MYSTIC LAKE STATUS UPDATE 2020

Prepared by Water Resource Services, Inc.

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Draft Report
October 2020

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Introduction

Mystic Lake is a Great Pond under the laws of the Commonwealth of Massachusetts and is a major water resource in the village of Marston's Mills in the Town of Barnstable on Cape Cod. Along with Middle Pond and Hamblin Pond, it comprises what are called the Indian Ponds (Figure 1). Mystic Lake covers 60 ha (149 ac) and provides habitat and recreational opportunity to the public as well as those living in the private residences along its shore. Mystic Lake achieves a maximum depth of 14.3 m (47 feet), with an average depth of 6.4 m (21 feet) and total volume estimated at 3.86 million m^3 (3128 ac-ft). Water levels fluctuate about 2 feet over the course of the year and are tied mainly to direct precipitation and ground water levels. Mystic Lake flows into Middle Pond, which exits to the Marston's Mills River, through which there is an annual herring run.

In the 1980s and early 1990s, Mystic Lake and Middle Pond were considered to be in excellent condition, with high water clarity and other positive attributes, including large populations of seven species of freshwater mussels, three of which were listed as rare species in Massachusetts. Hamblin Pond, in comparison, had suffered from cyanobacteria blooms for decades and, despite having a large town beach complex, was not useable for contact recreation for much of most summers. Hamblin Pond was devoid of mussels but was stocked with trout each year to maintain a put-and-take fishery. Hamblin Pond was treated with aluminum compounds in 1995 to inactivate phosphorus in surficial sediment that was responsible for high internal loading and support of algae blooms. That treatment greatly enhanced conditions in Hamblin Pond for 18 years, after which internal loading resumed rather abruptly and algae blooms returned. In 2015 Hamblin Pond was retreated and cyanobacteria blooms were again minimized while water clarity was maximized.

During the period after the first treatment of Hamblin Pond, a decline in the water quality of Mystic Lake was evident. There were signs of possible deterioration in Middle Pond, but conditions there were still much better than in Mystic Lake, which experienced periodic cyanobacteria blooms and low oxygen in deeper water. Conditions in all three Indian Ponds were detailed in a report from the Cape Cod Commission in 2006, and further investigation was conducted by AECOM in 2008. A dense layer of cyanobacteria was detected near the thermocline in Mystic Lake in 2008, but the thermocline was deep (8 m) and those algae did not come to the surface. A proposal to treat Mystic Lake with aluminum in the same manner as Hamblin Pond was rejected by the Natural Heritage and Endangered Species Program (NHESP) as too risky with regard to the highly regarded mussel community. In 2009 the same dense cyanobacteria layer (comprised mainly of *Planktothrix*) formed at the thermocline in Mystic Lake, but the thermocline had formed at a depth of only 5 m that year. A mixing event in August 2009 allowed the bloom to reach shallow water, spread over the lake, and move into Middle Pond. Approximately 2 million mussels died over the next few weeks, representing over 90% of each population, based on a study by Biodrawversity in 2010.

Planktothrix often produces a nerve toxin, and some mussels were found live but in a paralyzed state that went away after they were placed in well water for several hours; this is consistent with nerve toxins, but the link was never definitively proven. Oxygen, pH, pesticides and other common causes of mortality were ruled out, and samples of dead mussels collected later did contain some cyanotoxins, but the claim that cyanobacteria killed the mussels remains informed speculation. It is clear that water with the cyanobacteria was the agent of mussel death, as mussels in the path of water entering Middle Pond from Mystic Lake also died. Oxygen and pH were not causal factors. A second die off of mussels occurred in summer of 2010, further reducing the populations and increasing the urgency for treatment.

Figure 1. Mystic Lake, Middle Pond and Hamblin Pond in Marston's Mills, Massachusetts

Approval to treat Mystic Lake with aluminum was granted in 2010, but a limit of 50 g/m^2 was imposed by NHESP to protect the remaining mussels. Sediment testing suggested that some areas would benefit by a dose of 75 g/m^2, but the 50 g/m^2 limit was observed. Mystic Lake was treated in the last half of September and early October of 2010. Middle Pond was not treated. A required study of the impact of treatment on mussels, conducted by Biodrawversity in 2011, found no mortality or behavioral anomalies, but mussel populations remained very low compared to pre-2009 levels. Mystic Lake was then monitored through 2011 and a report was prepared by WRS in 2012 that detailed pre- and post-treatment water quality and biological resources. Conditions improved markedly, but not to the extent observed in Hamblin Pond.

Additional monitoring was conducted by WRS in 2012, most importantly including retesting of surficial sediment for Fe-P, which was much lower than before treatment. The Indian Ponds Association (IPA) conducts periodic monitoring of temperature, oxygen and water clarity and participates in the Pond and Lake Steward (PALS) program, so there are some data for the period of 2013-2016, but nutrient chemistry was not assessed more than once per summer and plankton was not assessed in any detail. The Town of Barnstable contracted with WRS to expand the monitoring program in 2017, to provide an update on the general state of Mystic and Middle Ponds.

The condition of Mystic Lake through 2017 was found to be much improved over pre-treatment conditions in 2010 and earlier, but occasional algae blooms were still reported in some years and late summer cyanobacteria surface accumulations were detected in 2017. Low oxygen was still detected near the lake bottom at water depths >30 feet. Phosphorus did still accumulate in the deeper water layer, indicative of release from sediment under deeper water, but not to the extent observed before treatment. Data for the upper 10 cm of sediment at water depths >25 feet revealed continued low levels of available phosphorus, similar to what was observed in 2012. However, the potential upward movement of phosphorus from the bottom of the core to the surface was not examined and could be important to internal phosphorus loading.

The mussel survey of 2011 was repeated by Biodrawversity in 2017, the same contractor from all previous mussel surveys of the Indian Ponds. Quantitative sampling revealed a major recovery of mussel species that were greatly depressed by the mortality events of 2009 and 2010. While a full recovery is still some years away, the progress made since treatment in 2010 was remarkable. While oxygen and cyanobacteria issues remain in Mystic Lake to some extent, conditions with regard to mussel health and reproduction have clearly been markedly improved.

Project Approach

Field water quality profiles were obtained at the deepest location in Mystic Lake and conditions near the bottom were also assessed at two additional stations (stations 3, 7 and 9 from past studies, Figure 2) with a Hach DS5 that measures oxygen, temperature, pH, conductivity, turbidity and chlorophyll-a. The instrument is calibrated prior to deployment in the field. Measurements were made at no greater than 2 m intervals from surface to bottom, with the deepest measurements collected near the sediment-water interface.

Water samples were collected at the same three stations, from near the surface and close to the bottom at station 7 and near the bottom at stations 3 and 9, to observe the change in phosphorus (P) and iron (Fe) levels and any build-up in the bottom waters. Samples were collected with a 2 L horizontal alpha bottle that was lowered to the target depth and closed with a messenger weight slid down the rope.

Figure 2. Mystic Lake sampling stations in 2020

The sampler was rinsed with lake water between samples and moved around at the target depth to promote exchange of water at the target depth. Samples were placed in dedicated plastic bottles with acid preservative, kept on ice in the dark, and delivered to the lab within 2 days. Samples were processed in the lab in accordance with standard methods.

Algae and planktonic animals are important links in the aquatic food web. Knowledge of the types and density of each in a lake over time helps with interpretation of the impact of phosphorus loading on the aquatic system. Blooms of cyanobacteria are of particular concern and have been reported from both waterbodies in the past. Zooplankton represent energy flow between algae and small fish, and the abundance and mean length of crustacean zooplankton can be a reflection of the fish community. As there are alewife in Mystic Lake and those planktivores can greatly depress zooplankton size and abundance, maximizing algae biomass for whatever level of fertility is present, this was considered an important factor to assess.

Phytoplankton samples were collected from just below the surface of Mystic Lake at station 7. If oxygen or chlorophyll-a peaked at an intermediate depth, possibly signaling an accumulation of algae at some depth, and additional sample at that depth was obtained. Whole water samples were collected in 250 mL bottles and preserved with glutaraldehyde to a concentration of 0.5%. Samples were settled in the lab and concentrated before quantitative examination under phase contrast optics at 200-400X. The final multiplication factor for cells observed to cells/mL of raw sample was <25 in all cases.

Zooplankton samples were collected by towing a net with 80 um mesh through 30 m of water from the same station where phytoplankton were collected. With a net diameter of 5 inches, this results in 380 L of water being filtered. Samples were preserved with glutaraldehyde at a concentration of 2%, settled in the lab, and quantitatively examined under phase contrast optics at 100X magnification. Final multiplication factors for converting observed specimens to density per liter were <1 in all cases.

Under anoxic conditions, P is often released from Fe-P compounds and enters the water column above. This is the primary means of P release from sediment, although not the only mechanism. The amount of Fe-P in the surficial sediments (upper 10 cm) can be used to provide an estimate of P release. Knowledge of Fe-P in surficial sediments is useful in evaluating potential loading and the status of sediments previously treated for P inactivation. After an inactivation treatment, there should be a gradient of Fe-P from the surface (lowest concentration) to the 10 cm depth (highest concentration, greatest depth of expected inactivation at any meaningful level). The overall Fe-P concentration is useful for assessing overall potential for P release, but it has been more recently found (Smith et al. 2011) that the amount of P in the upper 2 cm is what is most readily exchanged and may be the best measure of internal loading.

Surficial sediment was sampled at the water quality stations in Mystic Lake, which are also the approximate locations assessed in 2012 and 2017/2018 (Figure 2). Samples were collected with an Ekman dredge and only the upper 2 cm of sediment were collected. Samples were packed with freezer packs and overnighted to the laboratory. Samples were tested for total P, Fe-P, Al-P, Ca-P, biogenic P (the more available fraction of organic P) and organic P, along with solids content and concentrations of Fe, Al and Ca.

The goals of the 2020 assessment were to evaluate the accumulation of P in deeper water, assess the availability of P in the upper 2 cm of sediment interacting to the greatest degree with overlying water, and to assess the plankton community in relation to reports of blooms and related problems. These data will be compared to past data and possible future management actions will be considered.

Results

Field Water Quality

Temperature is an important water feature, having influence on the degree of mixing, the capacity of the water to hold oxygen, and the rate of metabolism of organisms in the water. Knowledge of the thermal regime over vertical space and time is essential to understanding lake processes and condition, making the collection of temperature profiles an important task in almost any lake survey.

Temperature data for Mystic Lake (Tables 1 and 2, Figure 3) indicate declining temperature with increasing depth, with an inflection point at about 7 m (23 feet) during summer 2020 that represents the thermocline (boundary between upper and lower water layers). The thermocline has varied in other years between 5 and 9 m (Figures 4 and 5), which can greatly change the volume of the two water layers and the area of sediment exposed to low oxygen during stratification, but there is no clear long-term trend of increasing or decreasing thermocline depth. Stratification breaks down at the end of summer, with nearly isothermal conditions observed in mid-October in 2020.

