Town of Falmouth - Partnership with Coastal Systems Program

School for Marine Science and Technology

University of Massachusetts Dartmouth

Mill Pond Nutrient Removal Pilots Update

Submitted by:

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Submitted to:

Water Quality Management Committee Town of Falmouth

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Acknowledgements

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In addition, the authors are grateful for the technical support provided by the Coastal Systems Program at the School for Marine Science and Technology, University of Massachusetts Dartmouth and its staff, graduate students, and interns, particularly Dr. Roland Samimy, Sara Horvet, Jen Benson, Ed Eichner and Amber Unruh for helping to maintain the continuity of monitoring with the prior work.

EXECUTIVE SUMMARY

Mill pond is a 16-acre freshwater pond with severe water and habitat quality impairments e.g. over-abundance of aquatic plant growth, periodic oxygen depletion of bottom waters and extremely poor water clarity. These impairments are mainly the result of nutrient over-enrichment from its watershed sources transported by surface freshwater and groundwater inflows. Work was conducted in Mill Pond from 2017-2020 and is still ongoing, first to determine pond water quality and attenuation of nitrogen and more recently to test various techniques for improving pond health and to test various approaches for nutrient remediation to improve quality in Mill Pond and downgradient Green Pond. The 2020 work continued to monitor baseline conditions in Mill Pond and upper Green Pond while 2 nutrient mitigation approaches were deployed (1) an aerator injecting nano-bubbles enriched in oxygen from August 14 through October 4, 2020, and (2) a late season harvest (October) of the above ground portions of the dense rooted plant growth in Mill Pond. Additional approaches will be evaluated in subsequent years including, use of horizontal PRBs and construction of a settling/detention basin within the cranberry bog footprint. The findings will be used to determine the appropriate management actions that can be implemented for N and P removal for restoration.

As part of the continuing baseline monitoring the stream inflow (corrected for recycled water) and outflow was combined with nutrient concentrations to determine the load of N and P entering/exiting Mill Pond. Over the months of June – December 2020. An average of 75 and 2.88 kg $month^{-1}$ nitrogen and phosphorus, respectively entered Mill Pond via surface water flow. After biological activities within the pond ecosystem, 34.3 kg TN $month^{-1}$ and 1.94 kg TP $month^{-1}$, was discharged from Mill Pond via surface water outflow. Comparing the input/output loads indicates that during the measurement period in 2020 the pond removed 54% (40.7 kg) of N and 33% (0.94 kg) of P from the surfacewater flowing through it. The actual N removal is even higher if the groundwater N input is factored in. However, a more accurate average of N removal was derived using a linear regression model. This indicates that there is a relatively consistent TN removal rate over the 4 years of measurement (all available data), which indicated a direct relationship between input TN load and output load. The fact that the relationship is linear and explains 77% of the variation, indicates that removal rates are fairly constant regardless of the input load and year. The slope of the regression indicates that an amount of TN equivalent to 53.4% of the Backus Brook discharge load is removed by the pond prior to discharge to Green Pond (and 100% of the Mill Pond local watershed load as well). Based upon the approach, this latter estimate of TN removal is seen to be more accurate for predicting outflow TN from inflow TN loads and removals and will be used to evaluate in-pond N removal technologies in the future as well as predicting pond outflow N loads as inflow loads change due to up-gradient N removal actions.

An in-pond technique for lowering P in Mill Pond was tested starting in August 2020. A nano-bubbler system (with oxygen enrichment) was deployed by Solitude Inc to address the hypoxic conditions and keep the iron-bound phosphorus locked in Mill Pond sediments, thus lowering water column P levels. The system began aeration on August 14, 2020, in the southeast quadrant of the pond. The aerator operated till October 2, and experiment was conducted until plant harvest which began October 8, 2020. To assess any effects on pond dissolved oxygen (DO)

status from the nano-bubbler system, a DO survey was completed prior to the starting of aeration, two during aeration and one following operation. There was no discernable impact on DO levels in the nearfield or farfield from the aerator. Similarly, the DO (in surface waters and 0.1 m above bottom) recorded by a recording DO sensors about 250 feet from the aerator indicated very low oxygen continuing after the aerator was operating. The aeration system, that was deployed did not appear to provide sufficient oxygenation to significantly raise oxygen levels (or change phosphorus levels) in the near or farfield to the aerator. Detailed measurements of DO at the aerator showed that the aerator was injecting oxygen, but the effect was very localized. To have a significant impact on pond sediment phosphorus release, a very much larger system would have to be installed and likely run for 6 months per year.

In some fresh ponds with dense macrophyte growth, phosphorus removal by plant harvest is employed. To test this approach, plants were harvested by mechanical harvester in October 2020. The mass of N and P held by the aquatic plants that were removed by harvest by this effort was found to be approximately 331.3 kg carbon, 21.4 kg nitrogen, and 0.516 kg phosphorus. This represents only 6.3 days of N input and 3.4 days of P input from Backus Brook to Mill Pond measured in summer of 2020. Based upon this pilot it must be concluded that harvesting would need to be more extensive and repeated annually to have the possibility of having any impact on the eutrophic conditions in Mill Pond.

At this point the potential nutrient management by aeration is uncertain and by plant harvest only if it can be more efficient and after the external nutrient load is reduced or in concert with other in-pond approaches (e.g., alum or dredging). As part of the nutrient input reduction, the new detention pond and PRBs in the up-gradient cranberry bog being piloted may provide the necessary guidance in the goal of improving Mill Pond.

I. INTRODUCTION

Scientific staff from the Coastal Systems Program (CSP) at the University of Massachusetts-Dartmouth (UMD), School for Marine Science and Technology (SMAST) has been actively collecting data to assess the application of restoration projects, by Science Wares, INC and CSP, and the impacts on the ecological health of the Mill Pond system. Scientists from the CSP-SMAST completed a comprehensive assessment of Green Pond under the Massachusetts Estuaries Project (MEP), which revealed that nutrient loading from its watershed has been adversely affecting the estuarine receiving waters of Green Pond within the Town of Falmouth (this was reported in the Massachusetts Estuaries Report from 2005[1] and a 2018[2] report to the Town of Falmouth). A main watershed source to Green Pond is Mill Pond and this is where we have focused our restoration efforts.

Mill pond is a 16-acre freshwater pond exhibiting signs of severe habitat impairment e.g., over-abundance of aquatic plant growth, periodic oxygen depletion of bottom waters and extremely poor water clarity[2]. These impairments are mainly the result of nutrient over-enrichment from its watershed sources transported by surface freshwater and groundwater flows which include residential and commercial development and an active cranberry bog. Work was conducted in Mill Pond from 2017-2020 and is still ongoing, first to determine pond water quality and attenuation of nitrogen and more recently to test various techniques for improving pond health and to test various approaches for nutrient remediation to improve quality in Mill Pond and downgradient Green Pond. The current Update continued to monitor baseline conditions in Mill Pond and upper Green Pond while 2 nutrient mitigation approaches were deployed (1) an aerator injecting nanobubbles enriched in oxygen (by Solitude) and (2) a late season harvest of the above ground portions of the dense rooted plant growth in Mill Pond. Six tasks were developed with the Town of Falmouth and Science Wares, Inc. for determination of the efficacy of these 2 approaches:

Task 1 – Quantification of Surface Water Flow and Nutrient Load In/Out of Mill Pond

Task 2 – Analysis of Dissolved Oxygen Conditions in Mill Pond

Task 3 – Water Quality Sampling in Mill Pond and Green Pond

Task 4 – Analysis of N and P Content in Macrophytes over the Growing Season

Task 5 – Analysis of N and P mass removal by harvest, 2020

Task 6 – Analysis of impact of aeration on Bottomwater Oxygen and Denitrification

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[1] Howes B., J.S. Ramsey, S.W. Kelley, R. Samimy, D. Schlezinger, E. Eichner (2005). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Great/Perch Pond, Green Pond, and Bournes Pond, Falmouth, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA, 205 pp. + Executive Summary, 11 pp.

[2] Unruh, A., B. Howes, E. Eichner, R. Samimy. 2018. Diagnostic Assessment of Nutrient Cycling for the Restoration of Mill Pond. Falmouth, Massachusetts. Technical Report: Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. pp.67.

II. TASK 1 - QUANTIFICATION OF SURFACE WATER FLOW AND NUTRIENT LOAD IN/OUT OF MILL POND

Data Collection

The overarching goal is to understand the nitrogen and phosphorus loading to and discharge from Mill Pond and to establish a baseline for assessing the effectiveness of both in-pond and watershed approaches for reducing nutrient level in the pond and in Green Pond. The present management actions were to pilot a nanobubble aeration system and N and P removal through plant harvest. Additional approaches will be evaluated in subsequent years including, use of horizontal Permeable Reactive Barriers (PRB's) and construction of a settling/detention basin within the cranberry bog footprint. The findings will be used to determine the appropriate management actions that can be implemented for N and P removal for restoration.

To quantify the surface water flow and nutrient load in/out of Mill Pond the CSP monitored the inflow from Backus Brook to Mill Pond and the pond outflow to the headwaters of the Green Pond Estuary. In June 2020 two stream gauges were again deployed by the CSP at the inflow (located at the Cranberry Bog) and outflow (culvert under the road) of Mill Pond with biweekly sampling conducted for the duration of the project (Figure II-1). The gauge sites were the same as in prior SMAST studies of Mill Pond for the Town. Water levels were determined using a vented stage recorder (10-minute intervals) with periodic direct measures of volumetric flow to construct a stage-discharge relationship (e.g., rating curve) for determining continuous volumetric flow rate (m^3 hr-1) for the inflow and outflow streams. Data is downloaded off the gauge and water samples collected bi-weekly. The nutrient samples were analyzed for water quality constituents as well as at a lower deeper pond basin sample. Coupling the volumetric flow rate with the measured nutrient concentrations yields detailed nitrogen and phosphorus loading into and out of Mill Pond.

In parallel with the inflow/outflow sampling water quality samples were collected twice a month from June-August and then monthly from September –November at a lower deep basin site in Mill Pond (Figure III-3) and in upper reaches of the Green Pond Estuary. Therefore nutrient samples were collected from the inflow and outflow of Mill Pond and PondWatch stations GP1, 2, 2A, and 3 in upper Green Pond (Figure II-1). Water samples were collected and returned to the Coastal Systems Analytical Facility and analyzed for standard water quality constituents, including chlorophyll-*a* and pheophytin-*a*, total nitrogen with its component species (NH^4, NO_3+NO_2, DON, and PON) , plus total phosphorus and ortho-phosphate and salinity. In addition, dissolved oxygen and water clarity were measured in the field.

