer TSS by section (June/July/August)

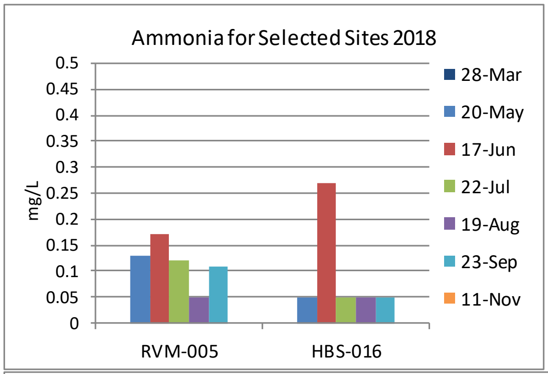


Ammonia

Ammonia (NH_3) is a form of nitrogen that can be toxic to aquatic life at high levels. 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 would set thresholds for chronic levels of 1.2 mg-N/L and acute levels of 7.2 mg-N/L (US EPA, 2013). The maximum levels we are measuring are 0.5 mg/L, with 90% of samples below 0.1 mg/L. This has been consistent for our period of record with a slight uptick in 2017 (Figure 49 and Figure 50).

Most samples from 2018 and 2019 had no detectable levels of ammonia. Only a spattering of samples at a few sites returned any measurable values (Figure 47). River Meadow Brook and Hop Brook Sudbury both had measurable values each year. Other sites with measurable ammonia levels in 2019 were Nashoba Brook at Wheeler Lane, Sudbury at Rt. 62, and two sites on the Assabet that are both just downstream of wastewater treatment plants. Wastewater treatment plant discharges for 2019 are shown in Figure 48.

Figure 47: Ammonia (as total ammonia nitrogen) for Selected Sites (2018/2019)



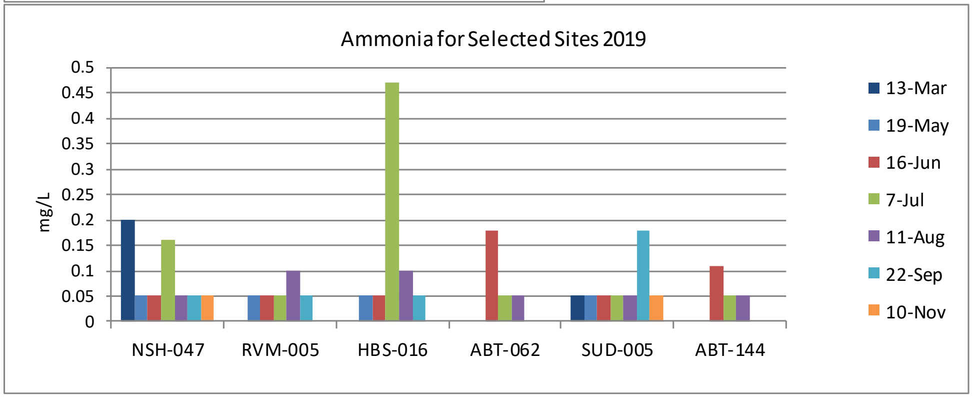


Figure 48: WWTP Ammonia (as total ammonia nitrogen) Discharge - daily load

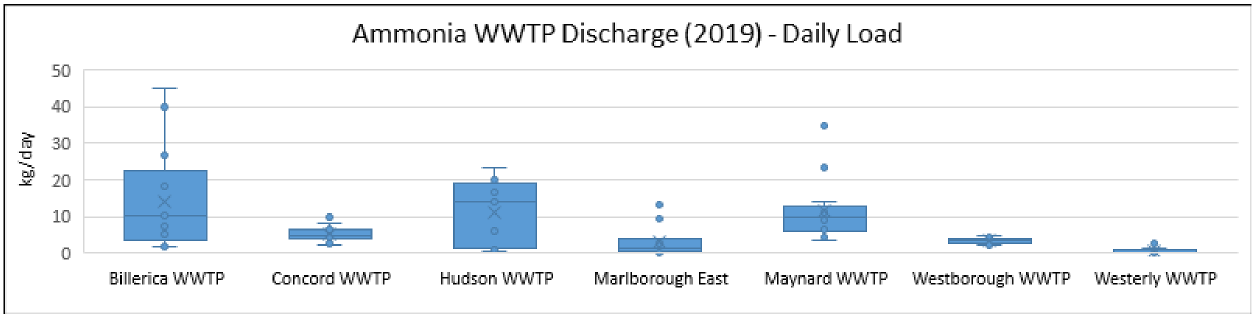


Figure 49: Year-on-year mean summer Ammonia by section (June/July/August)

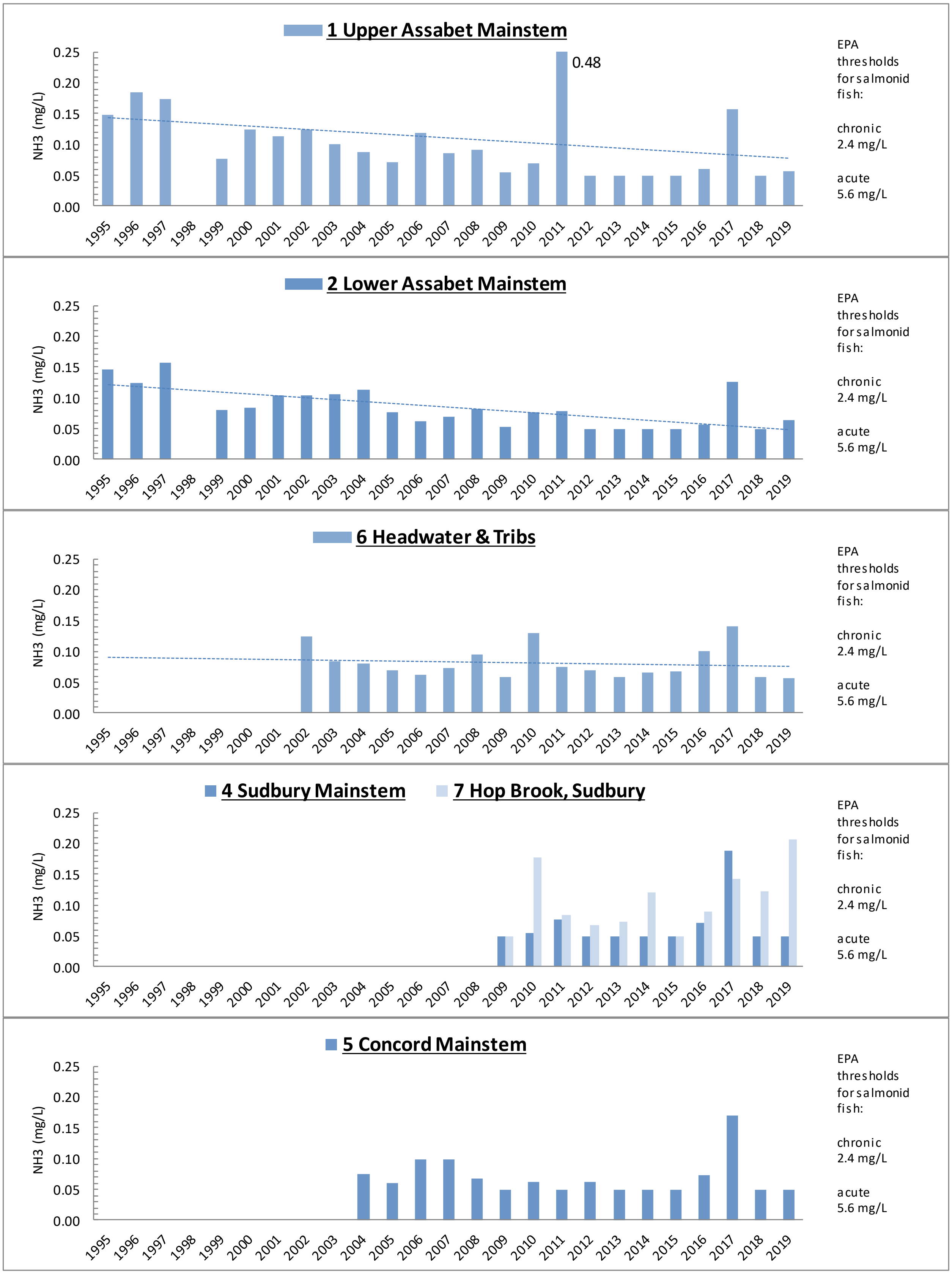
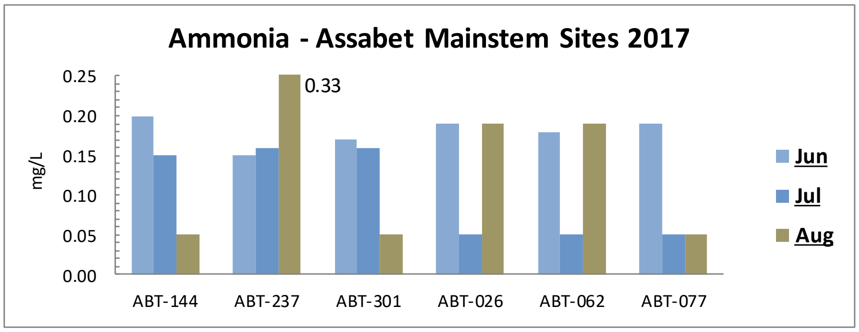


Figure 50: Ammonia 2017 Detail



Chlorophyll a

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 (25^{th} percentile 2 µg/L, 50^{th} percentile 4 µg/L).

Chlorophyll *a* was measured on the Sudbury River and Hop Brook Sudbury, in June, July, and August (Figure 51). The Concord and Assabet Rivers are not sampled for chlorophyll *a*. In 2018/2019, concentrations ranged from <2 to >20 µg/L with many readings above 4 µg/L and three above 15 µg/L. The downstream-most Sudbury site (SUD-005) consistently averages the highest chlorophyll-*a* levels, but SUD-086 (Wayland next to Route 20) had extremely high readings in August in both years. For the most part, the highest levels in 2018 were in June, but the highest levels in 2019 were in August. This difference is likely linked to higher streamflow in June 2019 than June 2018.

Year-on-year analysis of Chlorophyll *a* shows no change since 2010 (Figure 52).