Oxygen concentration is another critical feature of water, affecting suitability for aquatic life and controlling many chemical reactions. Loss of oxygen near the sediment-water interface is particularly troublesome, as it allows the release of a variety of contaminants, phosphorus being among them and very influential in algae growth. Assessment of the oxygen profile from top to bottom in a lake is therefore a very important part of almost any lake assessment.

Table 1. Water quality data for Mystic Lake station 7 in 2020

	Date	Time	Depth	Temp	DO	DO	Sp. Cond	pH	Chl-a	Turbidity	Secchi	Total P	Total Fe
Station	MM.DD.YY	HH:MM:SS	meters	°C	mg/l	% Sat	µS/cm	Units	µg/l	NTU	meters	µg/l	µg/l
Mystic 7	05.22.20	2:25:31	0.3	15.5	10.4	105.5	84	7.6	0.7	2.0	8.5	<10.6	<50
	05.22.20	2:25:54	2.0	15.1	10.5	105.4	84	7.5	1.1	4.3			
	05.22.20	2:26:09	4.0	15.1	10.5	105.4	84	7.5	1.1	3.7			
	05.22.20	2:27:12	6.0	14.6	10.4	103.3	83	7.5	1.9	2.7			
	05.22.20	2:27:45	8.0	14.3	10.4	102.7	83	7.4	2.3	2.6		15.4	66.2
	05.22.20	2:28:34	10.0	12.2	8.4	79.2	83	7.4	3.4	2.5			
	05.22.20	2:34:22	10.9	12.1	6.4	60.3	83	6.5	2.4	6.3			
	05.22.20	2:29:19	12.0	11.4	3.9	36.2	84	7.2	1.5	2.9			
	05.22.20	2:31:24	13.0	10.6	0.0	0.0	87	6.7	1.5	7.1		55.3	1350.0
	05.22.20	2:32:54	13.3	10.5	0.0	0.0	90	6.5	2.1	14.8			
Mystic 7	07.15.20	13:51:55	0.1	25.4	8.7	107.5	88	7.8	3.2	4.9	3.8	17.0	<50
	07.15.20	13:51:32	1.0	25.4	8.7	107.9	88	7.8	4.0	5.1			
	07.15.20	13:51:09	2.0	25.4	8.7	107.8	88	7.7	4.7	5.3			
	07.15.20	13:50:39	3.0	25.4	8.8	108.1	88	7.6	4.8	5.5			
	07.15.20	13:50:12	4.0	25.4	8.8	108.4	88	7.5	5.2	5.8			
	07.15.20	13:49:45	5.0	25.4	8.7	107.3	88	7.3	5.6	6.2			
	07.15.20	13:49:20	6.0	25.3	8.7	107.8	88	7.0	6.5	6.7			
	07.15.20	13:48:52	7.0	18.4	8.8	95.2	86	6.8	13.5	7.3			
	07.15.20	13:48:18	8.0	16.3	2.5	26.1	86	6.8	18.4	8.4		18.1	<50
	07.15.20	13:47:49	9.0	14.8	0.2	2.1	91	6.8	5.0	9.6			
	07.15.20	13:47:14	10.0	13.2	0.2	2.1	102	6.9	3.7	10.0			
	07.15.20	13:46:49	11.1	12.4	0.1	0.8	116	6.8	3.6	8.8			
	07.15.20	13:46:14	12.0	11.5	0.0	0.0	126	6.8	4.2	8.7			
	07.15.20	13:45:46	13.0	11.1	0.0	0.0	144	6.9	3.6	8.9		58.4	7200
Mystic 7	09.08.20	7:19:19	0.2	24.9	9.0	110.7	100	7.2	7.1	2.7	4.1	<10.6	<50
	09.08.20	7:19:39	1.0	24.0	9.3	111.5	100	7.2	7.1	3.0			
	09.08.20	7:20:06	2.0	23.8	9.2	110.4	100	7.3	4.0	3.0			
	09.08.20	7:20:31	3.0	23.7	9.2	109.9	100	7.3	3.2	3.0			
	09.08.20	7:20:52	4.0	23.6	9.1	109.0	100	7.3	3.4	3.1			
	09.08.20	7:21:24	5.0	23.6	8.9	105.7	100	7.3	4.4	3.3			
	09.08.20	7:21:42	6.0	23.5	8.7	104.2	100	7.3	4.5	3.3			
	09.08.20	7:21:57	7.0	23.0	8.5	100.0	100	7.2	14.1	3.5			
	09.08.20	7:22:47	8.0	20.6	1.1	11.8	98	6.9	26.5	3.9		20.2	83.8
	09.08.20	7:23:39	9.0	16.4	0.1	1.1	101	6.6	8.4	4.7			
	09.08.20	7:24:20	10.0	14.2	0.0	0.0	123	6.4	7.0	5.5			
	09.08.20	7:25:06	11.0	12.8	0.0	0.0	158	6.2	3.2	6.7			
	09.08.20	7:25:30	12.0	12.1	0.0	0.0	170	6.3	2.8	6.9			
	09.08.20	7:25:56	13.0	11.5	0.0	0.0	195	6.3	3.0	6.9			
	09.08.20	7:27:08	13.9	11.4	0.0	0.0	205	6.3	18.2	19.1		515	21400
Mystic 7	10.15.20	14:41:28	0.1	16.9	8.1	84.3	100	6.9	2.9	5.8	2.7	46.8	278
	10.15.20	14:40:52	2.0	16.6	7.8	81.1	101	6.9	6.0	6.0			
	10.15.20	14:40:32	4.0	16.5	7.6	79.0	100	6.9	5.8	6.1			
	10.15.20	14:39:52	6.0	16.4	6.9	71.4	100	6.9	5.3	6.3			
	10.15.20	14:39:23	8.0	16.3	7.0	72.5	101	7.0	7.7	6.3			
	10.15.20	14:38:33	10.0	16.3	7.6	78.6	100	7.0	8.1	6.0			
	10.15.20	14:37:15	11.0	16.3	7.7	79.7	101	7.1	9.1	5.9			
	10.15.20	14:36:34	12.0	16.3	6.8	70.6	101	7.0	8.4	6.0			
	10.15.20	14:35:48	13.1	12.0	0.0	0.0	263	6.7	4.6	12.1			
	10.15.20	14:33:38	13.4	11.6	0.0	0.0	315	6.5	0.0	102.9			

Table 2. Water quality data for Mystic Lake stations 3 and 9 in 2020

	Date	Time	Depth	Temp	DO	DO	Sp. Cond	pH	Chl-a	Turbidity	Secchi	Total P	Total Fe
Station	MM.DD.YY	HH:MM:SS	meters	°C	mg/l	% Sat	µS/cm	Units	µg/l	NTU	meters	µg/l	µg/l
Mystic 3	05.22.20	2:32:54	7.0									89.3	402
Mystic 3	07.15.20	14:35:38	6.0	21.9	6.3	72.6	86	7.5	16.2	3.9			
	07.15.20	14:36:12	7.0	18.4	0.0	0.0	114	6.9	8.2	10.3		23.4	664
	07.15.20	14:37:16	7.5	17.3	0.0	0.3	133	7.0	13.4	21.2			
Mystic 3	09.08.20	8:25:19	0.1	25.6	9.3	115.5	100	7.4	1.8	3.7			
	09.08.20	8:24:46	1.0	25.1	9.3	114.6	100	7.3	4.6	3.7			
	09.08.20	8:24:17	2.0	25.0	9.3	114.2	100	7.2	2.6	3.7			
	09.08.20	8:23:48	3.0	23.9	9.3	111.8	101	7.1	3.3	3.7			
	09.08.20	8:23:25	4.0	23.7	9.1	109.2	100	7.0	4.1	3.9			
	09.08.20	8:23:02	5.0	23.6	8.5	101.3	100	6.8	5.6	3.7			
	09.08.20	8:22:40	6.1	23.4	7.1	84.0	100	6.8	6.5	4.6			
	09.08.20	8:21:57	7.1	22.7	0.9	10.3	103	6.7	5.9	9.8		11.7	145
Mystic 9	05.22.20	2:32:54	10.0									29.8	236
Mystic 9	07.15.20	14:21:10	7.0	19.0	6.4	69.5	86	7.5	22.2	4.6			
	07.15.20	14:22:20	7.9	16.6	0.2	2.4	85	7.0	16.2	7.0			
	07.15.20	14:22:45	9.0	15.2	0.1	1.5	87	6.8	9.6	6.6			
	07.15.20	14:23:16	10.0	13.7	0.1	1.0	98	6.7	3.8	7.6		21.3	343
Mystic 9	09.08.20	8:01:54	0.3	24.7	9.1	111.4	100	7.4	1.8	3.5			
	09.08.20	8:03:31	2.0	24.0	9.3	112.3	100	7.5	2.0	3.3			
	09.08.20	8:04:03	4.0	23.7	9.2	110.4	100	7.5	3.4	3.4			
	09.08.20	8:04:31	6.2	23.4	8.6	103.0	100	7.4	7.0	3.6			
	09.08.20	8:05:00	7.0	23.0	7.6	90.0	100	7.3	18.9	4.0			
	09.08.20	8:05:58	8.0	19.5	0.1	1.5	98	6.8	35.1	4.9			
	09.08.20	8:06:34	9.0	16.1	0.1	1.0	105	6.6	22.5	6.0			
	09.08.20	8:07:07	10.0	13.4	0.0	0.0	145	6.3	5.3	6.8		48.9	1730