The duration of Mill Pond anoxia was determined by multiple pond-wide surveys with profiling with a YSI Pro DSS probe/meter and by deploying two YSI 6600 Multi-parameter Water Quality Monitors with optical dissolved oxygen, chlorophyll-*a*, and temperature sensors recording at 15-minute intervals in the lower deeper basin. The bottom sensor was ~10 cm above the pond bottom to reflex oxygen at the sediment surface. Bi-weekly calibration samples for dissolved oxygen and chlorophyll were collected throughout the deployment period (see Task 2).

Figure II-1. Site map showing the Green Pond watershed inclusive of the cranberry bog, Mill Pond, and Green Pond Falmouth, MA. The left photo indicates Mill Pond Inflow, Basin, and Outflow through Backus Brook into Green Pond (listed north to south). The right photo indicates three of the four sampling locations (GP1, 2, 2A) listed north to south (Image from Google Earth).

Results

Surface water loads into and out of Mill Pond were determined from the volumetric flow and nutrient concentration measurements at the gauge sites. A mass transport of N and P is determined based on flow and stage measurements combined with water quality samples. In Mill Pond surface flow is the main source and sink of nitrogen and phosphorus (see 2018 report). Significant removals of N or P will be reflected in the inflow/outflow balance and improvements in Mill Pond nutrient status will be seen in the in-pond measurements and the outflow loads.

Inflow load variability can be attributed to changes in irrigation practices and rainfall, during sampling timeframes, up-gradient of Mill Pond at Handy Bogs. The flow into Mill Pond travels through Backus Brook, a ground water fed stream that runs through an active cranberry bog system before entering Mill Pond. The groundwater transport nutrients from watershed land-uses into the bog system where additional nitrogen may be added. However, it should be noted that the bogs are now fertilized with low/no phosphorus fertilizers and nitrogen fertilization is low for cranberries.

The inflow and outflow volumes are altered as bog operations require water to be pumped in and out of Mill Pond during harvest and to protect the cranberries from freezing. The volume of water and its nitrogen and phosphorus loads entering Mill Pond was corrected for the recycling of water using measured and modeled inflows. Outflow volume and load from Mill Pond was more straight forward and did not need to account for recycling of water.

To accurately quantify the inflow loads to Mill Pond there were bi-weekly measurements of stream velocity and continuous stage measurements from which a stage-discharge relationship (rating curve) was developed to provide continuous flow. The inflow from Backus Brook to Mill Pond was measured just below the culvert where water flows over a control board and directly into the Mill Pond. A stream gauge was deployed from June 2020 to present, measures stream stage every 10 minutes. Multiple rating curves were required to account for different water control types which are dependent upon seasonal water usage. This seasonal specific method allowed the determination of continuous volumetric water flow from Backus Brook to Mill Pond, despite the manipulation of water flow.

The outflow from Mill Pond to upper Green Pond Estuary was measured at the concrete culvert under Route 28 and maintained as for the inflow gauge. These flow measurements correlated directly with the readings of stage levels and produced a single composite rating curve. This method of flow prediction closely matches the point measures of flow measured in the field.

The predicted inflow (corrected for recycled water) and outflow was combined with nutrient concentrations to determine the load of N and P entering/exiting Mill Pond. Over the months of June – December 2020, an average of 75 and 2.88 kg month^{-1} nitrogen and phosphorus, respectively entered Mill Pond via surface water flow. After biological activities within the pond ecosystem, 34.3 kg TN month^{-1} and 1.94 kg TP month^{-1}, was discharged from Mill Pond via surface water outflow. Comparing the input/output loads indicates that during the measurement period in 2020 the pond removed 33% (0.94 kg) of P and 54% (40.7 kg) of N from the surfacewater flowing through it. The actual N removal is even higher if the groundwater N is factored in. The ratio of phosphorus to nitrogen in a biologically balanced system according to the well-established Redfield [3] ratio is 16 N:1 P, whereas the inflow N/P is 26 and outflow 18 indicating that these waters will be stimulated by phosphorus additions.

The 2015 data consists of samples from August to December in which the average total nitrogen and phosphorus, per month, inflowing was 122.14 and 8.90 kg, respectively, entered Mill Pond via surface water. The average monthly discharge was quantified as 57.82 and 3.98 kg TN and TP. January to September 2017 has higher levels of flow which elevates the load concentrations

[3] Eduard Eichner, Howes, B, & Horvet, S. (2015). Town of Plymouth Pond and Lake Atlas. Final Report, June 2015

for N and P. The average monthly TN and TP, at inflow, were 167.91 and 5.24 kg. The discharge was quantified as 92.87 and 4.51 kg.

In 2016 the data collection spanned an entire year with the average monthly inflow of TN and TP at 121.03 and 4.83kg. The discharge was quantified on average as 81.17 kg TN and 3.98 kg TP. This year is the best to compare to the 2020 data as it is a drought year, as well. The N:P ratio for inflow is 25.1 and outflow is 20.

The flow comparison from 2020 to 2017 shows significant differences in annual flow and nitrogen concentrations in/out of pond. Yet, comparison of data from 2016 and 2015 to 2020 reveals significant similarities in annual flows (hydrologic variability), the nitrogen concentrations in / out of the pond were relatively constant (Table II-1). The precipitation for 2020 and 2016 points to a drought affecting the flows and subsequent loads. Changes in annual flows can be attributed to observed variations in regional precipitation and groundwater levels. Meteorological data is monitored by National Estuarine Research Reserve System in Waquoit Bay and yearly precipitation totals show the smallest amount of rainfall in 2016 with 926.2 mm (Table II-2, Fig. II-2).

Table II-1. Mill Pond inflow / outflow water volume and nutrient loads based on averaged daily load. MP IN and MP OUT are the measured stream flows and associated loads.

Stream	Sampling Period	Average Volume m3/d	PO4 kg/d	TP kg/d	NH4 kg/d	NOX kg/d	DIN kg/d	DON kg/d	TDN kg/d	TN kg/d	POC kg/d	PON kg/d
MP IN	Aug- Dec 2015	3725	0.12	0.30	0.14	1.75	1.90	1.63	3.52	4.15	7.39	0.63
MP OUT	Aug- Dec 2015	3963	0.03	0.14	0.08	0.08	0.34	1.22	1.57	1.97	3.61	0.40
MP IN	Jun-Dec 2016	3709	0.05	0.14	0.15	1.67	1.91	1.12	2.97	3.35	4.49	0.40
MP OUT	Jun-Dec 2016	2655	0.01	0.08	0.03	0.03	0.06	1.02	1.08	1.47	3.08	0.39
MP IN	Jun-Sep 2017	7275	0.09	0.22	0.16	3.40	3.55	1.96	5.52	6.36	10.28	0.81
MP OUT	Jun-Sep 2017	6799	0.04	0.16	0.17	0.85	1.01	1.79	2.80	3.33	4.57	0.53
MP IN	Jun-Dec 2020	2992	0.02	0.11	0.31	1.21	1.38	0.78	2.16	2.57	7.64	0.42
MP OUT	Jun-Dec 2020	2309	0.02	0.06	0.09	0.16	0.24	0.79	1.02	1.27	2.29	0.24

Table II-2. Total precipitation in Waquoit Bay, Falmouth from the National Estuarine Research Reserve Centralized Data Management Office (http://cdmo.baruch.sc.edu/dges/) for 2015-2018, 2020.

Year	Total Precipitation (mm)
2015	116.3
2016	926.2
2017	1501.8
2018	1569.9
2020	1024.2