Figure 51: Chlorophyll *a* for Sudbury Sites (2018/2019)

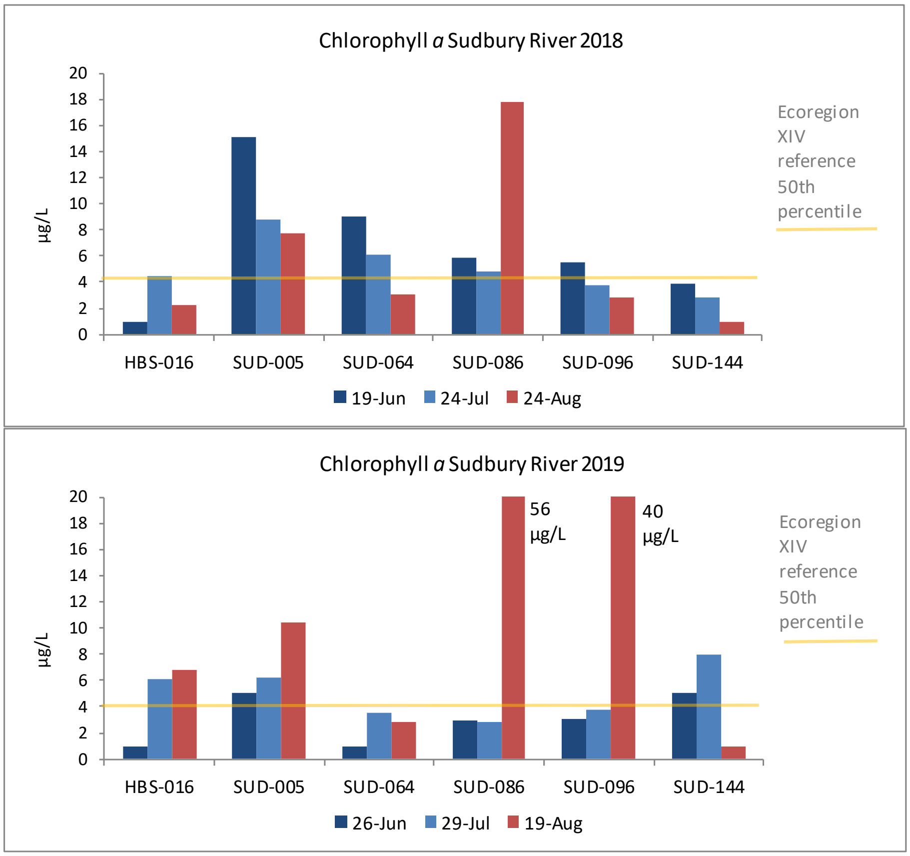
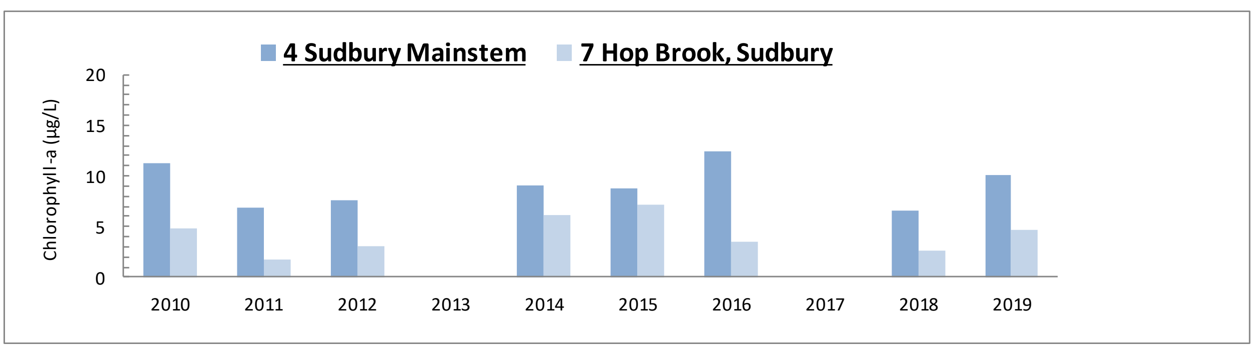


Figure 52: Year-on-year mean summer Chlorophyll *a* by section (June/July/August)



Water Quality and Stream Health Index Calculations

In previous reports, the Stream Health Index was used to assess conditions at six of the tributary stream sites. The Water Quality Index (a sub-index of the overall Stream Health Index without streamflow data) was also used to assess water quality at selected mainstem sites and Hop Brook Sudbury. This year we have chosen not to calculate these indexes in the annual report because they are a major component of the OARS River Health Report Card (see https://ecoreportcard.org), which is issued every two years.

Bacteria Results

OARS monitored for *Escherichia coli* (*E. coli*) bacteria at six locations in the Assabet, Sudbury, and Concord rivers starting in 2019. *E. coli* is used as an indicator of fecal contamination in water bodies, and the EPA has defined safety threshold values for recreational swimming and boating. 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. Also, for this same reason, averages of bacteria data are calculated using a geometric mean (**geomean**) instead of a normal arithmetic mean.

Table 18 provides a summary of the bacteria statistics for 2019. Based on single sample results, one site (SUD-237) exceeded the swimming threshold at least 25% of the time. Based on the geometric mean, three sites exceeded the threshold for the season. Two sites only had one exceedance over the summer, and one site never had any exceedances. None of our sites ever approached the boating threshold. See Figure 53 for a map of bacteria results by site.

Figure 54 shows a graphical view of bacteria results in relation to rainfall. 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 boxplot analysis in Figure 55 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. The analysis shows a strong increase in bacteria levels during wet days for three sites (ABT-162, CND-009, and SUD-237) and a weak increase at one site (ABT-077). The other two sites had characteristically low levels of bacteria all season.

Table 18: Bacteria statistical results (2019)

Site #	Description	Samples	Exceed-ences	% Exceeded	Geo-Mean
ABT-077	USGS gage, Maynard	15	1	7%	121
ABT-162	Cox Street, Hudson	15	2	13%	161
CND-009	Rogers St. Bridge, Lowell	15	2	13%	147
CND-110	Rte 225 boat ramp, Billerica	15	0	0%	40
SUD-096	Route 20, Wayland	15	1	7%	51
SUD-237	Rte 135, Ashland	15	4	27%	151

Figure 53: Map of Bacteria Monitoring Results (2019)

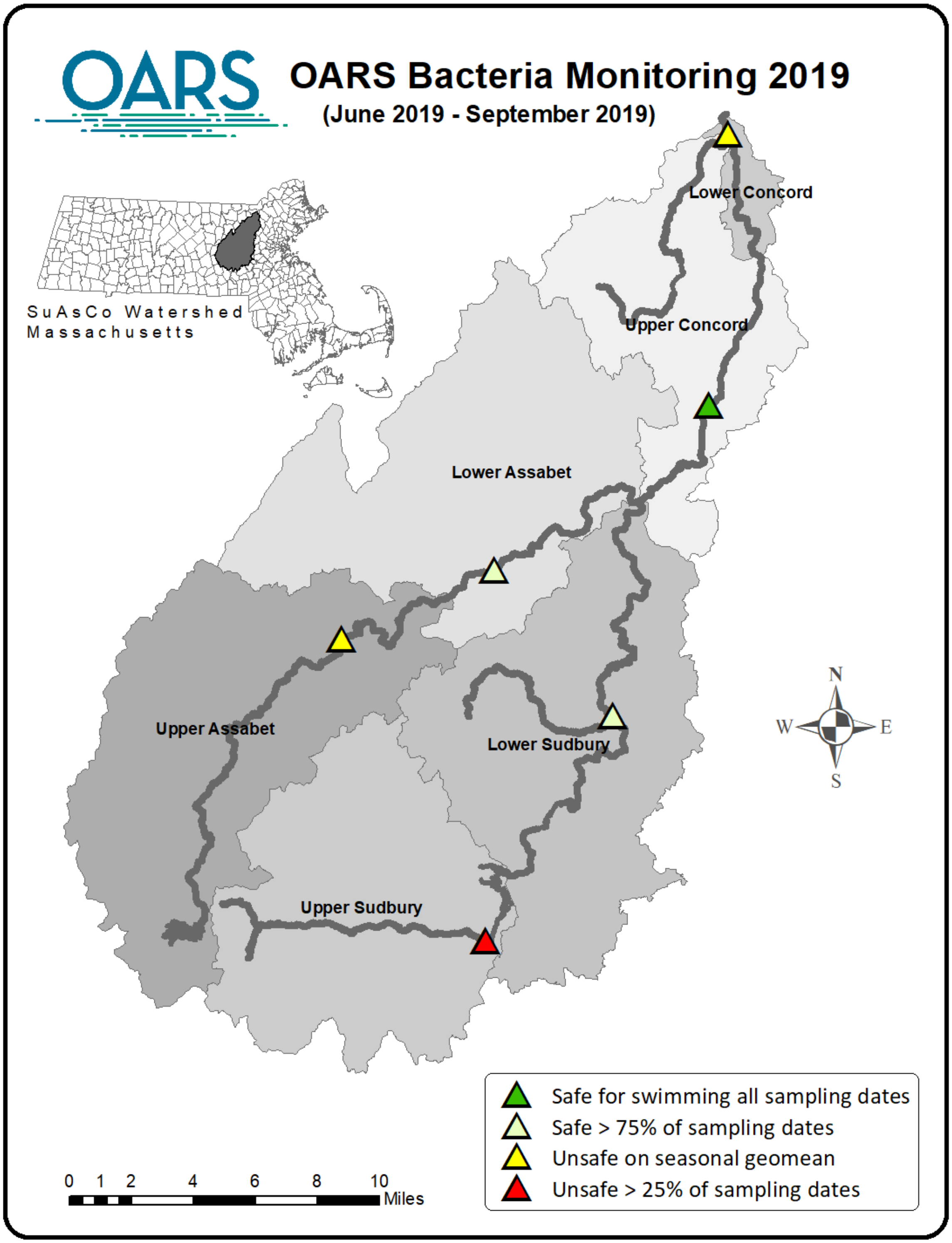


Figure 54: Graphical view of bacteria vs. rainfall (2019)