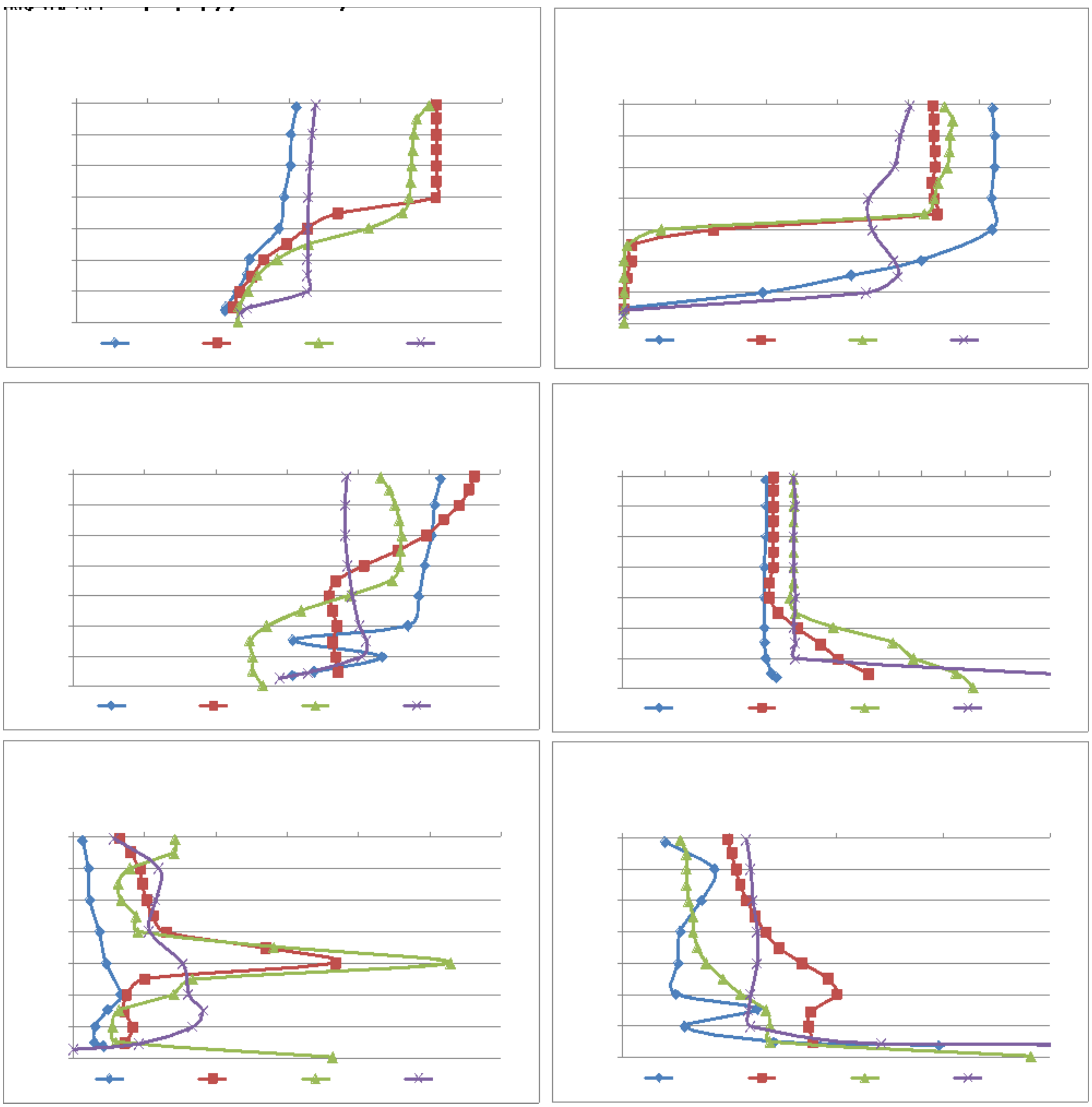


Figure 3. Field water quality at Mystic station 7 in 2020

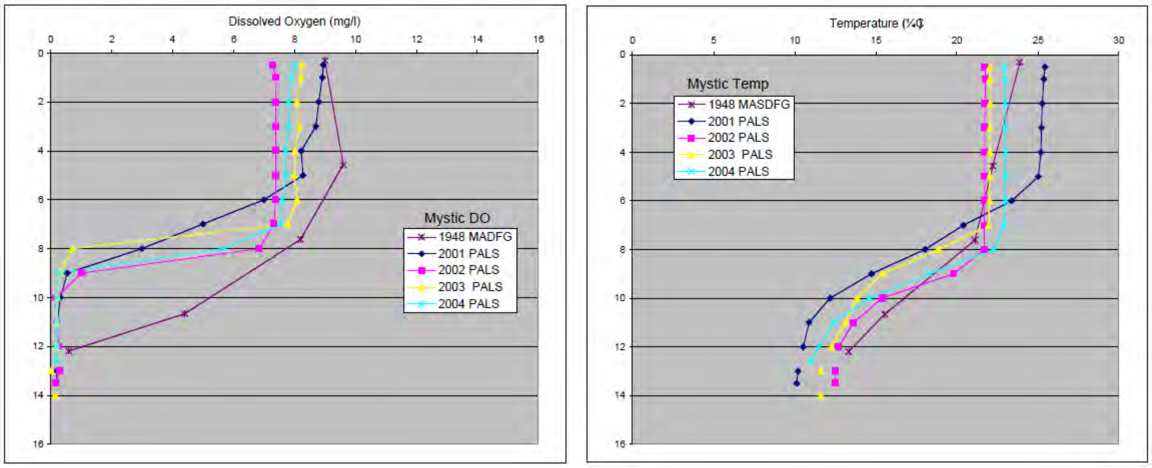


Figure 4. Late summer temperature and oxygen profiles for Mystic Lake between 1948 and 2004 (from CCC 2006)

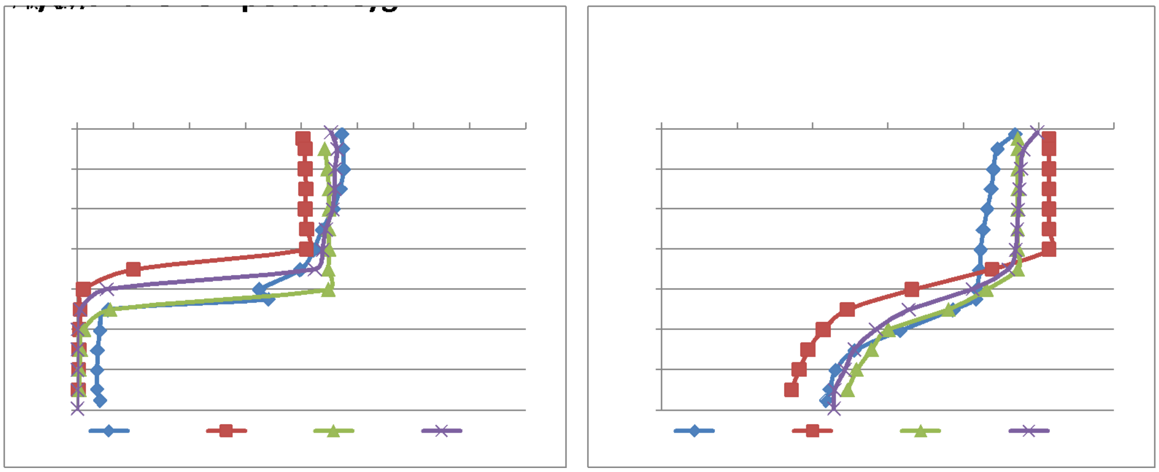


Figure 5. Late summer temperature and oxygen profiles for Mystic Lake between 2017 and 2020

Oxygen is fairly uniform from the surface to a depth of about 7 m during most of the year in Mystic Lake, but declines with increasing depth from 6 m to the bottom during summer when the lake is stratified (Tables 1 and 2, Figure 3). The thermal stratification limits mixing from above, so oxygen additions to deep water are minimal during stratification while decomposition removes oxygen and does so at an accelerating rate as the water warms. Oxygen <2 mg/L tends to correspond to low redox potential, which is an electrochemical feature that fosters reactions that release Fe and P from sediment. Low oxygen occurs at depths as shallow as 7 m by late summer over the last two decades, but may not occur until a depth of 9 m (Figures 4 and 5). Historically, low oxygen did not occur until a water depth of about 12 m (1948 in Figure 4). This difference in how large an area of sediment is exposed to low oxygen affects the rate and duration of internal P loading. The difference between low oxygen at 7 m and 9 m is 22.5 acres (48.5 ac exposed at 9 m vs 71 ac exposed at 7 m) and could greatly increase internal P loading through release from sediment. The depth of the thermocline and area exposed to low oxygen are largely functions of weather, especially during spring, so is somewhat unpredictable from year to year, but climate change is a factor.

The pH is a measure of hydrogen ion concentration, expressed as the reciprocal of the logarithm of that concentration, such that lower values mean higher hydrogen concentration, which means that the water is more acidic. Higher pH values mean lower hydrogen concentrations, or more basic conditions, with a pH of 7 standard units (SU) considered neutral.

Background pH in Cape Cod ponds tends to be <7 and often close to 6 SU, but the presence of algae removes carbon dioxide during photosynthesis, which raises the pH. At greater depths, where light limits photosynthesis and decomposition releases acids into the water, pH declines. The pH in the upper waters of Mystic Lake is between 7 and 8 SU (Tables 1 and 2, Figure 3), indicative of substantial algal activity. The pH is <7 in deeper water, more typical of background levels in Cape Cod waterbodies.

Conductivity represents the dissolved solids in water. It does not indicate the nature of those solids, but the total is linked to electrical conductance and is fairly easy to measure. Conductivity values <100 µS are considered low, and usually indicate low fertility as well. Values >400 µS are unusual in Massachusetts and suggest excessive dissolved solids, usually salt of some kind.

Conductivity (Tables 1 and 2, Figure 4) is fairly constant from the surface to a depth of at least 8 m in Mystic Lake at between 80 and 100 µS, then increases as a function of dissolved solids being released from sediment. In Mystic Lake the increase can be substantial during stratification and can exceed 300 µS. None of these values are extremely high, but the increase in deep water is indicative of releases of substances from the surficial sediments and will include P at potentially high concentrations.

Turbidity is a measure of light scattering by suspended particles in the water, which include algae and non-living particles suspended by wind or other mixing action. Values of <1 NTU are considered low and indicative of very clear water, while values >3 NTU start to indicate potentially undesirable accumulations of solids from a drinking water perspective and values >10 NTU suggest lowered clarity that will be quite noticeable to swimmers and other lake users.

Turbidity (Tables 1 and 2, Figure 3) is variable in Mystic Lake, ranging from about 2 to 6 NTU in the upper waters but increasing to values >10 NTU near the bottom. Accumulation of light organic particles is the likely reason for turbidity increases in deeper water. Resuspension of sediment or algae are usually responsible for higher turbidity in shallow water.

Chlorophyll-a is a photosynthetic pigment common to all algae and higher plants. Measured as fluorescence in the lake by a probe, it is indicative of algae abundance in the water column. Values <4 µg/L are generally considered low, while values >10 µg/L are considered elevated and values >20 µg/L are usually taken as indication of a bloom. However, fluorescence measures are compromised by natural light in shallow water and settled organic matter can fluoresce in the same wavelengths as chlorophyll-a in deep water, so one must exercise caution in the interpretation of field data.

The pattern of chlorophyll-a in Mystic Lake (Tables 1 and 2, Figure 3) includes concentrations <7 µg/L in the upper waters (<6 m deep) with values up to 25 µg/L in a layer slightly below the thermocline. This is indicative of a zone of high algae biomass, but plankton analysis did not detect any major increase in algae. Cyanobacteria and golden algae are most commonly the dominant forms in such deep algae layers. The increase near the bottom is likely a function of accumulated organic matter in that zone, not algae, as settling of very light particles is impeded as the water gets colder and denser and those particles can fluoresce at the wavelength measure by the probe.