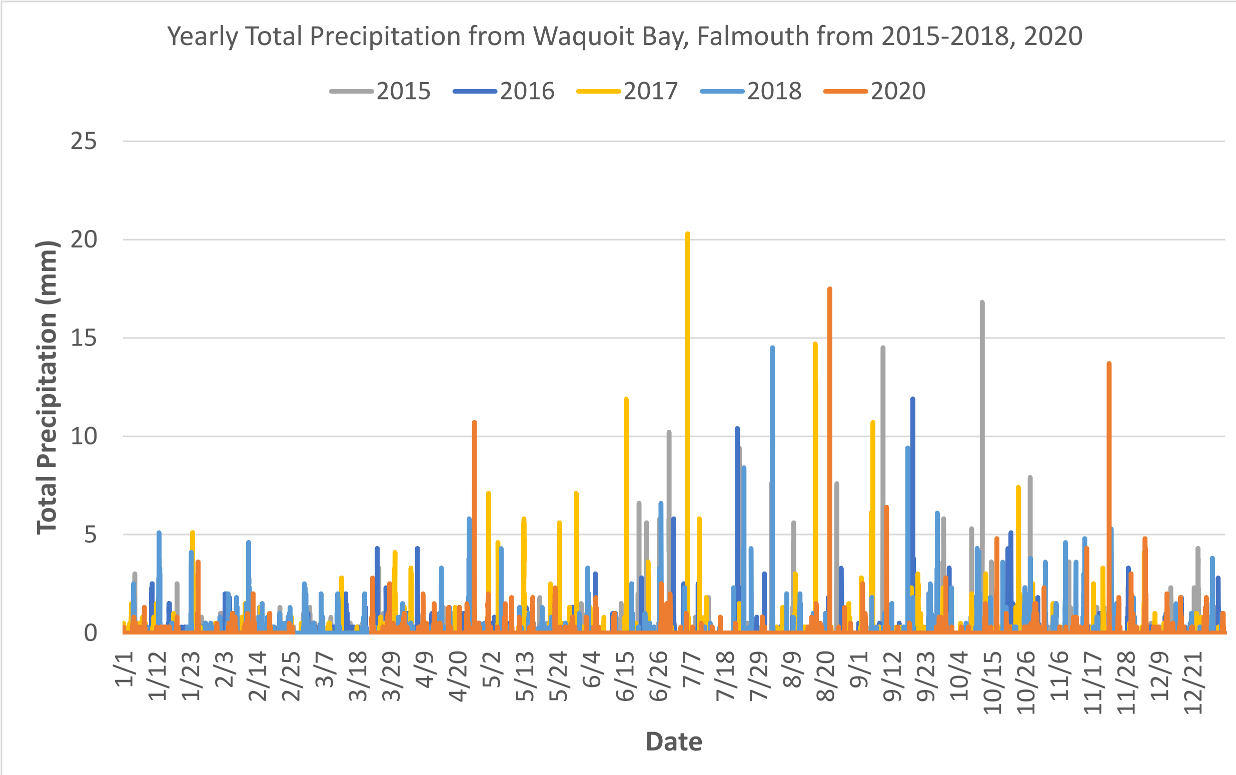
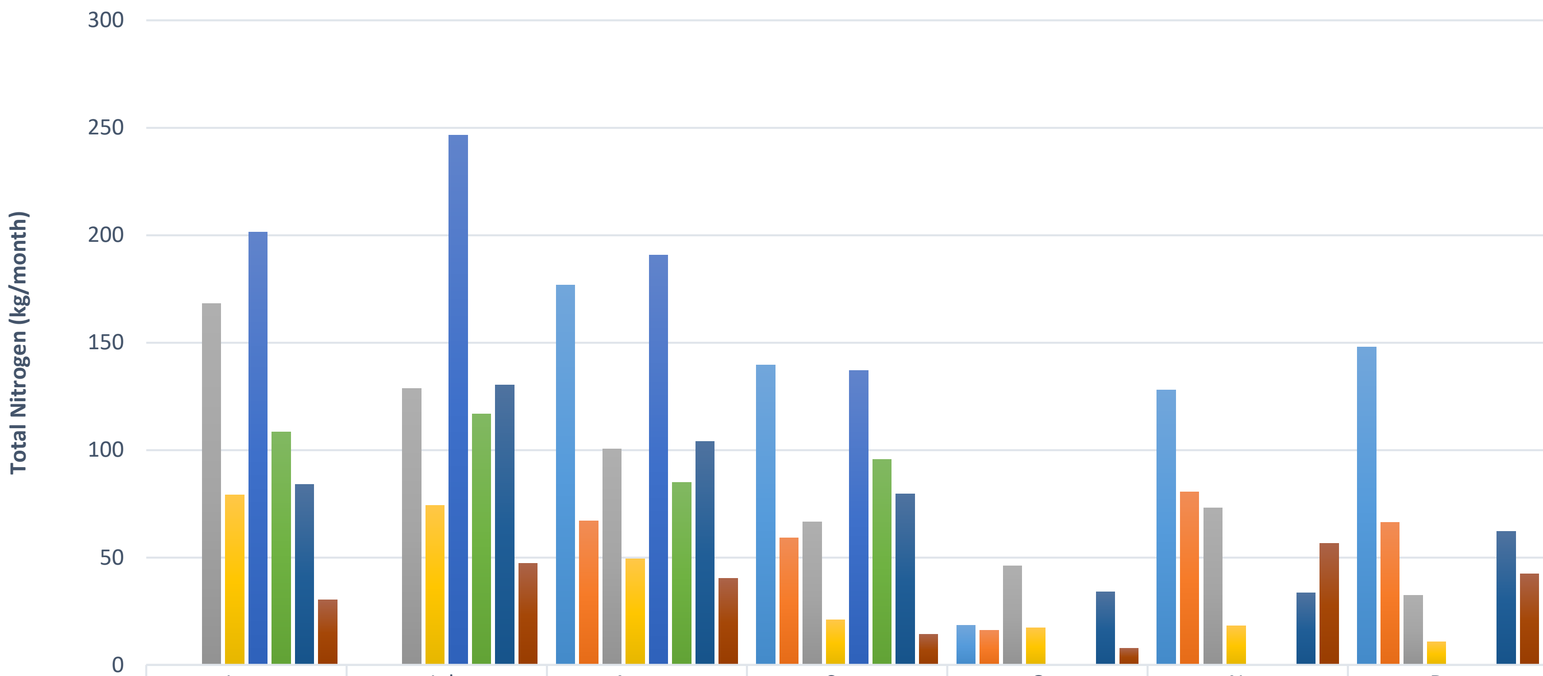


Figure II-2. Total precipitation in Waquoit Bay, Falmouth from the National Estuarine Research Reserve Centralized Data Management Office (http://cdmo.baruch.sc.edu/dges/) for 2015-2018, 2020.

Since multiple years of data exist on input/output TN and TP loads for Mill Pond, it is reasonable to examine the removal rates over a longer period than 2020 (this study). So available data was compiled, and TN and TP inflow and outflow loads determine for 2015, 2016, 2017 and 2020, which included the interannual variation in rainfall among other parameters (Figure II-3 and II-4). The 2015 data is a culmination of Aug-Dec data, 2016 and 2017 is a culmination of Jan-Dec data, and 2020 is Jun- Dec data. The time periods are of different length, so they were adjusted to per month rates, each year's data shows the Mill Pond is a significant sink for N and P in water entering from Backus Brook prior to discharge to upper Green Pond. A simple average of the removal gives and approximate 46.5% TN reduction and 36.25% of TP reduction over the 4 years. This TP and TN reduction is due to plant consumption, burial, and denitrification within the ecosystem.

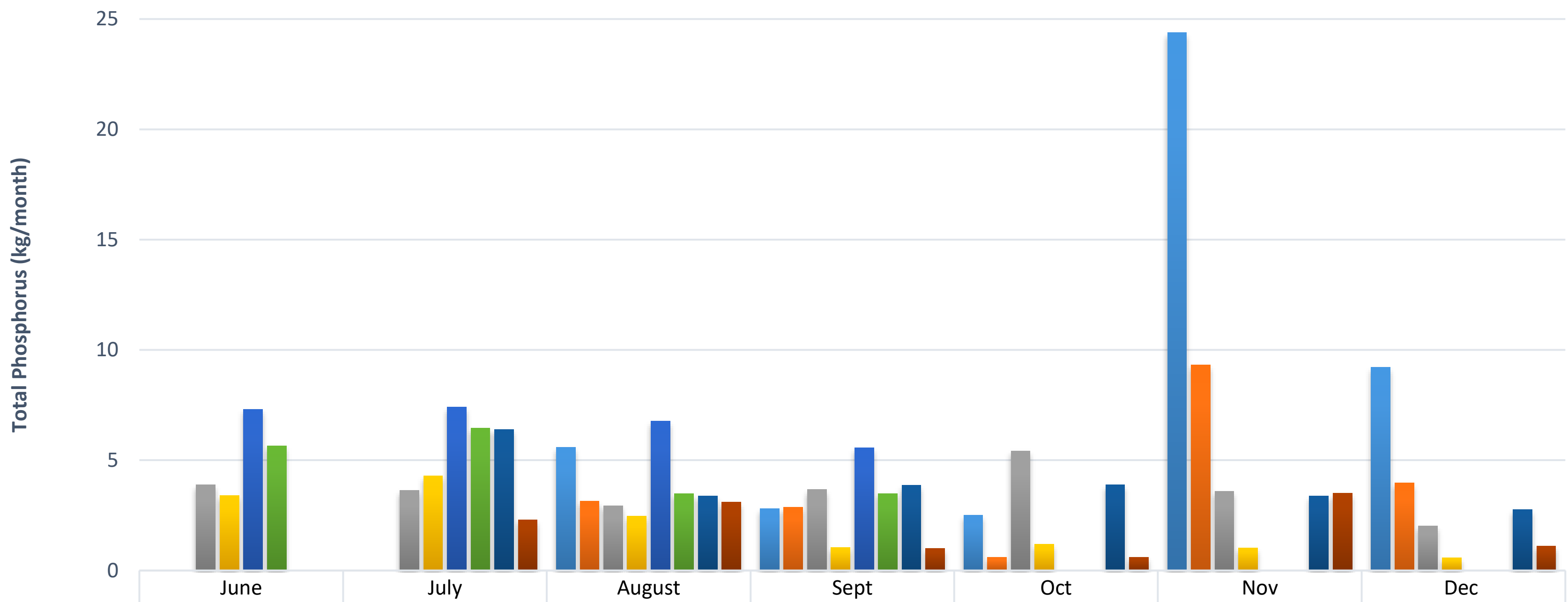
However, a more accurate determination of input/output loads using a linear regression model indicates that there is a relatively consistent TN removal rate over the 4 years of measurement (Figure II-5). Combining all data on input and output TN mass indicated a direct relationship between input TN load and output load. The fact that the relationship is linear and explains 77% of the variation, indicates that removal rates are fairly constant regardless of the input load and year. The slope of the regression indicates that an amount of TN equivalent to 53.4% of the Backus Brook discharge load is removed by the pond prior to discharge to Green Pond (and 100% of the Mill Pond local watershed load as well). Based upon the estimation approach, this latter estimate of TN removal is seen to be more accurate for predicting outflow TN from inflow

TN loads and removals and will be used to evaluate in-pond N removal technologies in the future as well as predicting pond outflow N loads as inflow loads change due to up-gradient N removal actions.



	June	July	August	Sept	Oct	Nov	Dec
2015 IN			176.71	139.69	18.48	127.92	147.92
2015 OUT			67.08	59.18	16.04	80.5	66.29
2016 IN	168.25	128.63	100.62	66.66	46.02	73	32.36
2016 OUT	79.13	74.32	49.35	21.02	17.36	18.21	10.68
2017 IN	201.35	246.63	190.73	136.97			
2017 OUT	108.39	116.74	85.04	95.65			
2020 IN	84	130.2	103.98	79.65	34.01	33.58	62.08
2020 OUT	30.2	47.2	40.2	14.3	7.7	56.6	42.3

Figure II-3. Inflow and Outflow Total Nitrogen loads from 2015-2017, 2020 for Mill Pond, Falmouth. Note that different time intervals of measurement required adjusting the transport rates to per month for comparisons of mass in/out from year to year, but all available data indicate a significant N removal by Mill Pond prior to discharge to upper Green Pond.



	June	July	August	Sept	Oct	Nov	Dec
2015 IN			5.59	2.81	2.52	24.39	9.22
2015 Out			3.14	2.87	0.60	9.32	3.98
2016 IN	3.90	3.62	2.94	3.67	5.43	3.60	2.02
2016 OUT	3.41	4.29	2.46	1.04	1.19	1.03	0.59
2017 IN	7.31	7.41	6.77	5.56			
2017 OUT	5.66	6.46	3.48	3.50			
2020 IN		6.4	3.39	3.86	3.9	3.37	2.77
2020 OUT		2.3	3.1	1	0.6	3.5	1.1

2015 IN 2015 Out 2016 IN 2016 OUT 2017 IN 2017 OUT 2020 IN 2020 OUT

Figure II-4. Inflow and Outflow total phosphorus loads from 2015-2017, 2020 for Mill Pond, Falmouth. Note that different time intervals of measurement required adjusting the transport rates to per month for comparisons of mass in/out from year to year, but all available data indicate a significant N removal by Mill Pond prior to discharge to upper Green Pond.