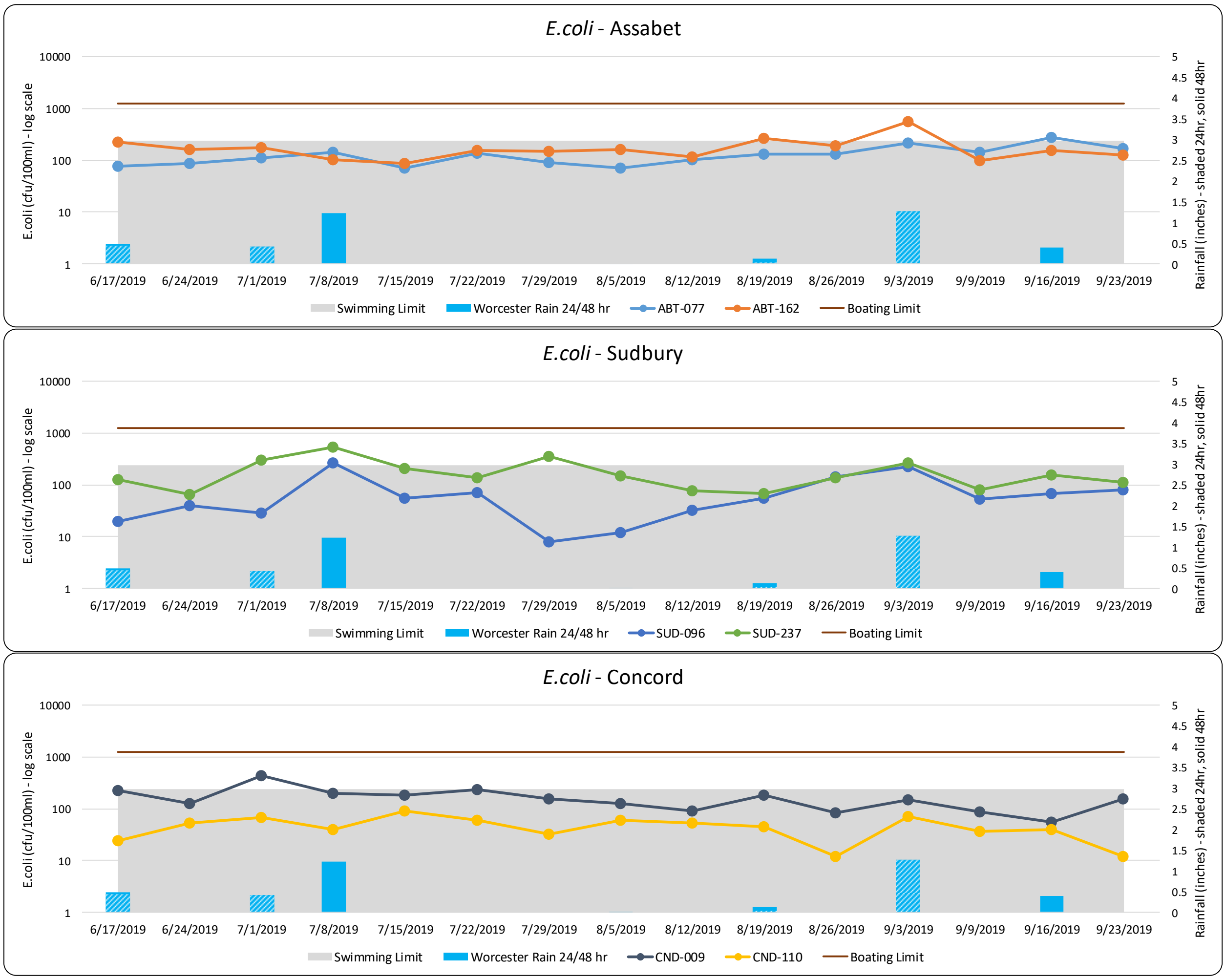
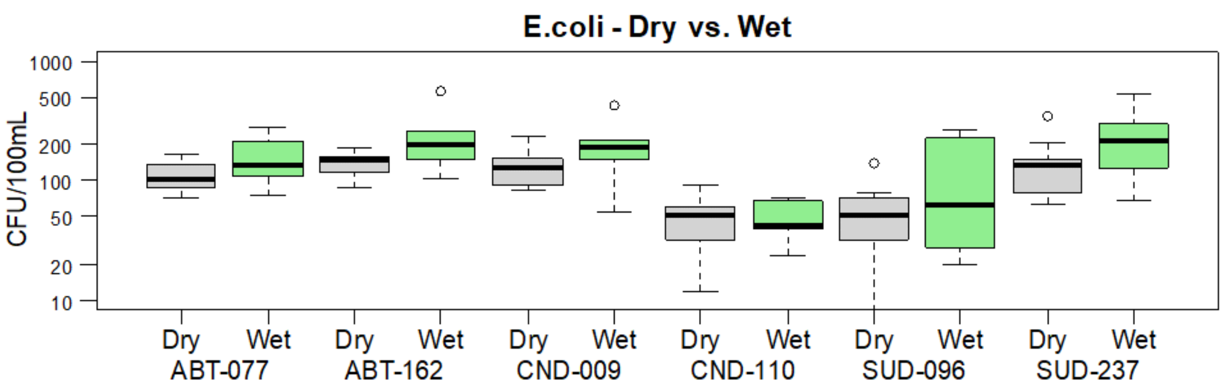


Figure 55: Boxplot analysis of bacteria for wet vs. dry days



Aquatic Plant Biomass Sampling
Three large impoundments of the Assabet River were visually surveyed for aquatic plant biomass using a grid-based system between mid-August and early September each year starting in 2005. Goals of the ongoing project are to assess the nature and extent of aquatic plant biomass in the major impoundments of the Assabet River to add to the multi-year database to assess changes in the river's condition and assess 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." (Mass DEP, 2004)

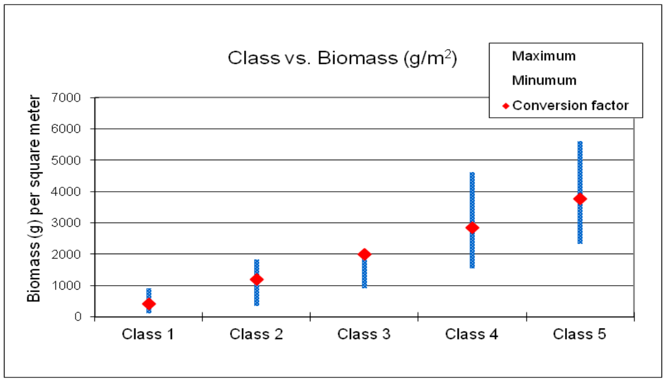
Biomass Survey Methods
These surveys have focused on three large impoundments as the most eutrophic areas of the river. Impoundment locations include:
(1) Hudson impoundment, Hudson, about 0.5 miles upstream from the dam at Route 85;
(2) Gleasondale impoundment, Stow, about 0.6 miles upstream from the 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, extending the grid system originally developed by USGS for MassDEP duckweed monitoring in 2007 (Zimmerman et al., 2011). Using this method, visual observations were conducted by OARS staff from a kayak or canoe at the peak of the growing season each summer starting in 2007. Observations were recorded in the field using hand-held GIS/GPS devices. A viewing tube ("Aquascope") and/or plant rake was used in some locations to help with identification of species and to help estimate the percent volume of the water column filled with plants. At each grid cell the following observations were recorded:

- water depth (measured with weighted tape or pole)
- 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
  - percent coverage of emergent plants
- dominant and other species in each category (floating, submerged, and emergent)
- presence of invasive species

To compare conditions between years and between impoundments, total wet weight of the floating plant biomass was calculated for each impoundment. Field estimates of total floating plant cover were 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 was summed for each impoundment; and total floating biomass wet weight was calculated using conversion factors developed by OARS (Figure 56). Caveat: these conversion factors were developed on a 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).

Figure 56: Class vs. Biomass Wet Weight



Biomass Results

The calculated wet weight of total floating biomass for the Hudson, Gleasondale, and Ben Smith impoundments from 2005 to 2019 is shown in Figure 57. Because aquatic plant growth is strongly affected by summer weather conditions, the mean of the monthly mean air temperatures for May to August (from the Worcester Regional Airport NWS station) are also shown. A correlation analysis of biomass wet weight and temperature or rainfall for Hudson and Ben Smith shows a weak positive correlation between biomass and temperature and a weak to strong negative correlation between biomass and rainfall (Table 19). Interestingly, Gleasondale has no statistical correlation and even biases in the opposite direction. For duckweed, the data are similar to biomass (Figure 59), with slightly stronger correlations (Table 20).

This survey is subjective, depending on estimates by the surveyor. The OARS aquatic scientist conducting the survey changed between 2018 and 2019. The survey is also subject to changes in dominant vegetation type that are not adequately accounted for in the general bio-volume to biomass conversion. Note also that these surveys are conducted in late August, after water chestnut (*Trapa natans*) has been removed.

Maps showing floating plant biomass in the Ben Smith, Gleasondale, and Hudson impoundments in 2019 are shown in Figure 60, Figure 61, and Figure 62 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 was that the Hudson impoundment had the least diverse floating species (mostly filamentous green algae (FGA)), while the Ben Smith impoundment had the most diverse floating species (with very little FGA). Low species diversity can be a sign of eutrophication.

Figure 57: Total floating aquatic plant biomass (2005-2019)

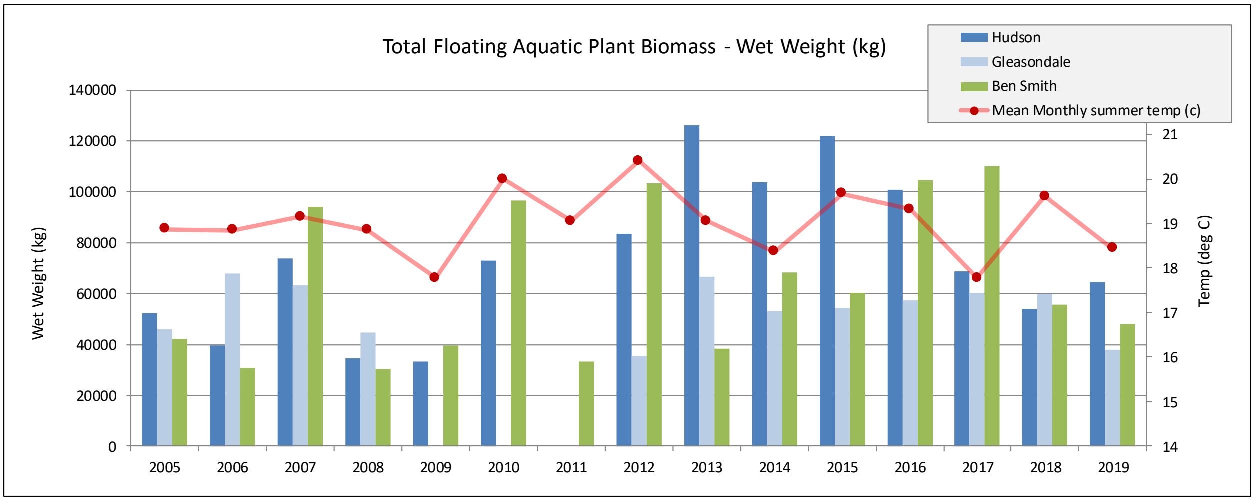


Table 19: Pearson Correlation Coefficients - Biomass vs Temperature and Rainfall

	Hudson	Gleasondale	Ben Smith
Temperature Correlation	0.33	-0.21	0.28
Precipitation Correlation	-0.36	0.05	-0.64

Figure 58: Mean summer temperature and rainfall (2005-2019)