Secchi disk transparency is a simple means of measuring water clarity, and relates to many other lake features, notably turbidity, chlorophyll-a, and algae abundance. Secchi transparency values >5 m represent clear water and a desirable target for most Cape Cod lakes. Secchi readings <1.22 m (4 feet) suggest very low clarity that represents a safety risk to swimmers and is usually linked to algae blooms, a further risk for both people and aquatic fauna, especially where cyanobacteria become dominant. In general, Secchi transparency <2 m suggests poor conditions and values <3 m are cause for some concern.

Secchi disk transparency (Table 1, Figure 6) declined from a very high value of 8 m in May to values between 3.8 and 4.1 m in July and September and to 2.7 m in October. The decline is likely linked to accumulation of algae, documented by the plankton assessments, but there are multiple factors fostering that accumulation. Temperature, nutrients and zooplankton are all influential in Mystic Lake. Slower growth of algae that include mostly diatoms and golden algae at colder winter-spring temperatures and abundant zooplankton in later winter and early spring that apply substantial grazing pressure leads to very low algae through May and very high clarity. Warming temperatures and arrival of alewife that spawn and lead to many small fish that eat zooplankton shifts the algae assemblage toward greens and cyanobacteria and maximizes the standing crop of algae for whatever level of nutrients are available. Internal P loading with less seasonal inputs of nitrogen (N) leads to a lower N to P ratio that favors cyanobacteria, with loading increasing as summer proceeds and the water warms, also favoring cyanobacteria due to their use of sugars as the primary energy storage form (which is more efficiently metabolized at warmer temperatures).

The warming of the surface water and the loss of grazing pressure by zooplankton exhibit year to year variation but are relatively consistent influences. Availability of nutrients and the N to P ratio are less predictable, with weather pattern playing a large role. A warm spring with substantial wind will cause the deeper water to be warmer when stratification sets in, leading to a greater oxygen demand and higher likelihood of more area being exposed to low oxygen. Stronger sunlight and fewer clouds will aid growth of cyanobacteria that start at the sediment-water interface in water of intermediate depth (enough light to photosynthesize but deep enough to have nutrient-rich sediment with low oxygen). The depth of the thermocline will vary and a shallower thermocline will cause the associated layer of algae to form at a shallower depth and be more subject to suspension by wind later in summer.

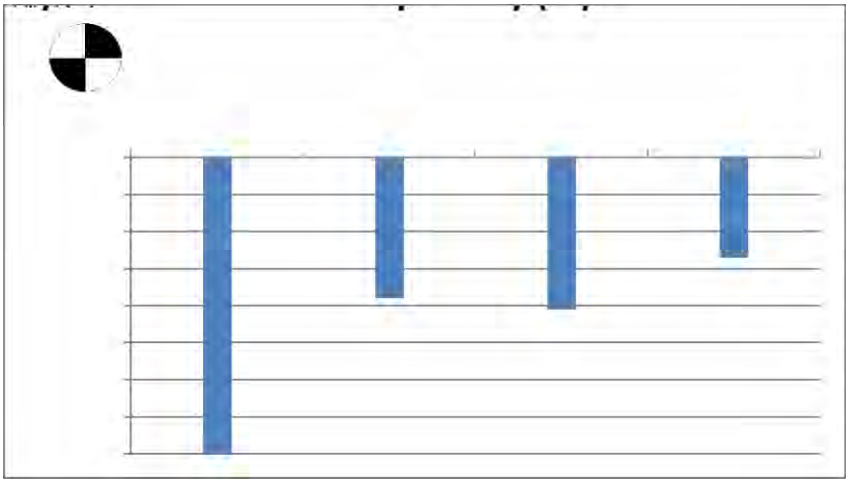


Figure 6. Secchi transparency at Mystic station 7 in 2020

The long-term record of Secchi disk transparency for Mystic Lake (Figure 7) suggests a long, slow decline in clarity as P-rich, oxygen-demanding, organic sediment built up in Mystic Lake and more area was exposed to low oxygen during stratification. Erratic values likely influenced by weather patterns are evident into 2010, after which there is an increase in clarity caused by the aluminum treatment that limited P release from sediment. The increase after treatment is not as stark as we usually observe with such treatments, but the die off of mussels released a lot of P into the water column and the treatment focuses on sediment P. Some P is stripped from the water column, not this is not an efficient process and it took several years for the elevated water column P to be reduced by flushing and sedimentation. Unlike Hamblin Pond, however, the clarity never reached values higher than 5 m for most of the summer, suggesting more P availability after treatment than desired.

For Mystic Lake, the 2001-2010 average Secchi disk transparency was 2.4 m with a range of 0.8-4.0 m. From 2012 through 2020, clarity averaged 3.7 m with a range of 2.3-8.0 m. This is a statistically significant increase, but there are still low clarity values at times, mostly late in summer or early in fall when P loading from sediment would be maximal and mixing of water layers occurs. Cyanobacteria blooms have not been documented during the main recreation season of Memorial Day to Labor Day but have occurred in September and October. Other algae are also more abundant as summer proceeds, utilizing what nutrients are available with minimal losses to grazing as zooplankton biomass is low. This process will be more evident to the reader as the additional data are presented and discussed.

Phosphorus and Iron in Water

In-lake total phosphorus (TP) concentrations <10 µg/L (0.01 mg/L) are indicative of low fertility and will not support algae blooms for any substantial length of time, while concentrations > 20 µg/L (0.02 mg/L) can support blooms. This is a fairly narrow transition range, making P management a top priority for lakes. TP concentration often has a laboratory detection limit of about 10 µg/L, and measurements near the detection limit can be difficult to accurately obtain, so we do not tend to get too concerned over TP concentration until it exceeds 15 µg/L with some regularity. TP concentrations tend to be highest near the bottom of a lake, both due to settling of algae and other organic matter that contains P and as a result of the release of P from surficial sediment. Values up to about 50 µg/L near the sediment-water interface are not a major concern, as that P may not move vertically during summer and is usually in a dark region of the lake where algae will not grow well. Higher concentrations, however, may signal a likelihood of some upward transfer by diffusion that could raise P concentrations in upper waters where algae do grow. Deep water concentrations 100 µg/L are a definite concern.

TP in Mystic Lake in 2020 (Tables 1 and 2, Figure 7) was low at the surface and elevated at the bottom, with an obvious hypolimnetic increase over the July-September period of sampling that suggested release of P from surficial sediment in deep water. This is the problem that was to be addressed by the aluminum treatment in 2010. Comparison with older TP data for Mystic Lake (Figure 7) indicates that the 100 µg/L threshold for hypolimnetic P was exceeded in late summer samples from 2012, 2013, 2014, 2017 and 2020 but that deep water concentrations of TP were lower after aluminum treatment than in most late summer samples prior to treatment. The aluminum treatment has reduced hypolimnetic P concentrations, just not as much as desired.

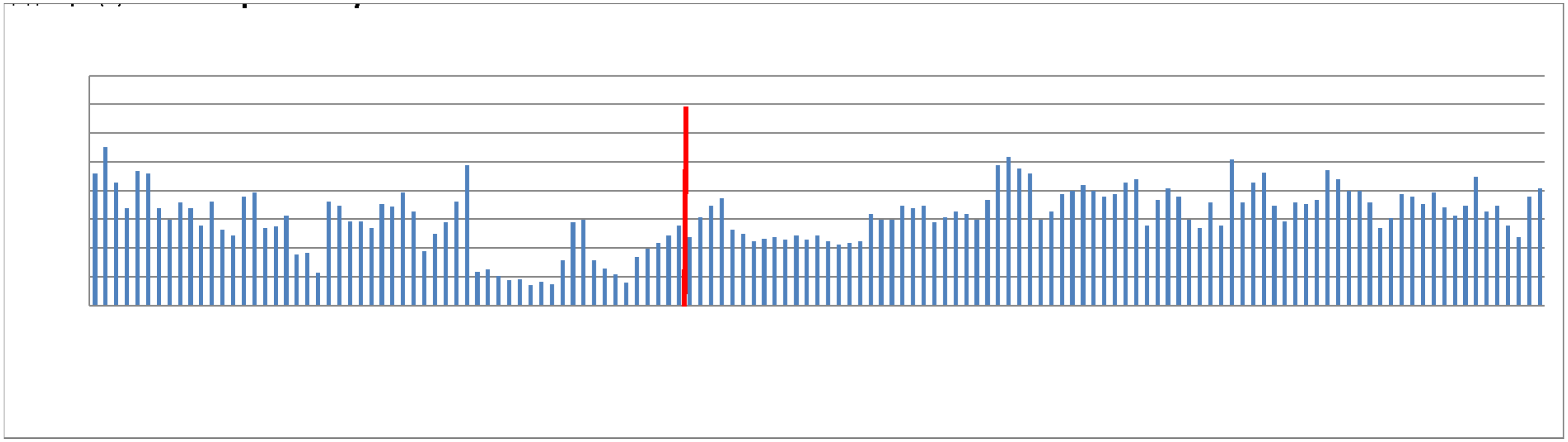
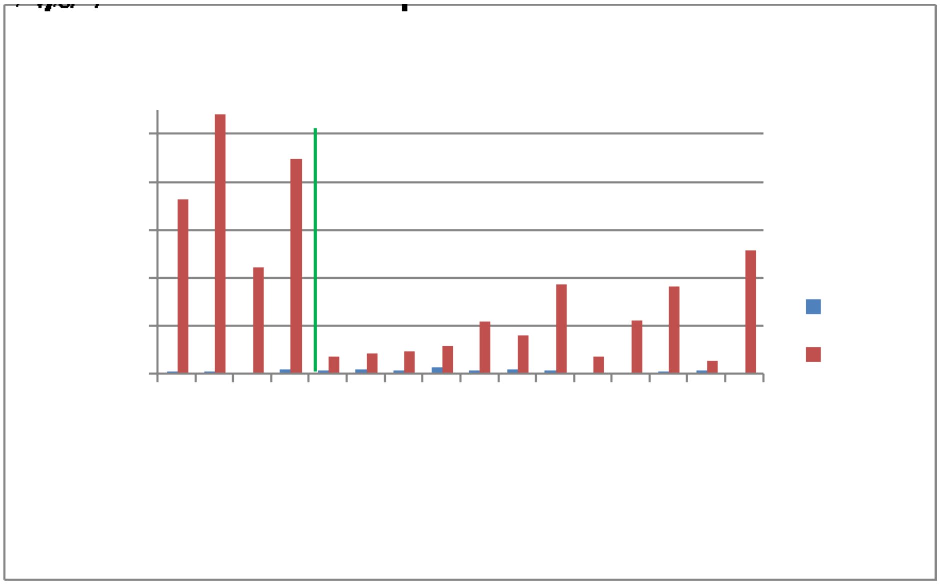