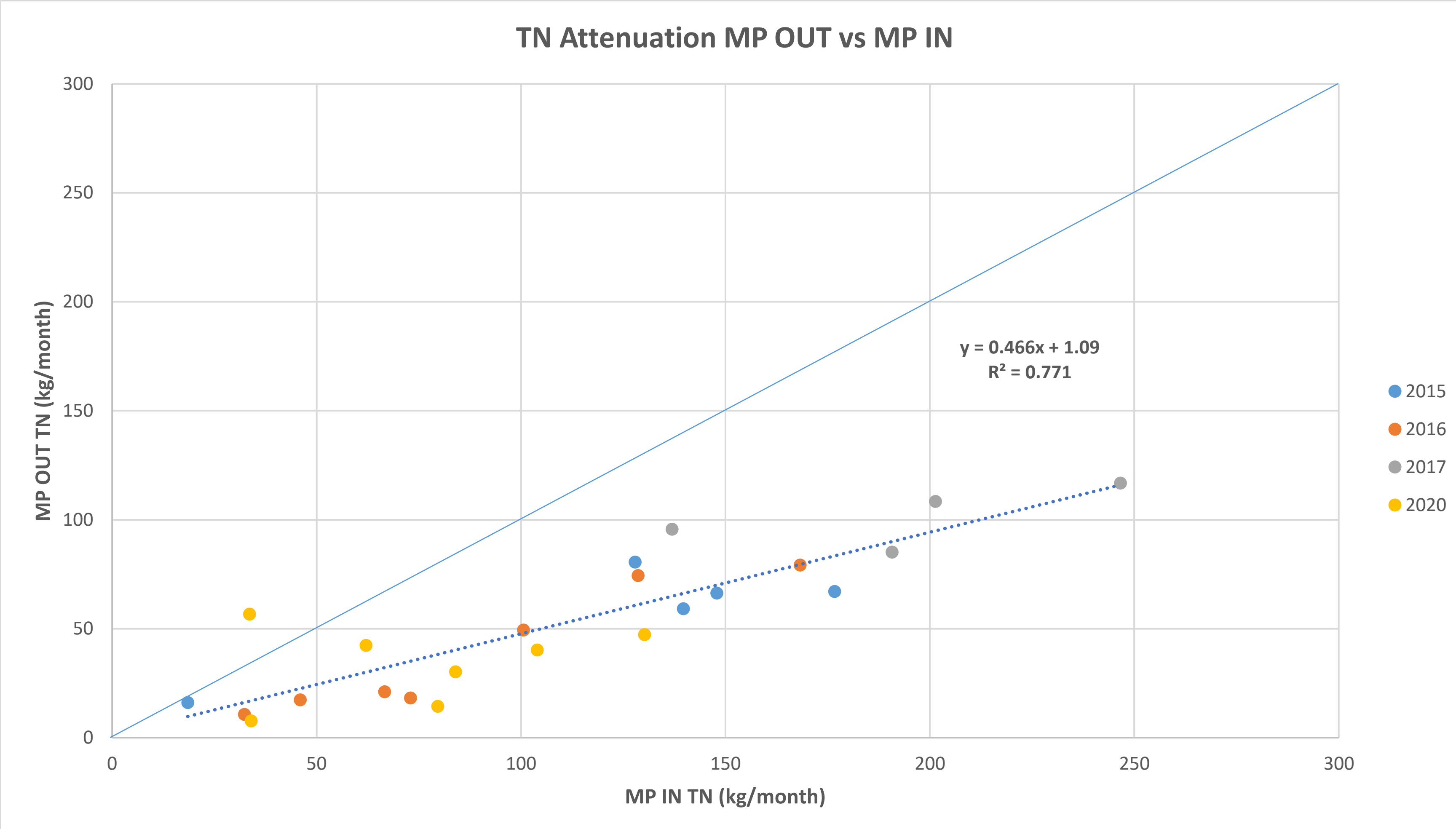


Figure II-5. Comparison of MP IN vs MP OUT TN mass data collected from 2015-2020. From the linear regression analysis (R^2=0.77), typically 53.4% of the nitrogen entering from Backus Brook is removed in passage through Mill Pond prior to discharge to Green Pond, 2015-2020. Direct groundwater discharge carrying N into Mill Pond is not included. The solid blue line represents a 1:1 line.

III. TASK 2: ANALYSIS OF DISSOLVED OXYGEN CONDITIONS IN MILL POND

Data Collection

In June 2020 two EUREKA Water Probes with optical dissolved oxygen, chlorophyll-*a*, and temperature sensors were deployed and DO profiles was taken in the Mill Pond Basin on survey dates with a YSI DO probe/meter. Samples DO sonde sensor calibrations were collected for oxygen determination by Winkler titration. The dissolved oxygen sensor was deployed 0.1m above the bottom at the deployment site (marked "Basin" in Figure III-3), as well as a second meter deployed near the surface to capture the water column mixing. These sensors remained in the water during plant harvesting (see below) and before and after the nano-bubbler was deployed to record the frequency and duration of low oxygen depletion and seasonal temperature changes.

The Oxygen status of Mill Pond changes seasonally and is a key metric to determining habitat quality and plays a key role in controlling phosphorus release from the Pond sediments. During summer's warmer temperatures biological oxygen uptake by sediments, plankton and plants reduce oxygen levels in-pond waters when uptake exceeds oxygen resupply from the atmosphere or photosynthesis. The low DO conditions allow release of chemically bound sediment phosphorus stimulating eutrophication during warmer months.

As P is the limiting nutrient in this system the addition of it can cause phytoplankton blooms or increased macrophyte growth. Mill Pond is covered in 80% of macrophytes (2018 Feasibility Study) which take up nutrients during growth and release them upon senescence and decay, also impacting oxygen uptake. Nutrient releases, particularly nitrogen, travels down-gradient of Mill Pond to the Green Pond estuary, where it stimulates phytoplankton growth and eutrophic impacts. Occasionally, nitrogen can be co-limiting with phosphorus. A nitrogen-limited system will have blooms or increased macrophyte growth when nitrogen is added to the system[2]. Co-limited systems are limited by both nutrients, which may change seasonally. Previous studies have identified nitrogen (N) as the primary driver of eutrophication in Green Pond and phosphorus (P) in the freshwater Mill Pond. This points to the need to control both N and P in this pond-estuarine system (refer to Falmouth Report 2018).

An in-pond technique for lowering P in Mill Pond was tested starting in August 2020. A nano-bubbler system (with oxygen enrichment) was deployed by Solitude Inc to address the hypoxic conditions and keep the iron-bound phosphorus locked in Mill Pond sediments, thus lowering water column P levels. The system began aeration on August 14, 2020, in the southeast quadrant of the pond (see Figure III-3), downhill from the East Falmouth Library. The aerator operated till October 2, when and experiment was conducted and then removed prior to the plant harvest which began October 8, 2020. To assess any effects on pond dissolved oxygen status from the nano-bubbler system, a DO survey was completed prior to the starting of aeration, two during aeration and one following operation. There was no discernable impact on DO levels in the nearfield or farfield from the aerator (Table III-1). Similarly, the DO in the bottom water (in surface waters and 0.1 m above bottom) recorded by the sonde about 250 feet from the aerator (at the Basin Site) indicated very low oxygen continuing after the aerator was operating (Figure III-4).

Figure III-1. Surface bubbles from bottom deployed nano-bubble aeration system in operation in the SE part of Mill Pond, Falmouth.

The Mill Pond aeration system put in place in mid-August 2020 was producing nano-bubbles with very little surface expression (Figure III-1). Its implication in Mill Pond was to release nano-bubbles that would oxygenate the sediments so that the phosphorus would remain trapped with the iron-oxides [2]. which in turn would improve water quality and habitat by limiting nutrient recycling of P that adds to P inputs from runoff and senescing plant matter. Phosphorus release has been found to be significantly controlled by limiting the level of oxygen depletion in bottom waters. This requires that the input of oxygen through aeration is sufficient to make up for the oxygen taken up in-pond waters and sediments.

Mill Pond is very shallow, at the head, and averages 0.7m in the Southern portion, so strong stratification does not occur due to wind driven mixing. However, vertical mixing is insufficient to maintain oxygenated bottom waters during summer. Surface, mid, and bottom id's, in the legend, correspond to MP Basin, monthly, data collection. Stratification was assessed using a vertical array of two temperature recorders located at MP Basin (between MP1 and MP2 Fig. III-2). There was some weak stratification in summer and early fall, which certainly helped to the DO depletion of bottom waters by reducing vertical mixing (Figure III-5). However, a significant temperature drop occurred between the end of September and the beginning of October which resulted in an overturning of the water column and destratification (Fig. III-4). This mixing event also increased DO levels beyond what had been recorded in Mill Pond previously (Table II-1).

The aeration system, that was deployed did not appear to provide sufficient oxygenation to significantly raise oxygen levels in the near or farfield to the aerator. It is not clear if a larger or different unit would provide the necessary oxygen input to enable sufficient increase of DO in this system.