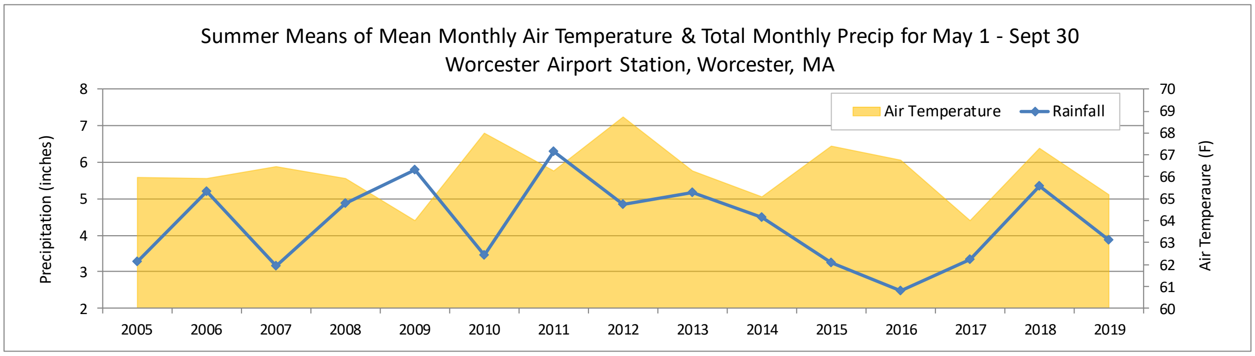


Figure 59: Total duckweed coverage (2007-2019)

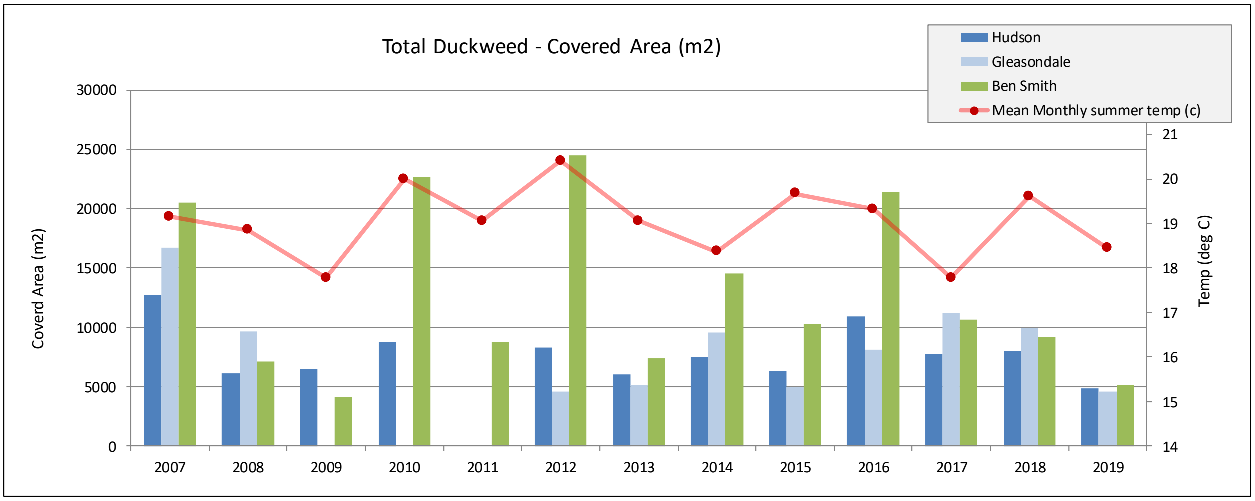


Table 20: Pearson Correlation Coefficients - Duckweed vs Temperature and Rainfall

	Hudson	Gleasondale	Ben Smith
Temperature Correlation	0.30	-0.30	0.64
Precipitation Correlation	-0.52	-0.26	-0.51

Figure 60: Total Floating Biomass - Ben Smith

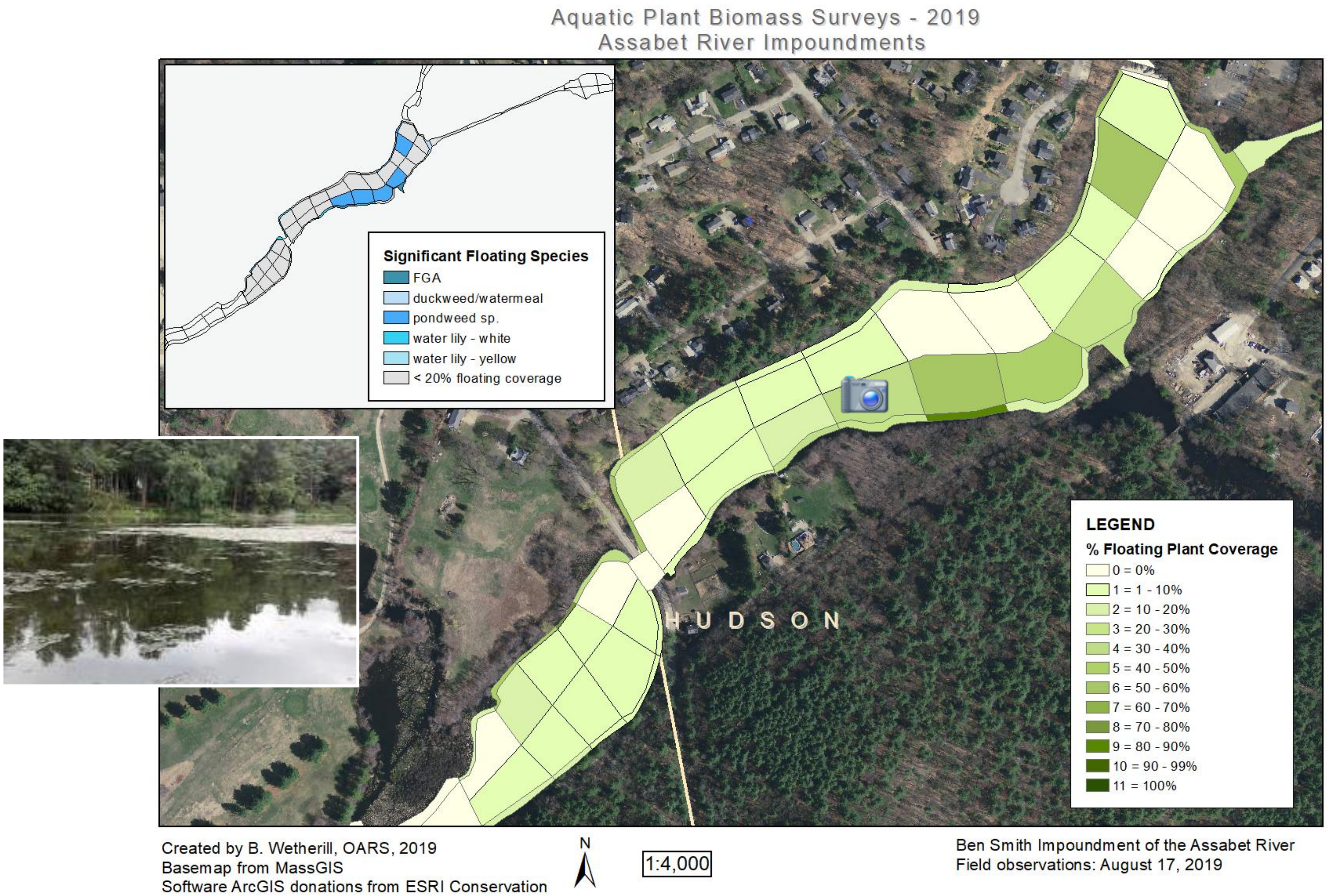


Figure 61: Total Floating Biomass - Gleasondale

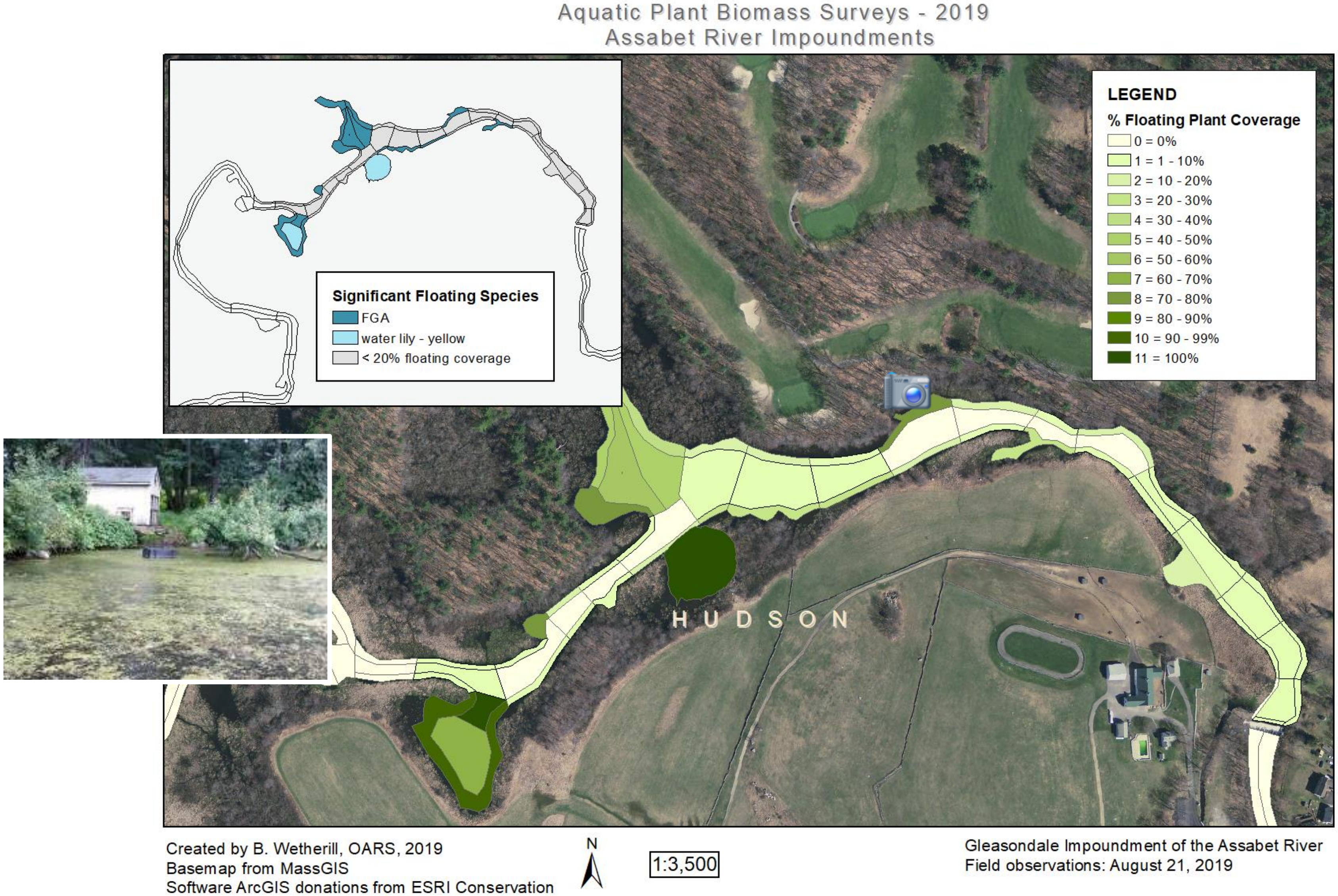
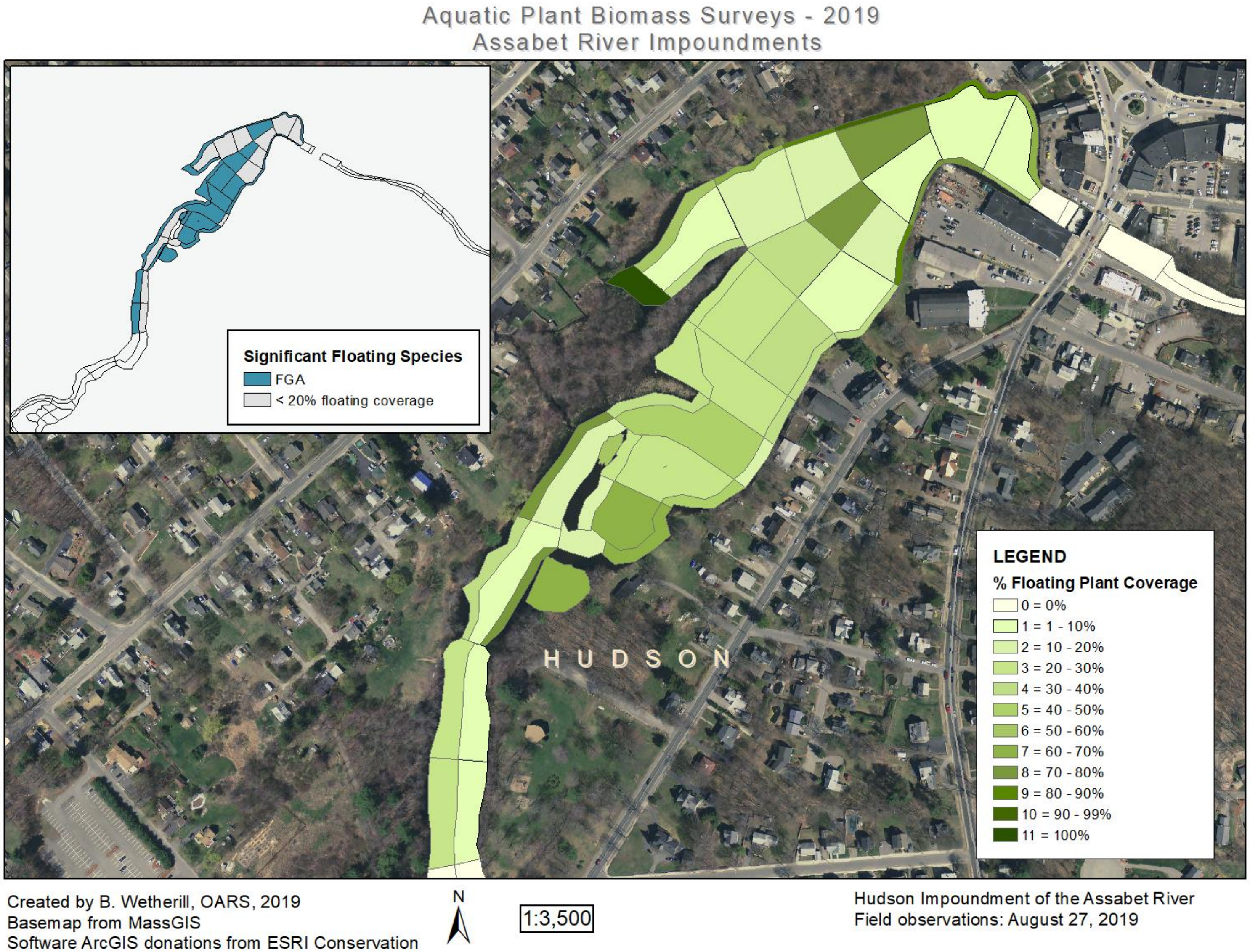