Figure 7. Historical summer Secchi disk transparency record for Mystic Lake



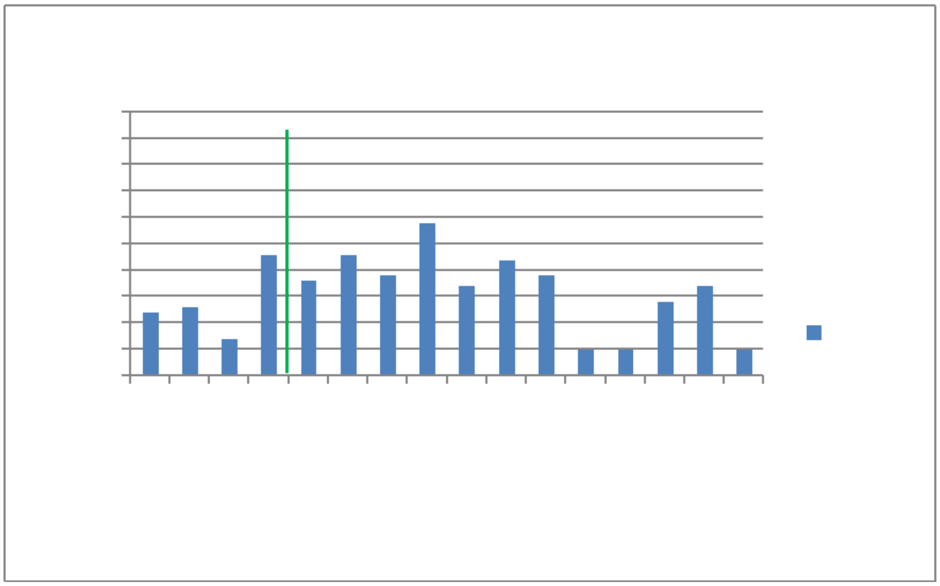


Figure 8. Summer phosphorus data for Mystic Lake for selected summer dates

Surface TP concentrations averaged 18 µg/L between 2001 and the aluminum treatment, while post-treatment TP has averaged 20 µg/L. The difference is not statistically significant, but the point is that surface TP has not decreased despite a significant reduction in deep water TP. Surface average TP concentrations are not excessive, but are close to the threshold where algae blooms are supported. As these concentrations are averages, we can expect some portion of those values to be higher, so bloom control has not been achieved. While deep water TP has been substantially reduced, concentrations are still high enough to contribute appreciably P to surface waters during mixing events and even by diffusion, particularly later in summer, and algae can be expected to grow near the sediment where light penetration is adequate. Shortly after stratification broke down in 2020 the surface concentration of TP was almost 47 µg/L after a summer of values averaging close to the detection limit. Considerable P was apparently mixed into the upper waters.

Iron (Fe) is not very soluble in the presence of oxygen, reacting and precipitating out. Fe binds well with phosphorus, so under oxic conditions it is expected that Fe will act as a P inactivator. Under low oxygen conditions in sediment, however, Fe will dissociate from P and both will become soluble. If the Fe and P move upward out of the sediment and encounter oxygen, they will re-precipitate, creating a cycle sometimes called the "ferrous wheel", a play on words involving ferrous (reduced, soluble) vs ferric (oxidized, insoluble) forms of Fe. If the water above the sediment has low oxygen, the Fe and P can accumulate in solution. So dissolved Fe is also an indicator of conditions and the likelihood of P loading from the sediment.

Data from 2020 (Tables 1 and 2) indicate an accumulation of Fe in deep water in Mystic Lake over the course of the summer, starting even in May. At station 7, the deepest part of the lake, Fe was already elevated at 1350 µg/L on May 22, 2020; under oxic conditions a value of <50 µg/L would be expected. By September 8, 2020 Fe had risen to 21,400 µg/L (Table 1), an extremely high level that the lab did not at first believe and re-ran the test. During this period the surface water Fe was consistently <50 µg/L and the water at the thermocline exhibited Fe between <50 and 84 µg/L. The presence of oxygen higher in the water column caused nearly all Fe to precipitate out as it diffused upward, a slow process with plenty of opportunity for oxidation. Correspondingly, P increased to high levels in the deepest water but remained relatively low in surface water. Some deep P may be making it to the surface, as values were not as low as desired, but the gradient is quite striking. Yet when stratification broke down in October, the surface Fe value was 278 µg/L and P rose to almost 47 µg/L. The mixing process was apparently fast enough to prevent complete Fe-P precipitation.

A similar process affected more by shallow depth and lower thermal gradient was observed at the two shallower stations (Table 2). At station 9 with a depth of 10 m, the thermocline is between 7 and 8 m and the bottom water layer is only about 2 m thick. Low oxygen occurred at deeper than 8 m on the May, July and August sampling dates and Fe increased from 236 to 1730 µg/L over that period. P was 30, 21 and 49 µg/L on successive sampling dates. The lower value in July is likely an indication that diffusion and/or mixing allowed some accumulated P to enter upper waters.

At station 3 with a depth of between 7 and 8 m there is not strong stratification but low oxygen was encountered at 7 m and Fe ranged from 402 µg/L in May to 684 µg/L in July to 145 µg/L in September (Table 2). Corresponding P concentrations were 89, 23 and 12 µg/L; the lack of a temporal pattern is likely due to periodic mixing at this station, which is not deep enough to have stable stratification. The water column is stable for days to maybe a week or two, allowing low oxygen to develop at the bottom and Fe and P to be released from the sediment, but periodic mixing occurs. With adequate oxygen, most of the Fe and P should precipitate out, but some movement into upper waters is possible.

The effective internal P loading direct from sediments at the shallower stations into overlying waters is not likely to be a dominant factor, although it could account for slightly elevated P in surface waters. The bigger issue is that with low oxygen at the sediment-water interface in water at least as shallow as 7 m, P will be available at that sediment-water interface and there is enough light for algae to grow. Adequate light for algal photosynthesis exists beyond twice the Secchi transparency but not to a depth three times the Secchi transparency. With typical summer Secchi readings in Mystic Lake of 3 to 4 m, that means that we can expect algae to grow at 7 m of water depth with some growth possible at even 10 m.

P concentrations are elevated at depths >7 m in Mystic Lake as a function of release from sediment and even if Fe and P recombine when diffusing upward, the algae can make use of the P as it exits the sediment. This is a major mode of bloom formation for many cyanobacteria and some other algae. For the cyanobacteria in particular, growth is slow but P uptake is high, resulting in P-rich cells that can divide several times with no further P source. Many cyanobacteria can form gas pockets in cells and rise, gaining exposure to more light and bringing P with them to form a bloom.

In deeper water where there is not adequate light to allow photosynthesis, low oxygen in the water column at depths of 7-10 m will allow Fe and P released from the sediment to remain in solution and be available to algae that grow in a layer in the water column, usually slightly below the thermocline. This is another mode of bloom formation, whereby the algal layer may remain below the surface indefinitely, but can be brought to the surface either by a mixing event or through gas pocket generation in cyanobacteria, usually in response to lowered light (cloudy periods or storms that induce turbidity).

It should also be noted that cyanobacteria that can fix dissolved nitrogen gas require Fe for the enzymes involved, so higher Fe levels that come with elevated P during sediment release further favors cyanobacteria (Molot et al. 2014). And nitrates, the form of N preferred by most other algae, tend to be is short supply in summer in most lakes, further favoring cyanobacteria that can utilize dissolved N gas.

As a result of these bloom formation mechanisms, Mystic Lake can experience algae blooms without truly excessive P in the surface water layer. When P near the surface is low, such blooms will be short-lived. With higher P, such as after turnover in October 2020, blooms can last much longer, having a source of P when internal reserves are exhausted. This is why the probability of blooms increases later in summer and in early fall, but unpredictable weather patterns add considerable variation. This is evident in the phytoplankton record.

Phosphorus in Sediment

Amounts and forms of P in surficial sediment can affect transfer into the overlying waters. P bound to iron (Fe-P) is of particular concern, as it can be released by redox reactions when oxygen at the sediment-water interface is low (<2 mg/L, with very high risk at <1 mg/L). An additional concern is biogenic P, the organic form most likely to be released by decay processes, but it is difficult to assess how available that organic P really is, so the focus has traditionally been on Fe-P.

The concentration of forms of P in the surficial sediment must be adjusted according to the percent solids and specific gravity of the solids (usually about 1.1 for organic muck) to calculate the mass of P that can become available, but in general we consider concentrations of Fe-P >50 mg/kg to have some potential for impact and values >200 mg/kg to have definite impact potential.

Loosely bound P, the most available P fraction in the sediment, is often negligible, but occasionally represents a significant P source from sediment. Other P fractions include calcium-bound P (Ca-P) and aluminum-bound P (Al-P). Ca-P and Al-P represent minimally available P forms in sediment.

Highly organic sediment, as is known to be the dominant sediment type in deeper waters in Mystic Lake from past sampling, tends to have a substantial amount of potentially available P in it if not treated for P inactivation. Solids content in organic sediment is typically low (<20%, often <10%).

Sediment data from March 2018 (Table 3) indicate that total phosphorus in the upper 10 cm of sediment is generally moderate in Mystic Lake. Loosely sorbed P is negligible. Fe-P was lower than Ca-P and much lower than Al- P in Mystic Lake. Organic P was moderate and was mostly biogenic, meaning that decomposition would be expected to release some P from organic matter. Overall, the impact of the aluminum treatment is evident, with much P that used to be bound to Fe now bound to Al in Mystic Lake. About half of all sediment P in the upper 10 cm was bound to Al.

While the upper 10 cm of sediment are generally considered to represent the depth to which any interaction with overlying water may occur, more recent research has suggested that the upper 2 cm are most important (Smith et al 2011). Further, it is expected that after inactivation there will be a chemical gradient established with less Fe-P near the sediment surface, and that Fe-P from deeper in the sediment will migrate upward. In nearby Hamblin Pond, it took 18 years for enough P to migrate to the surface to undo the benefits conferred by aluminum treatment of that waterbody. In Mystic Lake, where the dose was limited by permit to about 2/3 of the initially planned dose for a substantial part of the lake, it might be expected that the time necessary for enough upward migration of P to cause excessive internal loading would be less than for Hamblin Pond. We therefore chose to test just the upper 2 cm of sediment, avoiding any dilution of the average value over 10 cm. Financial limits prevented testing of both the upper 2 cm and next 8 cm, but the focus was on determining how much P was available for internal loading and the upper 2 cm was considered to provide the best assessment of that quantity.