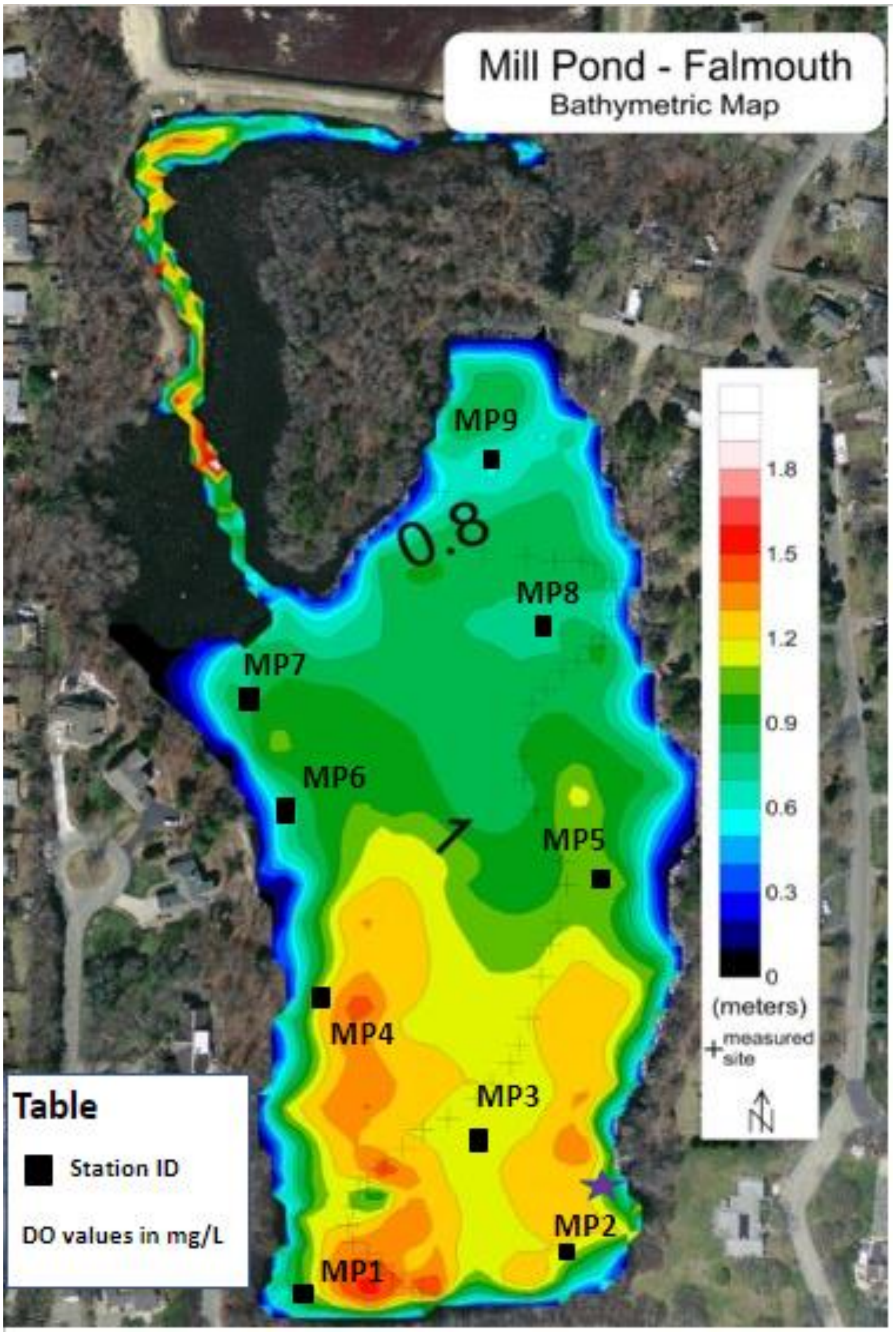


Figure III-2. Bathymetric map of Mill Pond, Falmouth with locations of DO Survey stations (MP_#) conducted pre-installation (8/4/20) and post-installation (through October 6, 2020) of the Nano-bubble aeration system (8/25/20, 9/29/20, and 10/15/20). The purple star indicates aeration unit location.

Table III-1. DO survey results measured with a ProDSS measurements were conducted to assess oxygen status throughout Mill Pond before (8/4/2020), during (8/25/2020 & 9/29/2020) and after deployment of the nano-bubble aerator. Stations MP-2 and MP-5 border the aerator deployment location. There is no discernable positive effect of the aerator on pond oxygen levels. The increasing DO levels late in the season (9/29/2020 and 10/15/2020) were due to declining temperatures. It should be noted that DO remained low in bottom waters on 9/29/20, 46 days after aeration began on 8/14/2021, and were very low 8/25/2021 at 11 days of aeration. Missing values are a result of changing water levels associated with the fall cranberry harvest.DO was recorded using a YSI ProDSS probe and meter calibrated prior to each use.

	8/4/2020		8/25/2020		9/29/2020		10/15/2020	
	DO (mg/L)	Temp (deg C)	DO (mg/L)	Temp (deg C)	DO (mg/L)	Temp (deg C)	DO (mg/L)	Temp (deg C)
MP1S	4.0	28.8	2.5	24.7	ND	ND	4.5	14.7
MP1M	1.7	26.8	1.86	24.2	2.96	20.1	3.16	14.1
MP2S	2.4	27.8	2.56	24.9	ND	ND	5.6	15.6
MP2M	2.1	26.5	0.4	23.8	2.88	19.5	4.83	14.8
MP3S	3.3	30.2	0.59	24.6	ND	ND	9.17	15.4
MP3M	0.3	26.4	0.19	23.6	2.28	19.7	6.37	15.8
MP4S	9.6	29.1	5.83	24.9	6.23	21.5	9.23	16.1
MP4M	12.0	26.9	5.15	24.3	4.91	20.3	5.83	15.7
MP4B	10.3	25.0	0.31	22.4	4.81	19.9	ND	ND
MP5S	2.7	28.4	0.7	24.8	4.1	22	5.43	16.6
MP5M	0.3	26.3	ND	ND	1.18	20.1	4.43	14.6
MP6S	16.5	30.4	4.75	24.6	8.58	22.3	7.4	15.9
MP6M	3.6	25.4	1.25	23.3	ND	ND	7.39	15.1
MP7S	10.3	28.2	12.05	24.5	11.5	22.2	6.59	16.6
MP8S	11.9	31.7	9.08	27.3	5.05	22.6	6.59	16.1
MP9S	11.2	32.3	10.4	27.2	6.14	23.3	9.74	17.6

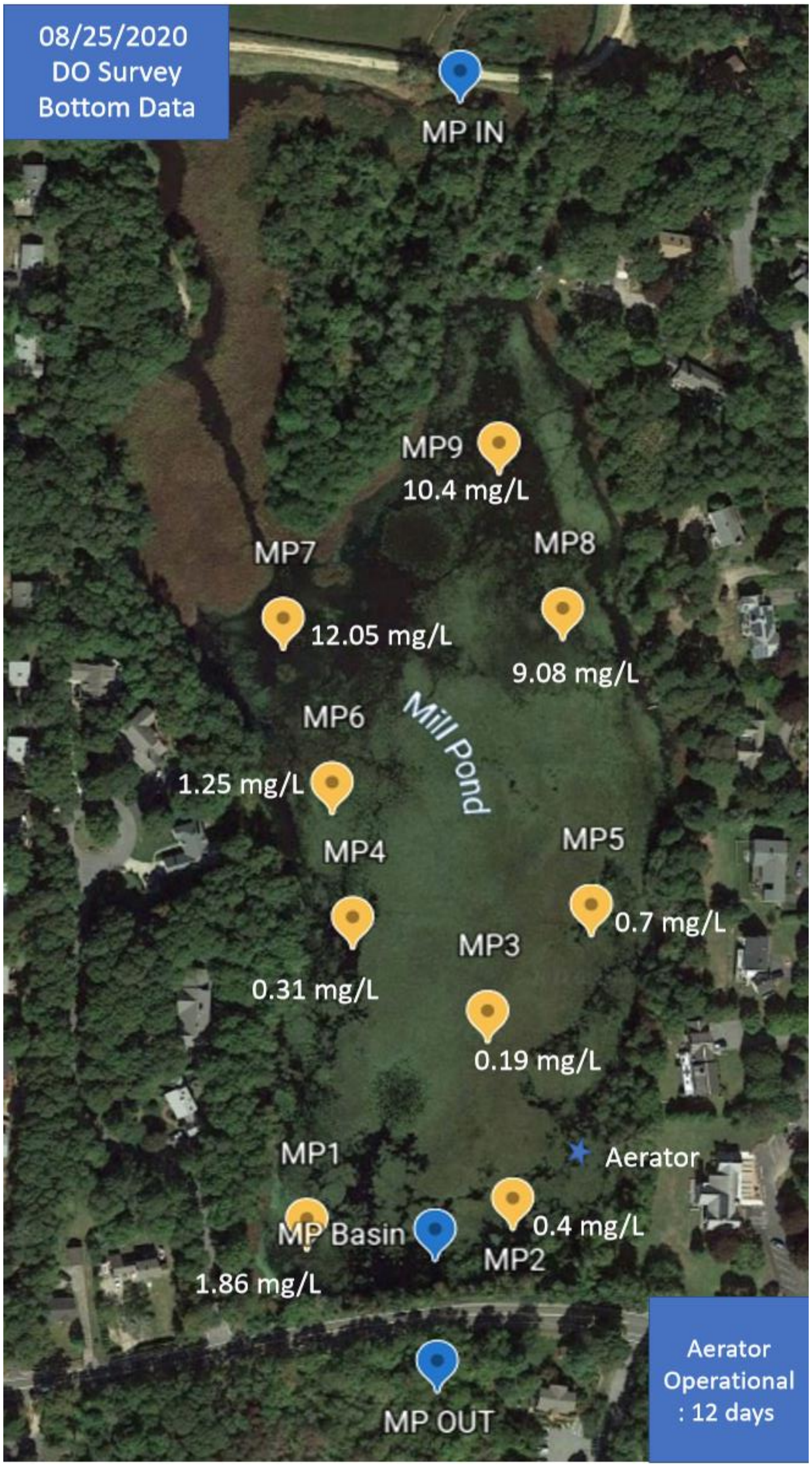


Figure III-3. In correspondence with Table III-1, each survey point is included with a focus on the bottom DO measurements for 8/25/2020 after the aerator had been running continuously for 11 days. There was no discernable effect of the aerator on general pond DO levels. The recording DO sensors were placed at the "Basin" site.

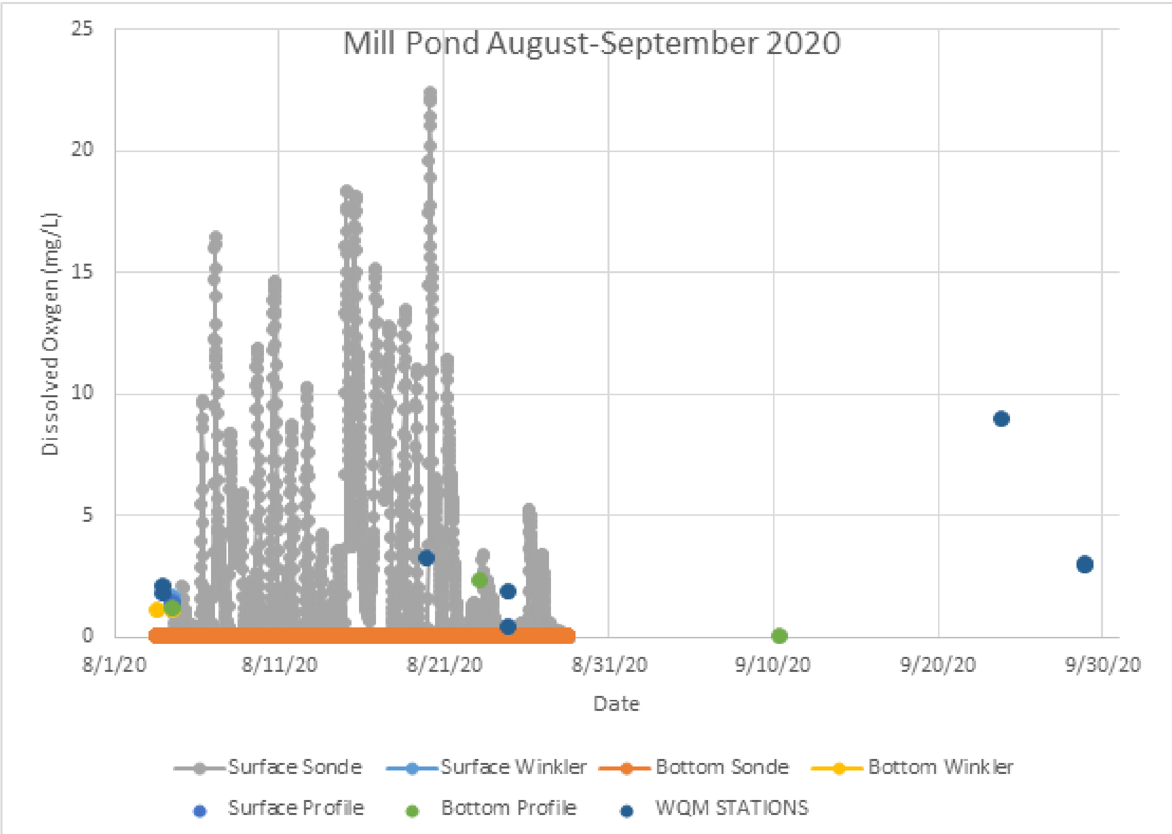


Figure III-4. Time-series records of surface and bottom water dissolved oxygen for Mill Pond, Falmouth 2020.