Figure 62: Total Floating Biomass - Hudson



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 2018 and 2019. Where possible with the data available, 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.

In 2018 and 2019, **Precipitation** was generally above average, except for two short near-drought periods in June-July 2018 and September-October 2019. River flows and groundwater levels were generally near or above historical averages for the whole period.

Water Temperature is an important characteristic for aquatic life that is particularly important to watch with concerns of global warming. Many of the tributaries that we monitor had temperature values exceeding target thresholds for fish. There were many exceedances of the Brown Trout threshold in July-August of both years and a few exceedances of the higher Brook Trout threshold. The trend analysis shows a possible upward trend in tributary temperatures since 1992, but it is not yet statistically significant.

pH readings are within threshold values, but data show a statistically significant upward trend in pH, especially driven by the 2012-2016 period. pH values are consistently the highest in the Lower Assabet, driven by ABT-062, which is just downstream of the Maynard and Acton wastewater treatment plants. pH values have declined in the last 2 years.

Conductivity levels are very high in the Upper Assabet and some tributaries. ABT-301 (below Westborough WWTP), HOP-011 (Hop Brook in Northborough), and RVM-005 (River Meadow Brook near Lowell) have consistently had very high conductivity levels – well above the EPA range for mixed fisheries. Additionally, our long-term data are showing a clear statistically significant upward trend in conductivity for all sections of the three rivers. Conductivity can be an indicator of a wide range of pollutants, so this is a condition that deserves more study.

Chloride can be an indicator of road salts in the water and sediments. It is very closely correlated with conductivity, but this correlation has a different signature at different times of year. Several of our sites had chloride levels in 2018-2019 exceeding the EPA Continuous Concentration Criterion. Two of these are the same sites that were highlighted for conductivity (ABT-301, HOP-011). Our data also support the hypothesis that road salts are retained in the soil and leached to the rivers all year long.

Dissolved Oxygen levels in the Assabet and Concord were consistently well above minimum water quality thresholds, which for DO is a favorable condition. Trend analysis shows that DO levels in the Assabet increased significantly in 2000 when WWTP improvements were made, but since 2000 there have not been any significant trends in DO. However, in the Sudbury, DO levels have been particularly low since 2017, meeting the "Class B - Aquatic Life" standard but not the "Class B – Warm Water Quality" standard. Hop Brook Sudbury has always failed to meet the Aquatic Life Standard for our period of record.

Total Phosphorus is the key indicator that we watched as improvements were being made to the waste water 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. The treatment plants are meeting their NPDES discharge permit limits, but we still have consistently high TP levels (over threshold) in Hop Brook downstream of the Marlborough Easterly WWTP. There are also intermittently high TP levels in many of the tributaries (River Meadow, Danforth, Nashoba, and Elizabeth). In 2019, we saw a slight jump in TP at many sites (with particularly large values at ABT-301 below the Westborough WWTP), which we have not been able to explain, and we have qualified the data due to data quality concerns. We will be studying this data quality issue further in 2020.

Nitrate levels have consistently been very high in the Assabet River for our whole period of record – well above the Ecoregion reference condition. The data clearly show a direct connection between the Westborough WWTP and these high levels. It should be noted that nitrate discharge was not addressed in the WWTP upgrades. On a positive note, our data show a statistically significant downward trend in Headwater and Tributary nitrate levels, and this downward trend does not seem to be restricted to only a couple of the tributaries. It is visible in all of the tributaries for which we have long-term data.

Total Suspended Solids have consistently been highest in the Concord River for our period of record, though not concentrated at any one location. In 2018 and 2019 Hop Brook Sudbury had abnormally high TSS levels during May/June/July of both years. This has not yet been explained, although some elevated TSS discharge levels were noted from the Marlborough Easterly WWTP.

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 have consistently been well below any toxicity threshold values for our whole period of record. We do see slightly elevated ammonia levels downstream of wastewater treatment plants (particularly Hop Brook Sudbury) and in River Meadow Brook, but these levels are still well below any concerns.

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 2018 and 2019 were primarily near the EPA Ecoregion XIV reference conditions, but the monitoring site next to Route 20 in Wayland had extremely high levels in August of both years. In future years, we will make an extra effort to document the visual depiction of chlorophyll at this site.

E. coli bacteria are an indicator of health safety of the river for recreational users. OARS started monitoring the river for bacteria in 2019. Our data from 2019 identified three sites where bacteria levels are a significant concern (SUD-237 in Ashland, CND-009 in Lowell, and ABT-162 in Hudson). We have initiated follow-up source testing in Ashland and Lowell for 2020. The remaining three sites had very good water quality and could possibly be considered as swimmable in terms of bacterial contamination if they perform similarly in future monitoring.

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 the years (except maybe for duckweed), but they do show a fairly strong positive correlation between biomass and air temperature and a negative correlation between biomass and rainfall. However, Gleasondale is an anomaly in both of these correlations. The 2019 survey highlighted indications of eutrophication in the Hudson impoundment, reflected primarily in the low diversity of floating plant species and the dominance of filamentous green algae. Addressing this Hudson impoundment eutrophication is an opportunity for the coming years.

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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. More: http://www.epa.gov/owow/watershed/wacademy/wam/step5.html

ammonia (NH_3): a form of nitrogen available for uptake by plants and microorganisms. Sources include the breakdown of organic nitrogen in sediments and untreated sewage. Other sources of ammonia include: fertilizer, home cleaning products and food processing. 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. For more information about the federal requirements on water quality standards: http://water.epa.gov/scitech/swguidance/standards/index.cfm. For the Massachusetts Surface Water Quality Standards: http://www.mass.gov/dep/service/regulations/314cmr04.pdf.

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 (I) 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 conductivity,” 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. Aquatic plants and bacteria in the sediments remove dissolved oxygen from the water when they respire (plants respire mainly at night). Therefore, the lowest dissolved oxygen concentrations of the day occur in the early in the morning. During the day plants add oxygen to the water column through 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." More information on the New England Ecoregions: http://www.epa.gov/wed/pages/ecoregions/new_eng_eco.htm

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. http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/upload/2009_01_13_criteria_goldbook.pdf

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; characterized by an inlet and an outlet stream.

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)**, and **total Kjeldahl nitrogen (TKN)**. **Total nitrogen** is calculated as the sum of TKN and nitrates. **Available nitrogen**, calculated as the sum of nitrate and ammonia, gives a measure of the nitrogen readily available for absorption by plants. Once absorbed, nitrogen is incorporated into proteins, amino acids, nucleic acids, and other molecules. 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.