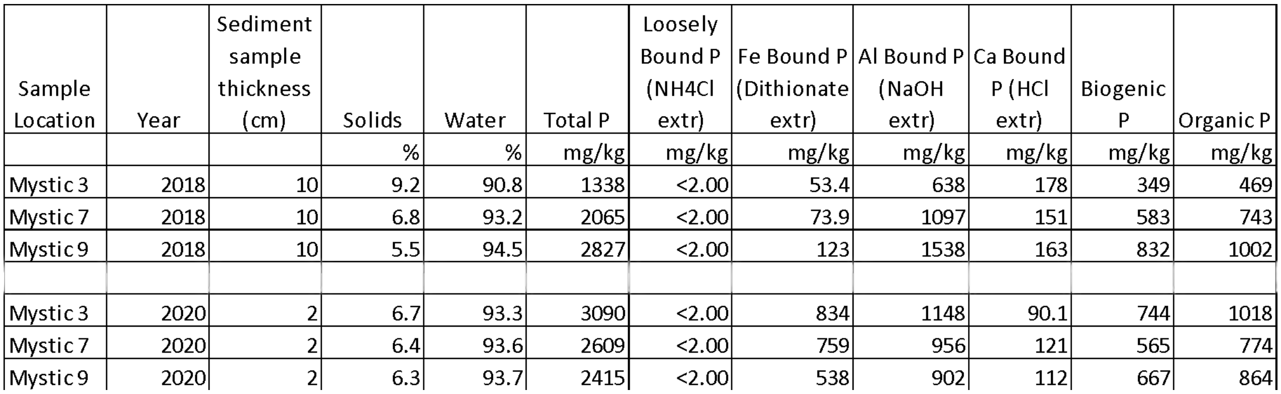
Sediment data from May 2020 (Table 3) show some similarity to the 2018 data but also some differences that may reflect sampling variation, lab variation, or temporal variation. With barely more than 2 years between the March 2018 and May 2020 samplings, comparison of these results should be valid. Within the range of variability expected from non-split samples and lab variation for sediment testing, the only difference that really stands out is the much higher Fe-P concentration in the upper 2 cm in 2020 vs the upper 10 cm in 2018. Total P and biogenic P in 2020 were also higher than in 2018, suggesting that the 2020 results may be somewhat high for reasons other than an actual increase (again, sampling and lab variation), but it appears that over the course of 10 years a lot of Fe-P has migrated upward in the sediment to near the surface where it can interact more readily with overlying water.

Comparison of key sediment features from four samplings (before treatment of Mystic Lake, about 1.5 years after treatment, about 7.5 years after treatment, and about 9.5 years after treatment, Table 4) demonstrates the substantial decrease in Fe-P in the upper 10 cm of treated sediment in Mystic Lake after treatment and that the Fe-P fraction has remained relatively low into the 8th year post-treatment. However, the 2020 results, which involve only the upper 2 cm, suggest that there has been a redistribution of Fe-P such that more is near the sediment-water interface and is facilitating more internal P loading.

Another way to look at the data is to calculate the mass of Fe-P in the sediment of interest. The range of Fe-P for Mystic Lake over the period of testing (Table 5) suggests high values for Mystic Lake in 2010 before treatment and low values for Mystic Lake 2012 and 2018 after Mystic Lake was treated. All of those masses are for a square meter of sediment area with a depth of 10 cm. The 2020 mass, representing only 2 cm of sediment depth, has more Fe-P mass than either the 2012 or 2018 sediment with depths of 10 cm. This is not very likely, and suggests some measurement error, but the relative condition over time is apparent; there is less Fe-P since treatment in 2010 but enough Fe-P is in the upper 2 cm to represent a threat of elevated internal loading. This is consistent with the measures of Fe and P from the deeper waters of Mystic Lake.

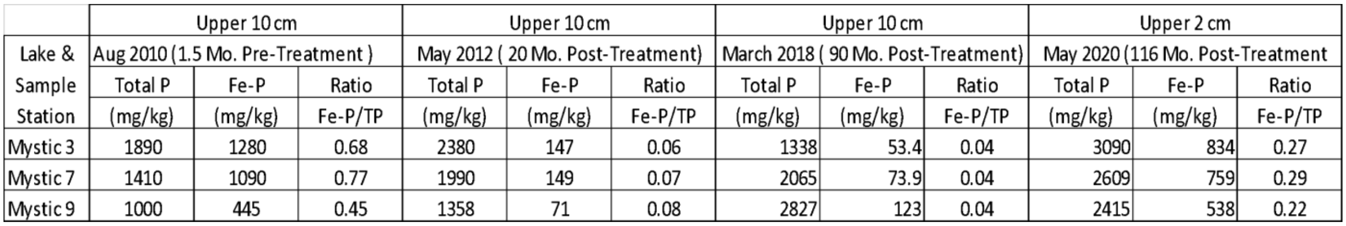
There are two key factors involved: 1) the inactivation dose in 2010 was lower than desired based on testing at that time, so more Fe-P was left as Fe-P than necessary to depress internal loading to the desired degree, and 2) Fe-P has migrated upward over the nearly 10 years since treatment, replenishing the supply of Fe-P near the sediment surface that interacts with the overlying water. Hamblin Pond, with what was considered an adequate dose in 1995, required re-treatment after 18 years of benefits, so it is not surprising that Mystic Lake may need re-treatment after only 10 years with treatment at a lower dose than recommended.

Table 3. Sediment data for Mystic Lake from 2018 and 2020



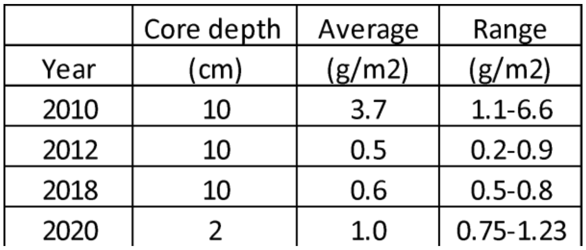
Sample Location	Year	Sediment sample thickness (cm)	Solids	Water	Total P	Loosely Bound P (NH4Cl extr)	Fe Bound P (Dithionate extr)	Al Bound P (NaOH extr)	Ca Bound P (HCl extr)	Biogenic P	Organic P
			%	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Mystic 3	2018	10	9.2	90.8	1338	<2.00	53.4	638	178	349	469
Mystic 7	2018	10	6.8	93.2	2065	<2.00	73.9	1097	151	583	743
Mystic 9	2018	10	5.5	94.5	2827	<2.00	123	1538	163	832	1002
Mystic 3	2020	2	6.7	93.3	3090	<2.00	834	1148	90.1	744	1018
Mystic 7	2020	2	6.4	93.6	2609	<2.00	759	956	121	565	774
Mystic 9	2020	2	6.3	93.7	2415	<2.00	538	902	112	667	864

Table 4. Phosphorus data comparison for sediment of Mystic Lake among years



	Upper 10 cm			Upper 10 cm			Upper 10 cm			Upper 2 cm		
Lake & Sample Station	Aug 2010 (1.5 Mo. Pre-Treatment)			May 2012 (20 Mo. Post-Treatment)			March 2018 (90 Mo. Post-Treatment)			May 2020 (116 Mo. Post-Treatment		
	Total P (mg/kg)	Fe-P (mg/kg)	Ratio Fe-P/TP	Total P (mg/kg)	Fe-P (mg/kg)	Ratio Fe-P/TP	Total P (mg/kg)	Fe-P (mg/kg)	Ratio Fe-P/TP	Total P (mg/kg)	Fe-P (mg/kg)	Ratio Fe-P/TP
Mystic 3	1890	1280	0.68	2380	147	0.06	1338	53.4	0.04	3090	834	0.27
Mystic 7	1410	1090	0.77	1990	149	0.07	2065	73.9	0.04	2609	759	0.29
Mystic 9	1000	445	0.45	1358	71	0.08	2827	123	0.04	2415	538	0.22

Table 5. Iron bound phosphorus mass in sediment of Mystic Lake among years



Year	Core depth (cm)	Average (g/m2)	Range (g/m2)
2010	10	3.7	1.1-6.6
2012	10	0.5	0.2-0.9
2018	10	0.6	0.5-0.8
2020	2	1.0	0.75-1.23

Plankton

Phytoplankton form the base of the aquatic food web, and are essential to supporting a desirable fishery, but with excess nutrients, algae can grow faster than they are consumed and accumulate biomass, causing blooms. Some phytoplankton are less edible than others, notably many cyanobacteria, and there are various strategies employed by different algal groups to gain advantage. Diatoms and golden algae metabolize oils, which is most efficient at colder temperatures, making them the more likely group to dominate in early spring. Cyanobacteria store food mostly as sugars, metabolized most efficiently at higher temperatures, making them more of a threat to bloom in summer. Green algae prefer high N:P ratios, while cyanobacteria prefer low N:P ratios. The most common pattern of algal succession in lakes involves dominance by diatoms and golden algae in spring, giving way to green algae, which yield to cyanobacteria later in summer. But this pattern can be disrupted by weather and nutrient ratios, which much like choice of food storage, affect the fitness of different algae groups.

The phytoplankton of Mystic Lake was sampled on four dates in 2020 and added to the longer term data set generated since 2009. Algal data are reported as biomass, converted from cell counts and size measurements, at the genus level, with aggregation by major algae division for graphic depiction (Figure 9). Detailed algal data are available but the focus here is on overall biomass and the relative abundance of the major groups of algae.

Prior to aluminum treatment, the phytoplankton of Mystic Lake had shown signs of increased cyanobacterial dominance, with a dense layer forming near the thermocline but not necessarily reaching the upper waters. In 2009, however, a mixing event in August caused a surface bloom that is believed to have been responsible for a major mussel die off. An additional surface bloom of cyanobacteria was observed in July of 2010 and lasted into August. Reports of late summer and early fall blooms were also noted, but without data. After aluminum treatment, cyanobacteria were less dominant, and green algae and diatoms became more abundant, but there were mild blooms in late summer of 2011 and 2012 of different types of cyanobacteria than observed prior to treatment and represented less threat of toxicity. Few samples were collected in 2013-2016, but there were reports of spotty blooms (both spatially and temporally). The expected increase in golden algae, common in slightly acidic systems with lower nutrient levels, did not occur. Overall biomass was still above the threshold for possible visual impairment of the water (lower water clarity), although severe depression of clarity was not observed.