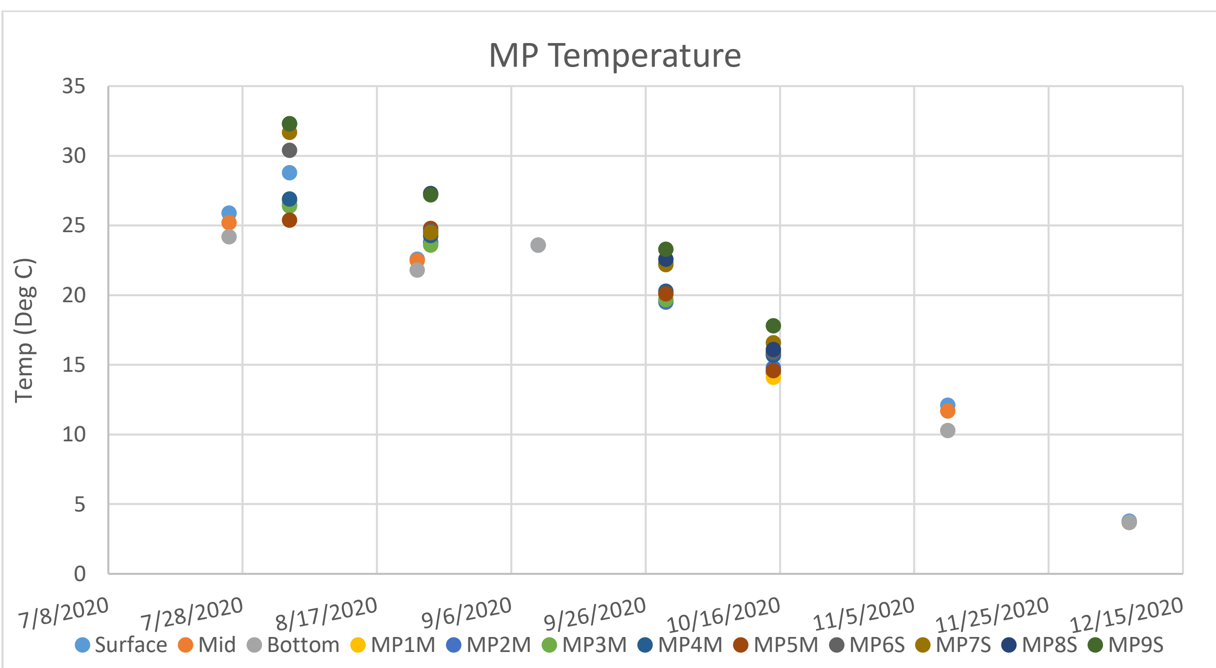


Figure III-5. In-pond temperature profiles for Mill Pond, Falmouth from June-October 2020. Note that there is some weak stratification during the summer period, diminishing in fall.

Aeration Testing

A test was conducted to determine oxygenation at the aerator site. The aerator was turned off 10/2/2020 and turned back on for a short experiment from 10/5/2020 to 10/7/2020 to see if there was any detectable oxygenation when the aerator was turned on (Figure III-6). In the figure the NB logger is located at the aerator at 0.5m depth in the water column. MP5 is 300ft north of the aeration unit and is also a DO survey location. The data gathered when the aerator was off was used to determine if there was a "spike" in oxygen when the aerator was turned back on and if the oxygen increase in DO (from 0.5 mg/L to 4.3 mg/L) when aerator began and DO levels remained >2.5mg/L until the end of the test. However, this was right at the aerator. At the 300ft away site there was no clear response to the aeration, as the pattern of DO concentrations was the same before and after the resumption of aeration. The pattern suggests that possibly photosynthesis is the primary factor in this DO pattern, but whatever the cause it is not indicative of effects that can solely be attributed to the aerator.

The conclusion is that the aerator was injecting oxygen, but the effect was very localized. To have a significant impact on pond sediment phosphorus release, a very much larger system would have to be installed and run, likely for 6 months per year.

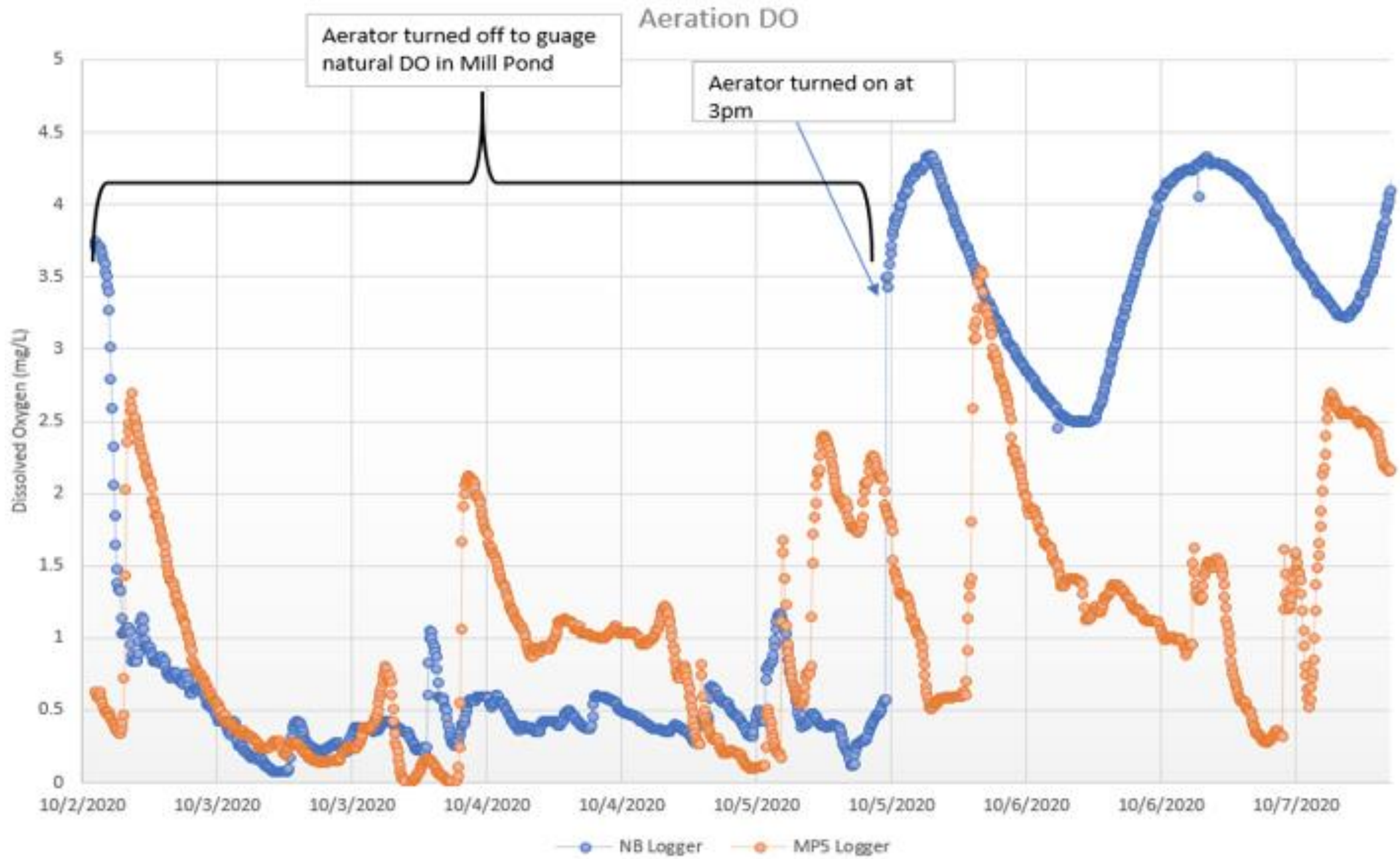


Figure III-6. Science Wares, Inc. results from an experiment conducted to look at the instantaneous effects of the aerator on surrounding waters. Oxygen sensors were deployed at the aerator site and 300ft away. Only the sensor at the aerator site showed significant oxygenation. The farther sensor did show changes in DO, but these changes were determined to be unrelated to the aeration system.