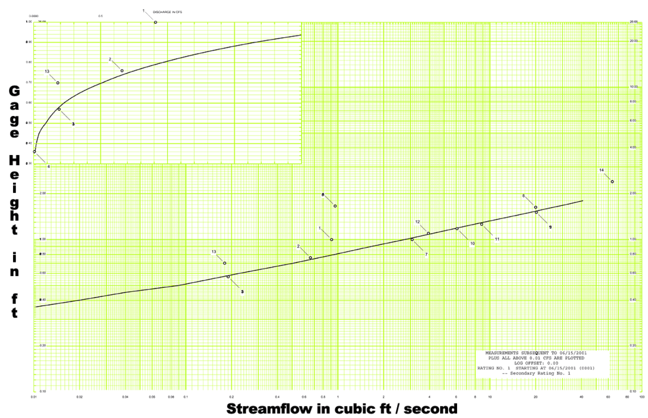
phosphorus: Plants need nutrients to grow; in particular, they need a balance of phosphorus (P) and nitrogen (N). Phosphorus is measured as **total phosphorus** (TP) and **ortho-phosphate** (ortho-P; soluble inorganic phosphate, the form required by plants). In most fresh waters, the concentration of

phosphorus available to plants is low enough that the plants cannot grow at their maximum rate. But in water bodies like the Assabet, where human activities add phosphorus to the environment, the added phosphorus allows much greater growth of aquatic plants (eutrophic conditions).
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"). Streamflow is measured on the mainstem Assabet in Maynard, Sudbury in Framingham, and Concord in Lowell at USGS gages and is reported on the USGS web page. Streamflow on the tributary streams is calculated from staff gage readings taken by OARS volunteers using a rating curve.

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 (figure below).



temperature affects the ecosystem in a number of ways: many organisms, especially cool water fish, are sensitive to high temperatures; the solubility of oxygen is lower in warmer water, decreasing the supply of dissolved oxygen; 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. More: http://www.epa.gov/owow/tmdl/overviewoftmdl.html

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 Water Quality Designations for the SuAsCo Rivers and Streams

Excerpted from 314 CMR 4.00: DIVISION OF WATER POLLUTION CONTROL
http://www.mass.gov/eea/docs/dep/water/laws/i-thru-z/tblfig.pdf

Boundary	Mile Point	Class	Qualifiers
Assabet River			
Source to Westborough WWTF	31.8 – 30.4	B	Warm Water High Quality Water
Westborough WWTF to outlet of Boones Pond	30.4 – 12.4	B	Warm Water
Outlet of Boones Pond to confluence with Sudbury River	12.4-0.0	B	Warm Water
Sudbury River			
Source to Fruit Street Bridge, Hopkinton	29.1	B	Warm Water Outstanding Resource Water
Fruit Street Bridge to Outlet to Saxonville Pond	29.1 - 16.2	B	Warm Water High Quality Water
Outlet Saxonville Pond to Hop Brook confluence	16.2 - 10.6	B	Aquatic Life High Quality Water
Hop Brook confluence to Assabet River confluence	10.6 - 0.00	B	Aquatic Life
Denney Brook, Jackstraw Brook, Piccadilly Brook, Rutters Brook and Whitehall Brook		B	Outstanding Resource
Hop Brook source to Sudbury River confluence	9.7 – 0.0	B	Warm water
Concord River			
Confluence of the Assabet and Sudbury to Billerica water supply intake	15.4 – 5.9	B	Warm Water Treated Water Supply
Billerica water supply intake to Rogers St.	5.9 – 1.0	B	Warm Water
Rogers Street to confluence Merrimack River	1.0 – 0.0	B	Warm Water CSO
Assabet River			
Source to Westborough WWTF	31.8 - 30.4	B	Warm Water High Quality Water
Westborough WWTF to outlet of Boones Pond	30.4 – 12.4	B	Warm Water
Outlet Boones Pond to confluence with Sudbury River	12.4 – 0.0	B	Warm Water

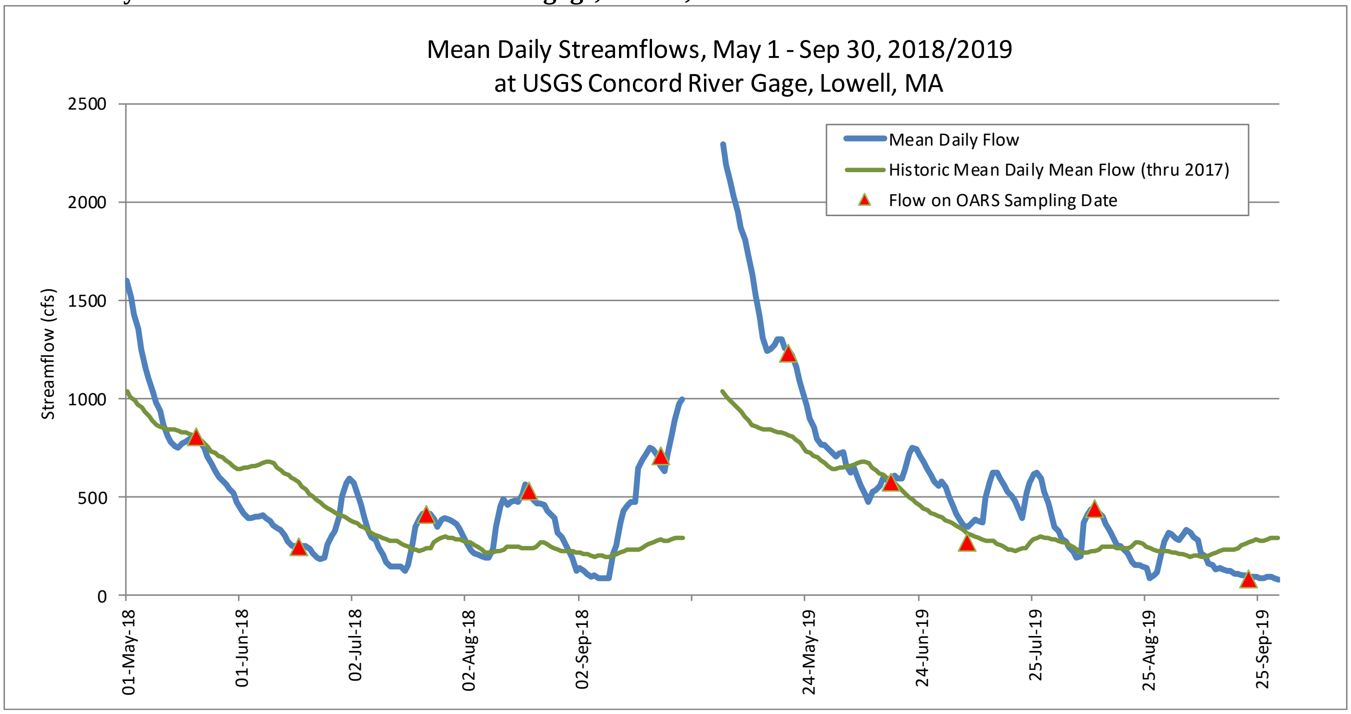
Massachusetts Division of Fisheries and Wildlife List of Coldwater Fishery Resources in the Concord (SuAsCo) basin (Accessed January 2018: http://www.mass.gov/eea/agencies/dfg/dfw/wildlife-habitat-conservation/coldwater-fish-resources-list.html)

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

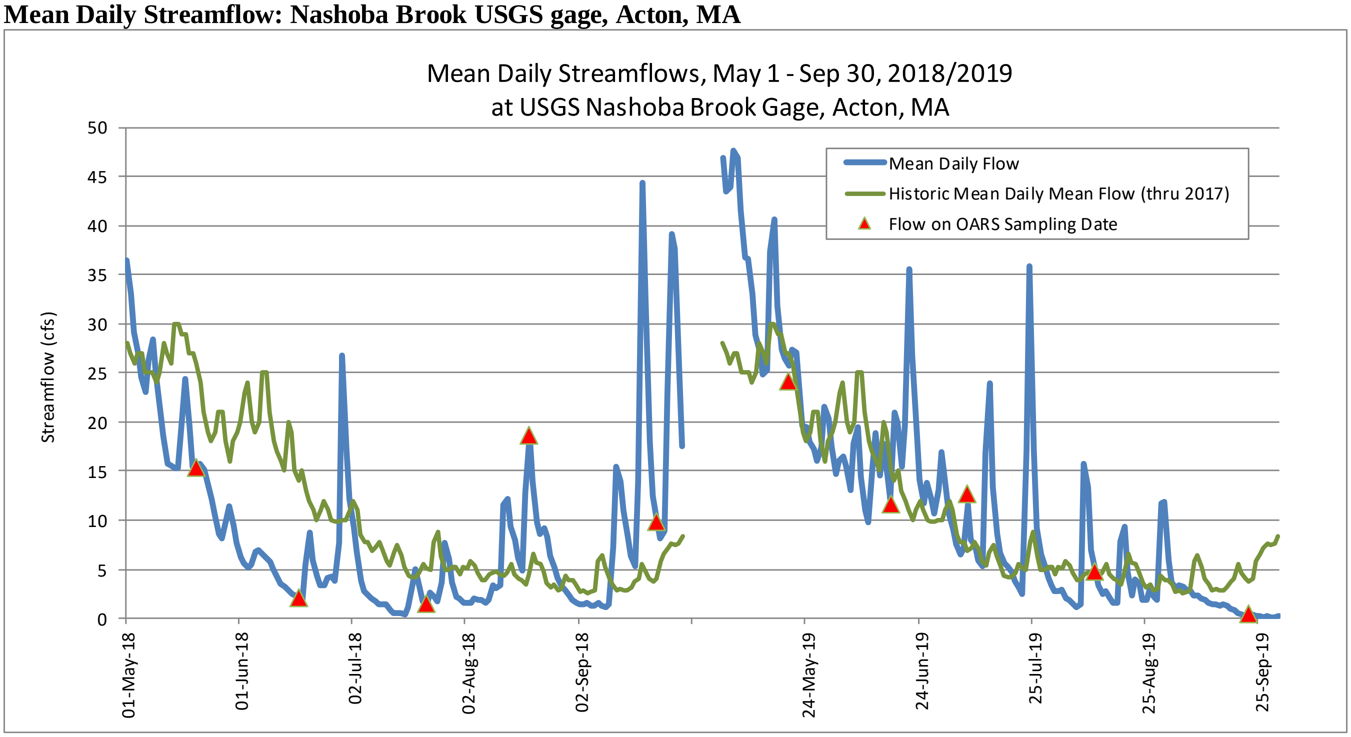
Appendix II   Streamflow Data from USGS Gages

(see Figure 4 and Figure 5 for Assabet and Sudbury River Mean Daily Streamflow)