The samples collected in 2017 from Mystic Lake revealed a mix of golden algae and diatoms at near the 3000 µg/L threshold for possible impairment in June, but these are generally innocuous algae that fuel a desirable aquatic food web. The same mix declined to the low level threshold in July, after which cyanobacteria in the upper water column became dominant in August and September at concentrations between the two thresholds (moderately abundant). Several types of cyanobacteria were present, with the very thin filamentous *Planktolyngbya* most abundant. However, the patch of surface scum observed in September was dominated by *Dolichospermum* (formerly *Anabaena*), a possible toxin producer that was present at >28,600 µg/L. This has been a problem species in the Indian Ponds previously but is not the alga suspected of causing the 2009 and 2010 toxic blooms (which was *Planktothrix*, absent in Mystic Lake since aluminum treatment). Very calm conditions allowed the buoyant *Dolichospermum* to form a patchy surface scum.

Phytoplankton samples from 2020 suggested no cyanobacteria of consequence in May or July, with cyanobacteria present but not dominant in September and October. Biomass routinely exceeded the low threshold but only once exceeded the moderate threshold, and with dominance by diatoms and golden algae, this is not a major concern. Water clarity is compromised, but no threat to human or

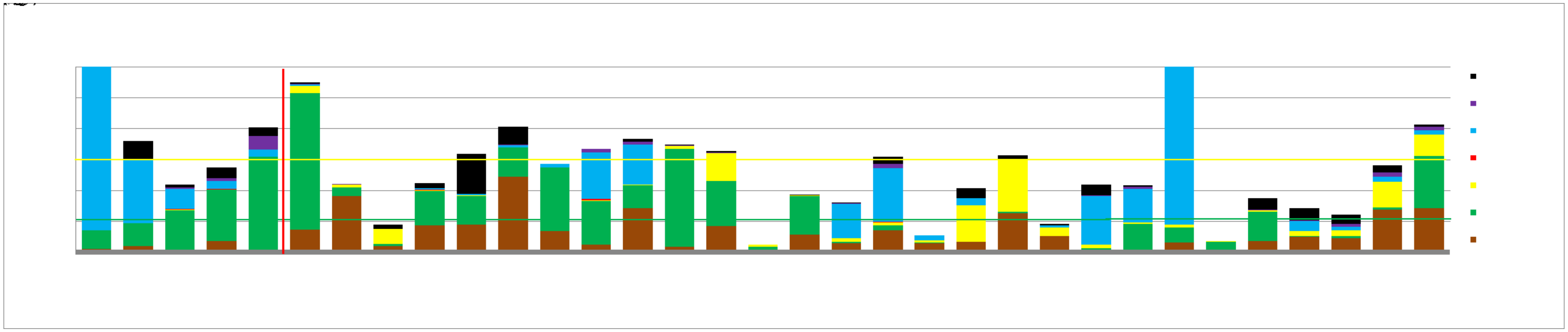


Figure 9. Phytoplankton biomass in Mystic Lake for all available samples

ecological health is indicated. There was a report of a patch of cyanobacteria in late September 2020, with photo documentation suggesting it to be a windblown accumulation of a buoyant form, but no such patches were found during surveys on September 8 and October 15 and cyanobacteria were not dominant in any samples. The elevated oxygen at mid-depth during summer of 2020 could not be positively linked with any algae in samples, but given the associated high chlorophyll-a concentration, it was likely to be golden algae. Cyanobacteria contain relatively little chlorophyll and mid-depth layers of several golden algae have been found in the Indian Ponds in recent years. Despite elevated P in deeper water, no widespread cyanobacteria bloom occurred in Mystic Lake during the sampling period of 2020.

Phytoplankton data are consistent with the combination of water quality data and weather conditions. Since treatment in 2010 available P has been reduced but not to a level that minimizes algae and maximizes clarity. Depending on the weather pattern, enough P can become available during summer to allow more algae than desired, including cyanobacteria, but major blooms are rare before late summer or early fall, when stratification breaks down and more P becomes available. Additionally, growth of cyanobacteria at the thermocline or on the bottom in water of moderate depth (where there is adequate light and P release from sediment) occurs but is slow, resulting in rising “patches” of buoyant cyanobacteria in late summer. Cyanobacteria blooms have not been lakewide but can result in potentially hazardous accumulations at the surface when calm or along shorelines with wind, although there has been no documentation of toxicity since the 2010 treatment. Additionally, other algae may be abundant enough over the summer to reduce water clarity noticeably, but extreme loss of clarity has not occurred since treatment.

Zooplankton have been sampled less frequently than algae in Mystic Lake, but enough data have been accumulated to understand the abundance pattern. Zooplankton belong to several major groups, swim freely but weakly in the water column, consume algae or each other, and are a preferred food of many smaller fish. As there is a herring run in Mystic Lake and Middle Pond with many young-of-the-year alewife present through summer and actively consuming zooplankton, the zooplankton community is usually minimal from late June into October. Biomass peaks in spring in Mystic Lake (Figure 10). Values below 50 µg/L are considered low, and concentrations >100 µg/L are preferred both for grazing of algae and as food for small fish.

Except for one sample in July 2011 which contained numerous water mites, which are not typically an important zooplankton component, all summer samples exhibited biomass <10 µg/L, a very low value usually associated with lakes hosting alewife populations. Winter, spring and fall biomass was somewhat higher, but only one sample (May 2020) had appreciably more than 100 µg/L of zooplankton biomass. That sample had one of the highest biomasses recorded for a Massachusetts lake, was dominated by large bodied *Daphnia*, which are very desirable as both phytoplankton grazers and fish food, and corresponded to very low algae abundance and water clarity of 8 m (26 ft). Once the alewife spawned and the young began feeding, zooplankton biomass plummeted to the usual very low level. One of the cover photos for this report (lower right) shows a comparison of the May 2020 and July 2020 zooplankton samples, showing how much biomass had decreased over 6 weeks as a result of alewife predation.

The size distribution of zooplankton is important too, with larger bodied forms having greater algae consumption potential, both in terms of the size of particles they can ingest and filtering rate (which is related to the cube of body length). Cladocerans like *Daphnia* are particularly valued, as they can filter much of the water column in a day at higher densities and represent high energy food packets that fish can see and consume. Smaller zooplankton like rotifers provide much less grazing capacity and lower food value, both in terms of availability and nutrition. Alewife both depress biomass and lower the mean size of remaining zooplankton (Figure 11).

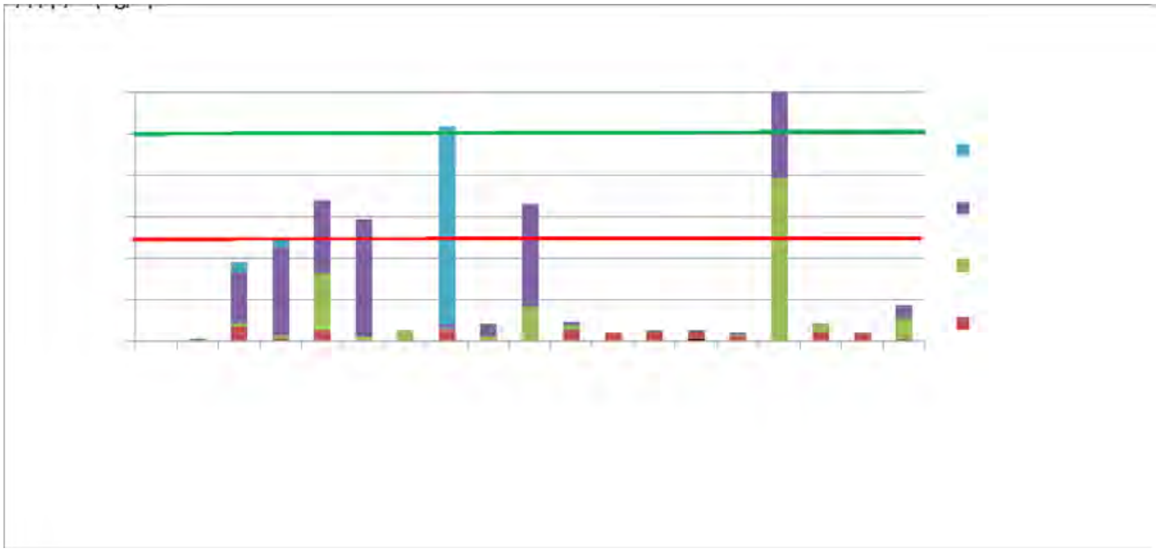


Figure 10. Zooplankton biomass in Mystic Lake from all available samples

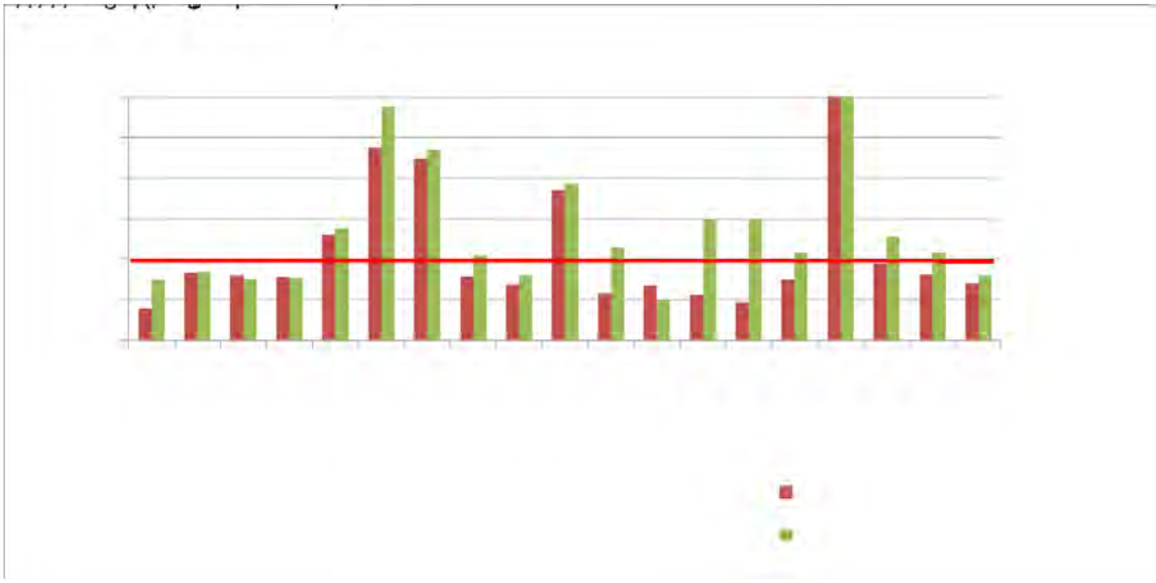


Figure 11. Zooplankton mean length in Mystic Lake from all available samples

Mystic Lake does not have enough zooplankton during summer to provide any significant grazing capacity for phytoplankton control. Nutrient availability will therefore be the dominant control over phytoplankton biomass. Other lakes with alewife populations, even those without serious fertilization issues, often experience lower water clarity during summer. There are enough nutrients to support at least moderate algae production and almost nothing to consume it, so water clarity declines. Other lakes treated with aluminum that also have alewife have demonstrated the same pattern. While hosting alewife reproduction and juvenile growth in a lake is of high benefit to the marine environment, it does predispose those host lakes to algae issues if nutrients are not kept at very low levels.