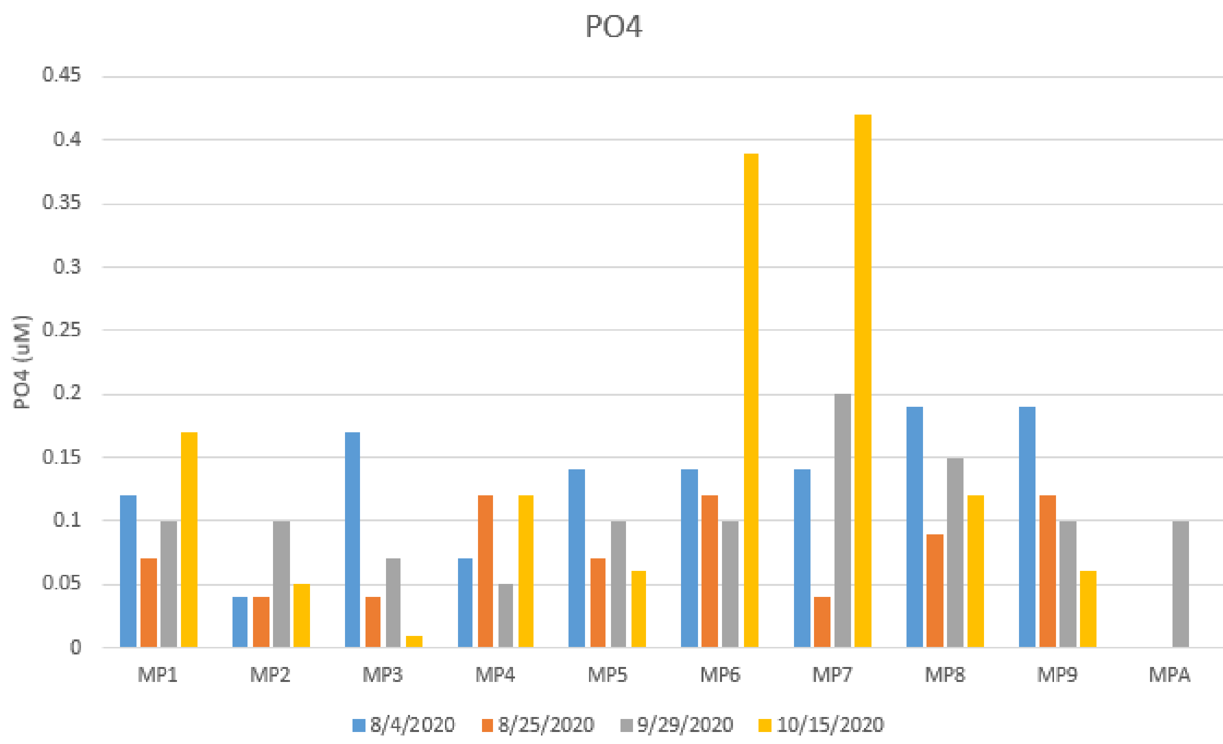


Figure III-7 PO_4 (uM) data collected during DO surveys prior to (8/4/20), during (8/25, 9/29), and post aeration (10/15/20).

When the aerator was turned on, ortho-phosphate levels declined at some stations and then tended to rise again. There was a large increase in ortho-phosphate in October that is like associated with bog operations during harvest (Figure III-7). Overall, the levels of ortho-phosphate were very low (<0.5 uM or ~0.01 mg/L) and indicate that almost all the phosphorus is in organic forms, due to uptake and release by plants and phytoplankton. There was no definitive pattern associated with the PO_4 and aeration effects.

In parallel with the oxygen surveys (Table III-1), water samples were collected for key water quality constituents (TN, TP, PON, and chlorophyll). Decreases in TP and TN were seen during aeration at sites MP2, 4, 6, and 9 (Figure III-8); the aeration system was turned on August 14th and turned off for the harvest which ended October 9th. Additional removal was observed at the end of October at the head of the pond. Increases seen after the harvest were at site MP1 and MP8 which are at the head and SW edge of the pond. MP1 is located at the SW end of the pond (Figure III-2) where the harvested material may accumulate as it is near the culvert that flows into Green Pond. High PON levels are seen due to harvest at MP1 but are not pond-wide.

Increases in P could be a result of the accumulation of plant material at the head prior to plant removal and SW corner, a collection zone, before export through the culvert. There was a delay in the harvest as the pond was drained for cranberry aquaculture usage. Total pigment (TPig) substantially decreased after harvest except at MP5, MP7 and MP9. High levels at MP7 and MP9 occurred as the harvest was not complete in those sections until 10/27/2020 and water levels were low because water was pumped out of the pond during cranberry harvest.

YSI 6600 & Sonde water quality meter results

Table III-2 is tabulated water quality data for the YSI 6600 Multi-parameter Monitor used during the DO survey studies. Measurements of total depth, secchi depth, dissolved oxygen, temperature, chlorophyll-*a*, and pheophytin-a were collected during these three surveys. The average depth of the North half of the pond is 0.39m and the southern half is 0.72m. In addition to the DO surveys, two EUREKA Water Probes were deployed at the MP basin location to monitor temperature, DO, and chlorophyll-*a*. They were programmed to measure parameters every 15-minutes 30 cm above the bottom from July 2020 to December 2020, but the recorder failed from late September to early August. Monthly dissolved oxygen and chlorophyll calibration samples were collected for the entirety of the deployment.

The available continuous record showed bottomwater anoxia (i.e., <0.5 mg/L) starting in July and lasting until the end of November. The surface waters experienced periods of oscillating oxic and hypoxic/anoxic conditions from July to September. In October there was a mixing event and the DO levels increased to range from 1 mg/L to 11 mg/L (Figure III.4). The days with less than 3mg/L still show substandard water conditions for optimal plant growth. Plant available nitrogen (DIN), the sum of ammonium and nitrite + nitrite, was greatest during August and September (Figure III-8). This also corresponds with the total phosphorus (TP) levels (Figure III.8). The length of bottom water anoxia relates to the release of phosphorus and ammonium from the sediments.

Figure III-8 quantifies the level of total chlorophyll-*a* pigment. This is indicative of phytoplankton blooms that can utilize the inorganic nutrients transforming them to organic forms. The chlorophyll bloom at the end of July correlates with the periods of lowest DO. A bloom in mid-October corresponds with the lowest DO levels seen in the fall.

Figure III-8 combines surface and bottom time-series DO data with DO calibration point measurements from the mooring location. These measurements were taken and analyzed using Winkler titrations. Points were included at sites to the east and west of the mooring (attained from YSI meter measurements), MP1 and MP2, respectively. Sensor data from the bottom waters shows minimal oxygenation from the aerator or vertical mixing. The surfacewater experiences higher DO levels due to the photosynthetic capabilities of the plants and mixing by wind, but does not translate to the bottom as there are thick mats of plants and decaying organic matter throughout the pond.

Figure III-8. Total Phosphorus (TP), particulate organic carbon (POC), total nitrogen (TN), and total chloropyll pigments (TPig) concentrations for DO survey locations in Mill Pond, Falmouth. Stations are listed from mouth to head of Mill Pond.

IV. TASK 3 - WATER QUALITY SAMPLING IN MILL POND AND GREEN POND

Mill Pond has two stream locations that receive biweekly sampling conducted for the duration of the project (see inflow and outflow from Mill Pond in Figure 1). This sampling looked at dissolved organic and inorganic nitrogen, particulate nitrogen and carbon, total phosphorus, and ortho-phosphate.

Dissolved oxygen (DO) measurements, water quality (WQ) samples, and water clarity (secchi depth) were collected twice a month from June-August and then monthly from September – November to gauge water quality conditions throughout the restoration projects. Further DO measurements can be seen in Task 2 to determine the effects of aeration.

The in-pond sampling occurred at the following stations, one in the outflow of Mill Pond and stations GP1, 2, 2A, and 3 in upper Green Pond (see Figure II-1). The duration of Mill Pond anoxia was determined by deploying two YSI 6600 Multi-parameter Water Quality Monitors with optical dissolved oxygen, chlorophyll-*a*, and temperature sensors recording at 15-minute intervals, 30 cm above the pond bottom and within the water column to evaluate water column mixing. Bi-weekly calibration samples for dissolved oxygen and chlorophyll were collected throughout the deployment period.

Samples were analyzed for standard constituents, including chlorophyll-*a*, total phosphorus and total nitrogen, plus ortho-phosphorus and nitrogen component species (NH_4, NO_3+NO_2, DON, and PON) and salinity.

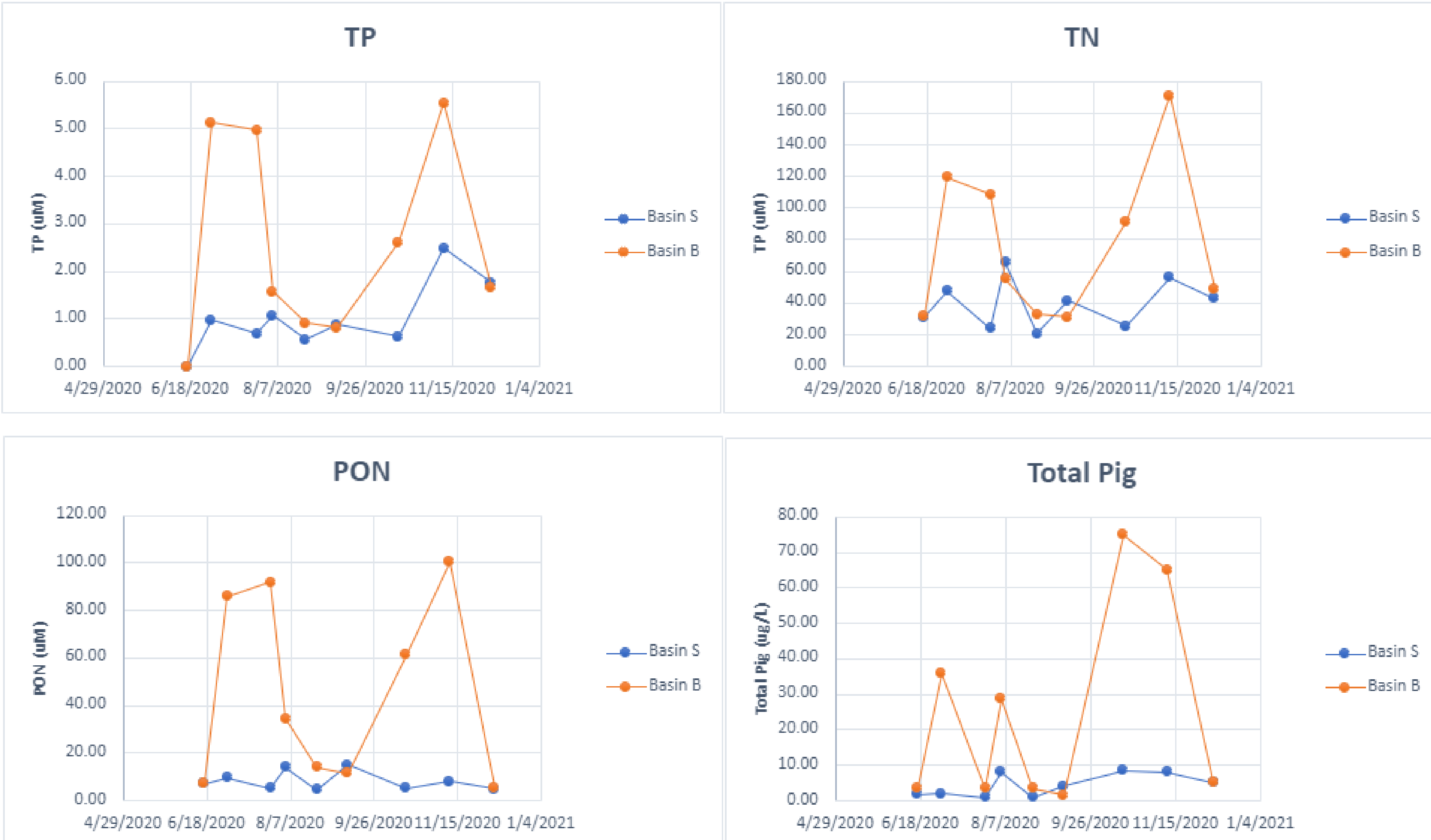


Figure IV-1. Mill pond basin, located at the outlet of Mill Pond, concentrations for total phosphorus (TP), total nitrogen (TN), particulate organic nitrogen (PON), and total chlorophyll pigments (Total Pig).