Mean Daily Streamflow: Concord River USGS gage, Lowell, MA



Mean Daily Streamflow: Nashoba Brook USGS gage, Acton, MA



Appendix III Mainstem Reach and Tributary Statistics

	Reach Statistics 2018 (calculated on 1/2 detection level where sample is Below Detection Limit)															
	Reach	# Sites	statistic	Avg. Time	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 28, 2018	Concord Mainstem	2	Mean	9:43 AM	6.2	95	11.7	445	7.1	2.0	0.015	0.005	0.61	0.05	204	
	Headwater & Tribs	7	Mean	10:19 AM	6.6	96	11.9	* 313	7.4	0.9	0.007	0.005	0.26	0.05	139	
	Lower Assabet Mainstem	2	Mean	9:45 AM	6.5	102	12.5	426	7.3	1.0	0.015	0.005	0.85	0.05	193	
	Sudbury Mainstem	2	Mean	9:27 AM	6.6	99	12.1	455	7.2	1.5	0.008	0.005	0.33	0.05	215	
	Upper Assabet Mainstem	1	Single	11:30 AM	9.3	111	12.6	760	7.0	2.0	0.020	0.005	4.30	0.05	322	
May 20, 2018	Concord Mainstem	2	Mean	6:31 AM	17.4	74	7.1	515	7.1	6.0	0.035	0.005	0.28	0.05		
	Headwater & Tribs	8	Mean	7:11 AM	14.9	90	9.0	410	7.0	2.4	0.019	0.005	0.18	0.06		
	Hop Brook, Sudbury	1	Single	6:52 AM	14.3	37	3.7	453	6.7	32.0	0.050	0.020	0.61	0.05		
	Lower Assabet Mainstem	2	Mean	6:41 AM	16.1	94	9.2	466	7.1	4.0	0.030	0.010	0.68	0.05		
	Sudbury Mainstem	5	Mean	6:26 AM	16.1	59	5.8	542	6.9	9.0	0.016	0.005	0.14	0.05		
	Upper Assabet Mainstem	1	Single	7:40 AM	16.6	95	9.2	443	7.2	3.0	0.040	0.010	3.40	0.05		
June 17, 2018	Assabet Impounded Sites	3	Mean	7:05 AM	20.3	100	9.0	788	7.4							
	Concord Mainstem	4	Mean	7:12 AM	20.6	100	8.9	636	7.4	8.3	0.043	0.005	0.31	0.05		
	Headwater & Tribs	8	Mean	7:27 AM	18.3	82	7.7	* 555	7.3	3.7	0.036	0.006	0.26	0.07		
	Hop Brook, Sudbury	1	Single	7:00 AM	20.0	41	3.9	509	7.0	23.0	0.160	0.060	0.84	0.27		1.0
	Lower Assabet Mainstem	3	Mean	6:50 AM	20.4	* 91	8.2	727	7.6	4.3	0.023	0.005	1.30	0.05		
	Sudbury Mainstem	5	Mean	6:35 AM	19.8	* 74	6.7	662	7.0	* 11.6	0.021	0.012	0.16	0.05		7.9
	Upper Assabet Mainstem	3	Mean	7:18 AM	19.2	89	8.2	922	7.4	2.7	0.033	0.010	* 6.77	0.05		
July 22, 2018	Concord Mainstem	4	Mean	6:49 AM	25.0	90	7.4	639	7.2	5.5	0.018	0.006	0.54	0.05		
	Headwater & Tribs	9	Mean	11:56 PM	22.0	82	7.1	* 566	7.3	4.5	0.044	0.014	0.14	0.06		
	Hop Brook, Sudbury	1	Single	7:15 AM	21.1	15	1.3	577	6.7	7.0	0.060	0.060	0.25	0.05		4.4
	Lower Assabet Mainstem	3	Mean	6:32 AM	23.7	89	7.6	579	7.4	3.7	0.023	0.007	0.60	0.05		
	Sudbury Mainstem	5	Mean	6:34 AM	23.6	59	5.0	624	6.7	6.4	0.019	0.012	0.04	0.05		5.3
	Upper Assabet Mainstem	4	Mean	2:47 AM	22.2	79	7.4	612	7.2	2.0	0.015	0.010	2.33	0.05		

	Reach	# Sites	statistic	Avg. Time	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 19, 2018	Assabet Impounded Sites	3	Mean	7:33 AM	23.6	* 70	5.9	570	7.2							
	Concord Mainstem	4	Mean	6:55 AM	24.8	75	6.2	580	7.2	6.0	0.039	0.006	0.39	0.05	178	
	Headwater & Tribs	8	Mean	7:18 AM	22.0	79	6.9	416	7.2	* 9.9	0.034	0.011	0.12	0.05	125	
	Hop Brook, Sudbury	1	Single	7:23 AM	22.1	11	0.9	537	7.0	10.0	0.210	0.130	0.10	0.05	151	2.3
	Lower Assabet Mainstem	3	Mean	7:02 AM	23.8	91	7.6	558	7.4	3.7	0.023	0.015	0.65	0.05	153	
	Sudbury Mainstem	5	Mean	6:47 AM	24.1	* 41	* 3.4	612	7.0	2.5	0.024	0.017	0.07	0.05	192	6.5
	Upper Assabet Mainstem	3	Mean	7:18 AM	22.2	86	7.4	647	7.1	4.7	0.018	0.012	1.53	0.05	211	
September 23, 2018	Assabet Impounded Sites	3	Mean	7:49 AM	17.3	83	8.0	461	7.0							
	Concord Mainstem	2	Mean	7:12 AM	18.5	78	7.4	460	6.9	5.5	0.035	0.025	0.27	0.05		
	Headwater & Tribs	8	Mean	7:46 AM	16.3	90	8.8	* 411	7.2	4.4	0.023	0.022	0.13	0.06		
	Hop Brook, Sudbury	1	Single	7:32 AM	15.4	37	3.7	467	6.8	0.5	0.040	0.030	0.78	0.05		
	Lower Assabet Mainstem	2	Mean	7:36 AM	17.8	89	8.5	448	7.0	4.0	0.030	0.030	0.56	0.05		
	Sudbury Mainstem	5	Mean	7:05 AM	18.3	* 52	4.8	470	6.8	2.0	0.020	0.020	0.05	0.05		
	Upper Assabet Mainstem	1	Single	8:10 AM	17.6	97	9.2	418	7.4	2.0	0.010	0.010	0.81	0.05		
November 11, 2018	Concord Mainstem	2	Mean	9:27 AM	6.4	88	10.8	251	6.7	5.0	0.075	0.015	0.13	0.05	101	
	Headwater & Tribs	8	Mean	1:10 PM	5.1	95	12.1	179	6.9	0.7	0.064	0.008	0.18	0.05	69	
	Lower Assabet Mainstem	2	Mean	9:15 AM	5.7	98	12.3	246	7.1	1.5	0.075	0.020	0.40	0.05	90	
	Sudbury Mainstem	2	Mean	8:31 AM	7.2	82	9.9	264	6.9	1.0	0.060	0.010	0.14	0.05	110	
	Upper Assabet Mainstem	1	Single	9:45 AM	7.0	87	10.5	197	6.8	1.0	0.070	0.005	0.87	0.05	81	

* = Median significantly different from Mean
Blank = not sampled/not recorded/censored

	Reach Statistics 2019 (calculated on 1/2 detection level where sample is Below Detection Limit)															
	Reach	# Sites	statistic	Avg. Time	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 13, 2019	Concord Mainstem	2	Mean	11:40 AM	2.3	102	13.9	655	7.0	1.3	0.055	0.005	0.84	0.05	218	
	Headwater & Tribs	7	Mean	1:25 PM	2.4	103	14.1	* 539	7.1	1.9	0.060	0.005	0.48	0.07	* 151	
	Lower Assabet Mainstem	2	Mean	3:33 PM	3.3	110	14.6	775	7.2	1.5	0.060	0.005	1.15	0.05	230	
	Sudbury Mainstem	2	Mean	12:02 PM	3.3	105	13.9	667	7.2	0.8	0.045	0.005	0.64	0.05	210	
	Upper Assabet Mainstem	1	Single	12:45 PM	6.7	110	13.4	749	6.9	2.0	0.150	0.070	3.40	0.05	202	
May 19, 2019	Assabet Impounded Sites	3	Mean	7:10 AM	15.5	94	9.4	* 502	7.0							
	Concord Mainstem	2	Mean	6:47 AM	15.4	93	9.3	458	6.9	3.0	0.015	0.013	0.26	0.05		
	Headwater & Tribs	8	Mean	7:15 AM	15.0	98	9.9	* 406	7.1	2.8	0.023	0.009	0.22	0.05		
	Hop Brook, Sudbury	1	Single	7:47 AM	15.1	43	4.2	438	6.8	0.5	0.005	0.005	0.72	0.05		
	Lower Assabet Mainstem	2	Mean	7:03 AM	15.6	102	10.2	461	7.0	4.0	0.025	0.020	0.66	0.05		
	Sudbury Mainstem	5	Mean	7:06 AM	15.9	78	7.8	466	7.0	2.4	0.012	0.005	0.22	0.05		
	Upper Assabet Mainstem	1	Single	8:15 AM	14.9	98	9.9	578	7.1	4.0	0.040	0.010	1.90	0.05		
June 16, 2019	Assabet Impounded Sites	3	Mean	7:24 AM	19.2	93	8.6	697	7.1							
	Concord Mainstem	4	Mean	7:06 AM	20.7	77	6.9	531	7.0	20.0	0.100	0.020	0.36	0.05		
	Headwater & Tribs	8	Mean	7:26 AM	19.0	86	8.0	* 461	7.1	3.3	0.088	0.022	0.27	0.05		
	Hop Brook, Sudbury	1	Single	7:00 AM	19.3	30	2.8	491	6.8	19.0	0.150	0.040	0.59	0.05		1.0
	Lower Assabet Mainstem	3	Mean	7:03 AM	20.1	95	8.6	681	7.2	4.0	0.080	0.020	1.23	0.09		
	Sudbury Mainstem	5	Mean	7:10 AM	20.4	55	5.0	465	6.8	2.2	0.072	0.017	0.11	0.05		3.4
	Upper Assabet Mainstem	3	Mean	7:32 AM	18.5	87	8.1	784	7.2	4.0	0.063	0.020	* 2.60	0.07		
July 7, 2019	Assabet Impounded Sites	3	Mean	7:16 AM	25.2	* 49	3.9	* 850	7.2							
	Concord Mainstem	4	Mean	6:53 AM	26.7	74	5.9	529	7.0	5.0	0.011	0.005	0.21	0.05		
	Headwater & Tribs	8	Mean	7:23 AM	23.8	* 78	6.6	* 451	7.2	* 7.3	0.033	0.009	0.30	0.06		
	Hop Brook, Sudbury	1	Single	7:28 AM	23.7	16	1.3	411	7.3	6.0	0.180	0.120	0.39	0.47		6.2
	Lower Assabet Mainstem	3	Mean	6:57 AM	26.2	* 84	6.8	* 731	7.6	2.2	0.005	0.005	1.05	0.05		
	Sudbury Mainstem	5	Mean	6:48 AM	26.0	* 48	3.9	425	7.5	4.2	0.036	0.008	0.11	0.05		4.9
	Upper Assabet Mainstem	3	Mean	7:30 AM	23.8	70	5.9	* 1006	7.0	* 6.3	0.077	0.010	2.37	0.05		