Diagnostic Conclusions

Mystic Lake is a kettlehole pond in Marston's Mills, Massachusetts. It is subject to some overland runoff inputs and discharges from cranberry bogs, but hydrology is dominated overall by direct precipitation and ground water seepage. Onsite wastewater disposal is a potential human source of nutrients via ground water. Yet internal loading of phosphorus represents a recycling of this nutrient after input from the watershed over many years and was the dominant source of phosphorus to Mystic Lake prior to inactivation of surficial sediment with aluminum in 2010. From the available data, it appears that internal P loading is still the dominant P source. Mystic Lake flows into Middle Pond, potentially representing a major input source to Middle Pond.

The decline of Mystic Lake leading up to 2010 appears related to loss of oxygen in water deeper than 30 feet and possibly as shallow as 20 feet with release of phosphorus bound to iron as a function of chemical reactions that occur in the surficial sediment when oxygen is absent. The depth of the boundary between the upper and lower water layers, the extent of exposure of sediment rich in Fe-P to low oxygen, and the depth of light penetration are all important factors in determining the influence of internal P loading on the lake and are affected by weather patterns that are not easily predictable from year to year.

Where light is adequate to allow algae growth near the boundary between upper and lower water layers and/or at the sediment-water interface in slightly shallower water, cyanobacteria can flourish. Many types of cyanobacteria can form gas pockets in cells that allow them to rise to the surface once adequate nutrients have been absorbed. This has resulted in surface blooms, some of which are known to be toxic. While direct evidence is incomplete, such a bloom in 2009 and 2010 appears responsible for the death of >95% of the mussel populations in Mystic Lake and substantial mortality in Middle Pond, as the contaminated water flowed from Mystic Lake into Middle Pond. Recovery of the mussel populations since those mass mortality events suggests improved conditions, but late summer cyanobacteria appearance, albeit at lower extent, represents a threat.

The treatment of Mystic Lake with aluminum in September of 2010 was intended to inactivate the phosphorus bound to iron in the surficial sediments, minimizing release when oxygen was depleted by decomposition in deeper water. Lowered phosphorus availability was expected to limit algae growth, and the raising of the ratio of nitrogen to phosphorus (N is not reduced by aluminum treatment) was expected to favor algae other than cyanobacteria, which prefer lower N:P ratios. A decline in phosphorus concentration was indeed observed after treatment but was not as pronounced as desired. A combination of lower than recommended dose, due to regulatory constraints, and lower efficiency of treatment in late summer after so much phosphorus had already been released from the sediment and from dead mussels, was suspected as the cause. Yet blooms of potentially toxic cyanobacteria were reduced and water clarity improved overall.

Follow up monitoring has been conducted once per year in late summer as part of the Pond and Lake Stewards program, but more intensive assessments were conducted by WRS in 2011, 2017-18, and 2020. Considering all past investigations, water clarity has increased since treatment and cyanobacteria abundance has been limited to patchy appearance of surface scums and windblown accumulations in late summer or early fall. Mystic Lake exhibits a decline in clarity over the course of late spring through early fall, caused by increasing algae abundance with minimal grazing pressure as young alewife consume nearly all the zooplankton in the lake between June and October. When grazing pressure declines in late spring, the base level of fertility in Mystic lake is not low enough to prevent observable algae increases.

It is not apparent that conditions in Mystic Lake have deteriorated appreciably since the 2010 treatment, but it does appear that conditions did not improve as much as hoped and periodic issues with lower clarity and visible cyanobacteria accumulations remain. Nearby Hamblin Pond, by comparison, exhibited marked improvement after its 1995 treatment, regressed to lakewide blooms over a span of months after 18 years, due to upward migration of Fe-P in the sediment, and with re-treatment in 2015 regained outstanding clarity and minimized cyanobacteria abundance. The Mystic Lake situation appears to be one of inadequate treatment coupled with higher susceptibility to algae accumulation brought on by a minimal summer zooplankton community controlled by alewife predation.

The Mystic Lake predicament is exacerbated by the upward migration of Fe-P in the sediment such that the quantity of Fe-P near the surface of the sediment, readily available for release into the overlying water, has reached a level of concern after 10 years. There is not nearly as much Fe-P mass as before treatment, but there is enough to result in excessive P in the deep water. With some transfer to shallower waters, this mechanism may be keeping the surface water P concentration high enough to allow algae growth during summer that compromises water clarity. This mechanism favors cyanobacteria and patchy accumulations along shore or as surface scums that occur in late summer. Substantial lakewide cyanobacteria blooms have not been observed since treatment, but elevated biomass of a variety of algae does reduce clarity to a noticeable degree as summer proceeds.

Management Implications and Options

It is apparent that internal loading remains an issue in Mystic Lake, as concluded by the 2017-2018 investigation. Other sources are less controllable even if significant, but the spatial and temporal distribution of P concentrations suggests that internal loading remains the primary driver of conditions in Mystic Lake. Management of internal loading requires control of the interchange between sediment and overlying water, especially where oxygen is low. There are three main options for achieving such control: dredging, P inactivation, and oxygenation. Each can be effective, but cost and regulatory/community acceptability are also important in choosing an approach.

Dredging is true restoration, removing problem sediment and setting the lake back in geologic time. Dredging would be the best technical approach to improving water quality, but this approach suffers from great expense and regulatory constraints. It is very unusual for a lake to be dredged when lost depth does not need to be recovered. The cost of dredging is a minimum of \$50,000 per acre-foot of sediment removed, with values up to 3 times that cost possible if there are technical difficulties (e.g., uphill pumping of sediment slurry, disposal area limitations) or sediment contamination (especially by hydrocarbons and metals). The exact depth of sediment that would need to be removed is unknown, and a proper feasibility study could cost \$100,000, but the cost would likely be millions of dollars after completion of engineering and permitting. This is an unlikely course of action for Mystic Lake, as concluded in 2018.

P inactivation involves adding chemicals that bind the currently available P and prevent its release from sediment, even with future exposure to anoxia. The primary target P is bound to iron, and under anoxia the iron and P can dissociate and dissolve in the overlying water. This is what was done in Mystic Lake in 2010, but at a dose that was apparently insufficient and with increased Fe-P availability near the sediment surface after a decade. Additional P is bound in easily decayed organic matter (biogenic P) that may be harder to inactivate and has been documented to be moderately abundance in Mystic Lake surficial sediment. Much P released from organic matter may be inactivated naturally by Fe in this system, another possible cause of the increased Fe-P in the upper 2 cm of sediment. Unfortunately, that Fe-P represents a time bomb under the extent of low oxygen observed.

Inactivation in low oxygen situations can be accomplished with the addition of calcium, aluminum, or lanthanum. Calcium treatments have not been overly successful, as calcium tends to stay in the sediment only with very high pH, and the pH on Cape Cod is routinely low. Lanthanum is a newer inactivator, applied with a clay solution that is not yet approved for use in Massachusetts. However, it is applied with bentonite clay and has a high specificity for P, so it has the potential to be more efficient than other inactivators and the clay may coat the organic sediment and reduce oxygen demand on the overlying water. Adding an excess of this product, tradenamed Phoslock, could seal sediments to some degree and provide longer term P inactivation as P migrates upward through the sediment. Phoslock is more expensive than aluminum in most comparisons but may offer some advantages. If approval could be gained, this approach may be worth at least testing.

Aluminum compounds have been the most applied P inactivators and aluminum has been used very successfully in Massachusetts lakes, including in Hamblin Pond in 1995 and 2015. Not all applications have resulted in conditions as desirable as in Hamblin Pond, however. Lovells Pond in Cotuit and Cliff Pond in Nickerson State Park in Brewster were treated and while conditions are far better than before treatment, they have had cyanobacteria at levels of concern on an intermittent basis both spatially and temporally. In cases where benefits have been less than expected, underdosing is suspected and additional application of aluminum could provide further benefit. Current thinking for aluminum treatments is that the efficiency of inactivation is improved by adding larger doses in several smaller increments over multiple years (James 2017), although waiting a decade has not been suggested. Based on the sediment data collected in 2018 and 2020, a dose of 25 g/m^2 may be adequate to manage current internal loading and a dose of no more than 50 g/m^2 would be recommended.

Oxygenation involves adding enough oxygen to counter the existing demand, thereby avoiding low oxygen and keeping Fe-P sequestered in the sediment. This approach could also oxygenate the bottom waters to a degree that would better support aquatic life such as fish and invertebrates during summer when there is currently inadequate oxygen in water deeper than 7 m. Oxygenation can be accomplished by destratifying the lake, using air bubbled from the bottom or by pumping water upward or downward. Oxygenation can also be accomplished by adding oxygen to deep water, either directly or in chambers that facilitate input without destratifying the lake.

Upward pumping or air-driven circulation carries the risk of bringing poor quality water to the surface if the system is undersized or shuts down and is restarted later; both have been problems with this approach, as illustrated by Santuit Pond in Mashpee and Lovells Pond in Cotuit. Downward pumping is usually not attempted where the water is <9 m deep, as sediment can be resuspended by the water flowing downward if it cannot be released below the thermocline but far enough above the sediment-water interface. That could be an issue in Mystic Lake, as low oxygen occurs at about 7 m of water depth and much of the target area is <9 m deep. Destratifying approaches are probably not worth pursuing for Mystic Lake, as maintenance of stratification is ecologically desirable, and the technical problems of the options are challenging.

The alternative approach of adding oxygen to the deeper waters without destratifying the lake could involve air or pure oxygen. Use of air can be effective but requires an interchange chamber and is inefficient, and power costs have limited recent application of that approach. Use of pure oxygen is more efficient and has been applied by releasing fine bubbles of pure oxygen near the bottom with the intent of having them completely dissolved before they reach the thermocline and cause destratification. This has worked well where the hypolimnion is at least 5 m thick, but that is not the case in much of Mystic Lake. Nanobubble technology has been developed to avoid this problem, but has not been reliable in trials to date, including one in an Orleans pond for the last two years. This leaves sidestream supersaturation, where water is pulled from the target zone, oxygenated, and put back, as the most viable technique. It is a more expensive option than inactivation, even just considering capital cost, and it must be applied each year, adding significant operational cost.

While discussion of options and priorities within the ILA and Town of Barnstable is encouraged, it appears that simply expanding the inactivation of sediment P with aluminum is the least expensive method and most likely way to achieve water clarity and algae management goals. Based on recent costs of similar projects and an apparent need for 25 g/m^2 over an area of 82 acres, project costs should be no more than \$100,000. The dose and cost could be doubled to provide a margin of safety, or additional sediment testing could be conducted to narrow the range.

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