	Reach	# Sites	statistic	Avg. Time	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 11, 2019	Assabet Impounded Sites	3	Mean	7:18 AM	22.2	* 92	8.0	541	7.0							
	Concord Mainstem	4	Mean	7:21 AM	23.6	80	6.8	545	7.0	6.0	0.055	0.020	0.44	0.05	144	
	Headwater & Tribs	8	Mean	7:25 AM	20.3	85	7.7	* 438	7.1	1.4	0.066	0.019	0.16	0.06	114	
	Hop Brook, Sudbury	1	Single	7:31 AM	19.5	19	1.7	489	6.8	10.0	0.180	0.070	0.38	0.10		6.8
	Lower Assabet Mainstem	3	Mean	6:49 AM	22.6	91	7.8	557	7.3	1.7	0.037	0.020	1.03	0.05	143	
	Sudbury Mainstem	5	Mean	7:00 AM	22.8	* 50	4.3	482	7.0	4.0	0.064	0.024	0.04	0.05	131	* 22.0
	Upper Assabet Mainstem	3	Mean	7:14 AM	20.7	* 78	* 7.1	561	7.2	2.0	0.073	0.030	1.93	0.05	130	
September 22, 2019	Assabet Impounded Sites	3	Mean	8:11 AM	17.3	* 85	8.1	878	7.3							
	Concord Mainstem	2	Mean	7:40 AM	19.2	99	9.1	668	7.5	6.5	0.023	0.005	0.94	0.05		
	Headwater & Tribs	8	Mean	8:21 AM	15.7	* 78	7.7	* 613	7.3	4.3	0.011	0.006	0.21	0.05		
	Hop Brook, Sudbury	1	Single	8:20 AM	15.4	58	5.8	580	7.0	2.0	0.050	0.030	1.60	0.05		
	Lower Assabet Mainstem	2	Mean	8:03 AM	17.4	83	7.9	863	7.3	0.5	0.005	0.005	2.50	0.05		
	Sudbury Mainstem	5	Mean	7:47 AM	18.7	83	7.7	* 605	7.2	3.3	0.015	0.008	0.35	0.08		
	Upper Assabet Mainstem	1	Single	8:10 AM	18.5	76	7.1	1000	7.1	0.5	0.030	0.005	13.00	0.05		
November 10, 2019	Concord Mainstem	2	Mean	8:45 AM	5.2	93	11.7	523	7.2	4.0	0.035	0.013	0.38	0.05		
	Headwater & Tribs	7	Mean	9:59 AM	3.4	92	12.2	* 434	7.3	1.8	0.053	0.009	0.16	0.05		
	Lower Assabet Mainstem	2	Mean	9:13 AM	4.6	97	12.5	633	7.6	4.5	0.075	0.020	1.45	0.05		
	Sudbury Mainstem	2	Mean	8:21 AM	5.2	93	11.7	466	7.4	2.0	0.023	0.005	0.14	0.05		
	Upper Assabet Mainstem	1	Single	9:50 AM	8.8	95	11.0	1622	6.7	7.0	0.280	0.160	7.10	0.05		

* = Median significantly different from Mean
Blank = not sampled/not recorded/censored

Appendix IV 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 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 2018 and 2019 includes:

Date	Parameter	Qualified/ Censored	Sites	Problem / Action
6/17/2018	TP	Q	HBS-016	Field duplicate exceeded DQO. Comment on field sheet "impossible to keep samples from getting silt in them"
6/17/2018	TSS	Q	HBS-016	Field duplicate exceeded DQO. Comment on field sheet "impossible to keep samples from getting silt in them"
6/17/2018	NH3	Q	HBS-016	Field duplicate exceeded DQO. Comment on field sheet "impossible to keep samples from getting silt in them"
7/22/2018	TSS	Q	All sites	2 field duplicates missed DQO.
7/22/2018	TP	Q	All sites	1 TP field duplicate missed DQO and 2 TSS field duplicates missed.
8/19/2018	TSS	Q	Middle Assabet sites	Field duplicate missed DQO.
8/19/2018	TP	Q	Concord sites	Field duplicate missed DQO.
9/23/2018	TSS	Q	Upper Assabet sites	Field duplicate missed DQO.
11/11/2018	TP	Q	Concord sites	Field duplicate missed DQO.
3/13/2019-3/14/2019	Conductivity	Q	Middle and Upper Assabet sites	Post-sampling calibration exceeded DQO
5/19/2019	DO	Q	Sudbury sites	Membrane was old. Post-sampling calibration exceeded DQO
5/19/2019	TP	Q	Lower Assabet sites	Field duplicate missed DQO by small amount
6/16/2019	TP	Q	All sites	All 3 field duplicates missed DQO
6/16/2019	pH	NR	Upper Assabet sites	Post-sampling calibration exceeded DQO and data looked incorrect
6/17/2019	*E. coli*	Q	Concord sites	Sample storage temperature exceeded 10°C for a significant period.
7/7/2019	TP	Q	Lower Assabet sites	Field duplicate missed DQO by small amount

8/11/2019	TP	Q	All sites	All 3 field duplicates missed DQO
8/11/2019	DO	NR	ABT-144	Abnormally high DO value for one site. Calibration data looked fine.
8/11/2019	ortho-P	Q	Middle Assabet sites	Field duplicate missed DQO by small amount
8/19/2019	Chlorophyll-a	Q	SUD-086	Original value for this site was abnormally high, but field duplicate returned a normal value. Used field-duplicate for data.
8/26/2019	*E. coli*	Q	CND-009	Original sample yielded ND (unusual for this site, but field duplicate returned a normal value. Used field duplicate data.
9/16/2019	*E. coli*	Q	All sites	All samples were held 6-8 hours before analysis.
11/10/2019	TP	Q	Upper Assabet sites	Field duplicate missed DQO by small amount

Data Quality Objectives

Instrument/ Laboratory	Parameter	Data Quality Objectives			
		Accuracy	**Field Precision**	**Lab Precision**[a]	**Field Blank Cleanliness**
YSI 6000-series Thermistor probe	temperature	± 1 °C	< 10% RPD	< 10% RPD	na
YSI 6000-series Glass Electrode	pH	± 0.2 S.U. at pH 7.00	± 0.5 S.U.	± 0.5 S.U.	na
YSI 6000-series Rapid Pulse	DO	± 5% at 100% saturation	< 10% RPD or < 20% RPD if <4.0 mg/L	< 10% RPD	na
YSI 6000-series 4-electrode cell	Conductivity	± 50 µS/cm at 0 and 1000 µS/cm	< 20% RPD or < 30% RPD if <250 µS/cm	< 20% RPD	na
Nashoba Analytical	TSS	85-115% recovery of lab fortified blank	< 30% RPD or < ± 1 mg/L if < 2 mg/L	< 20% RPD	BDL
Nashoba Analytical	TP	85-115% recovery of lab fortified blank	< 20% RPD or ± 0.01 mg/L if <0.030 mg/L	< 20% RPD	BDL
Nashoba Analytical	ortho – P	85-115% recovery of lab fortified blank	< 20% RPD or ± 0.01 mg/L if <0.030 mg/L	< 20% RPD	BDL
Nashoba Analytical	NO3	85-115% recovery of lab fortified blank	< 30% RPD	< 20% RPD	BDL
Nashoba Analytical	NH3	85-115% recovery of lab fortified blank	< 30% RPD	< 20% RPD	BDL
Alpha Analytical	Chlorophyll *a*	75 – 125% recovery of lab QC sample (with known Chl *a* content)	< 20% RPD or ± 2.0 if < 15 µg/L	< 20% RPD	BDL

[a] Lab Precision for field parameters is evaluated by comparing side-by-side meter readings in a bucket of river water.

Note that in 2019 we qualified 45% of our Total Phosphorus measurements because field duplicate RPD values exceeded the Data Quality Objective of ±0.01 mg/L. Most of these exceedances occurred when measurements were very close to the Minimum Detection Limit for TP (0.01 mg/L), which leads us to think that the DQO for TP may be overly stringent. Our analysis of Total Phosphorus spanning many years of data raised a question about the allowable laboratory holding time for these samples prior to analysis. We plan to review the TP DQOs and laboratory procedures prior to our next sampling season. We also plan to submit splits to another laboratory for selected sampling events for backup testing.

Appendix V Water Quality Data

(contact OARS for full data set)

Appendix VI Aquatic Plant Biomass Survey Data 2005 - 2019

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	14359	22317	9632	2297	2770	4917
	2006	27233	15496	2813	3923	4491	2334
	2007	0	23466	10510	16708	3623	1984
	2008	2350	46928	2059	2432	2385	136
	2009	11137	32268	9193	2453	1241	0
	2010	8856	28152	328	5638	1166	12151
	2011	na	na	na	na	na	na
	2012	4268	11859	23204	5861	3071	8028
	2013	6091	3291	13083	5776	8919	19132
	2014	2582	14147	16239	3417	5188	15018
	2015	0	11270	12278	3918	15675	13149
	2016	3005	11618	12369	0	3299	19013
	2017	0	23449	22646	3830	0	6365
	2018	1404	23188	23843	6038	957	269
	2019	0	23047	21892	4046	5863	983
Ben Smith Impoundment	2005	28956	36541	2873	444	648	5339
	2006	45966	20107	944	4171	1178	2436
	2007	5600	44197	4219	4770	0	16015
	2008	15954	52967	4799	1081	0	0
	2009	45010	11103	6890	7976	3823	0
	2010	14329	25799	6351	11656	8779	7888
	2011	17858	51623	591	3657	1073	0
	2012	10212	21619	20419	6242	4728	11581
	2013	26352	37015	6088	1000	3198	1148
	2014	2643	39721	25551	2047	1511	3329
	2015	12746	38965	13520	1067	7439	1065
	2016	0	23187	26493	4817	7202	8708
	2017	0	19739	29076	7464	4829	10135
	2018	488	47051	25092	601	1570	0
	2019	19757	32404	14058	8090	492	0
Gleasondale Impoundment (2009 – 2011 not assessed)	2005	24626	1991	2056	0	2011	9797
	2006	12402	6518	3523	0	4112	12993
	2007	0	19821	6015	3937	728	9979
	2008	2293	24230	3619	1869	6003	2467
	2009	na	na	na	na	na	na
	2010	na	na	na	na	na	na
	2011	na	na	na	na	na	na
	2012	19768	9029	3061	198	4766	3659
	2013	9355	9656	3365	3143	4738	10224
	2014	7227	16156	2856	3522	4979	5741
	2015	8106	8339	6316	7018	3989	4764

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
	2016	5206	15306	5027	2507	3832	7592
	2017	1712	15967	11502	2253	4850	5680
	2018	7151	10187	9995	889	4547	7636
	2019	7296	18610	4349	4765	1825	2702
	2005	24626	1991	2056	0	2011	9797

Conversion Factors (based on mean OARS field measurements and trend line):
Biomass (g/m^2): Class 0 = 0 g/m^2; Class 1 = 427 g/m^2; Class 2 = 1186 g/m^2; Class 3 = 2000 g/m^2; Class 4 = 2855 g/m^2; Class 5 = 3782 g/m^2.
Area * class conversion factor /1000 = total wet weight in kilograms.