Figure IV-2. Green Pond surface concentrations for total phosphorus (TP), total nitrogen (TN), particulate organic nitrogen (PON), and total chlorophyll pigments (Total Pig). Stations listed from head to mouth of Green Pond, Falmouth.

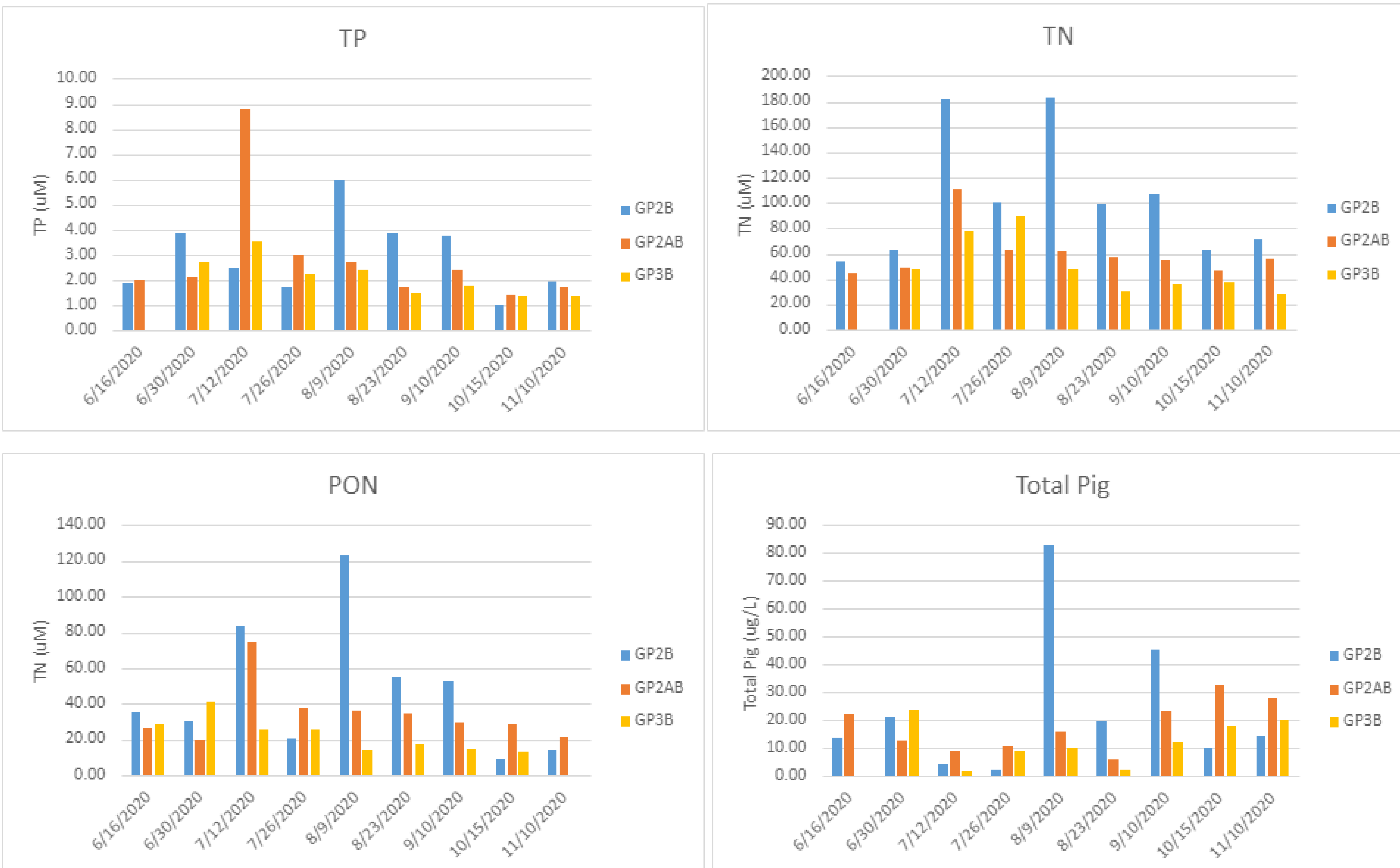


Figure IV-3. Green Pond bottom WQ Data concentrations for total phosphorus (TP), total nitrogen (TN), particulate organic nitrogen (PON), and total chlorophyll pigments (Total Pig). Stations listed from head to mouth of Green Pond, Falmouth

Results

The water quality surveys of Mill Pond and Green Pond (Figure IV-1) found that nutrient related constituents tended to peak twice in Mill Pond (early summer and fall) but only once in upper Green Pond waters in fall. The notable major event was a large phytoplankton bloom (seen as chlorophyll *a*) in both Mill Pond in late October-November and Green Pond in September.

The Mill Pond bloom and nutrient peak in fall was at the end of the plant harvest and found mainly at depth. Therefore, some might conclude that it results from a pulse of particulate and dissolved nutrients released in the bottom waters as the plants were harvested. This can be seen in the particulate nitrogen data. However, there is also a spring peak in these constituents also only at depth, and not associated with any management action. At this point it is uncertain if there is a linkage, rather than the natural spring and fall cycle seen in temperate basins. In addition, the Green Pond fall bloom cannot be linked to actions in Mill Pond since it preceded the plant harvest which was in October and also preceded the nutrient peaks in the Mill Pond bottom waters (Figures IV-1, IV-2). We must conclude at this time that the plant harvest did not appear to have any clear effect on the Mill Pond water quality and did not link to the Green Pond water quality. Similarly, the aerator did not raise oxygen levels, so it is understandable that there was no effect on ortho-phosphate or other water quality parameters during operation.

Staff will be following up on potential cause of the constituent peaks and phytoplankton bloom only showing up in Mill Pond bottom waters in spring and fall. It may be linked to stratification, but it will be important to understand relative to managing export from Mill Pond.

Table IV-1 Mill Pond surface and bottom sample results.

		TP uM	TN uM	PON uM	Total Pig ug/L
Basin S	6/16/2020	missing	30.80	7.01	1.75
Basin S	6/30/2020	0.99	47.80	9.62	2.03
Basin S	7/26/2020	0.71	24.10	5.16	1.06
Basin S	8/4/2020	1.06	65.56	14.16	8.09
Basin S	8/23/2020	0.55	20.46	4.58	0.88
Basin S	9/10/2020	0.89	41.32	14.88	4.19
Basin S	10/15/2020	0.63	25.40	5.14	8.64
Basin S	11/10/2020	2.50	56.11	8.09	8.16
Basin S	12/7/2020	1.76	42.64	5.05	5.11
Basin B	6/16/2020	missing	32.18	7.52	3.74
Basin B	6/30/2020	5.15	119.47	85.99	35.80
Basin B	7/26/2020	4.97	108.39	92.01	3.52
Basin B	8/4/2020	1.57	55.24	34.69	28.77
Basin B	8/23/2020	0.92	33.12	14.06	3.44
Basin B	9/10/2020	0.82	31.01	11.63	1.59
Basin B	10/15/2020	2.61	91.57	61.32	74.93
Basin B	11/10/2020	5.54	170.91	100.41	65.04
Basin B	12/7/2020	1.66	48.89	5.42	5.31

V. TASK 4 – ANALYSIS OF N AND P CONTENT IN MACROPHYTES OVER THE GROWING SEASON

Data Collection

Previous macrophyte surveys (in 2017) identified that the main aquatic plants in Mill Pond, are Yellow Floating Heart (*Nymphoides peltata*), the majority of the surface plants, and Yellow Water Lily (*Nymphaea mexicana*), Coontail (*Ceratophyllum demersum*) or Eurasian Watermilfoil (*Myriophyllum spicatum*), which were submerged throughout the pond[2].

Aquatic vegetation was collected in October 2017 using 0.25 sq. meter quadrats to determine the biomass and the nitrogen and phosphorus content of the plants, as well as, during samplings in the summer of 2020. The macrophytes were collected in the same northern and southern locations of the pond and were patted dry for determination of wet weight, and then dried at 64 ˚C to constant weight for dry weight. The macrophytes nitrogen and carbon content was determined using a PE2400 Series II CHN Elemental Analyzer. Phosphorus content was determined on the same samples by acid digestion. The plants averaged 37.2% carbon by weight, 2.4% nitrogen and 0.05% phosphorus (of dry weight) for the October 2020 harvest. The nitrogen and carbon content were used to determine the total mass of C and N held within the vegetation. The mass of N and P held by the aquatic plants pond-wide in summer is estimated to be approximately 21.38 kg nitrogen and 0.506 kg phosphorus. The N: P ratio of the plants is approximately 42 N: 1P.

Macrophyte samples from 2017- 2020 are currently held at the CSP lab. These samples were processed for % nitrogen and % phosphorus content at the time of macrophyte harvesting.

Table V-1. Macrophyte harvest dry weight carbon, nitrogen, and phosphorus percentages.

C, N, P content in harvested Macrophytes				
		%C	%N	%P
Oct	2017	36.6	2.8	0.06
Sept	2018	41.8	2.2	ND
May	2019	43.2	3.3	0.28
June	2019	42.1	2.3	0.18
Aug	2019	42.7	2.0	0.15
Oct	2019	42.9	2.0	0.13
Aug	2020	41.2	2.1	0.07
Sept	2020	42.5	2.3	0.08
Oct	2020	38.1	2.3	0.06

Table V-1 depicts the C, N, and P percentage content in the harvested macrophytes ranging in samples from the growing season from 2017-2020. The values calculated are consistent with literature[4] of macrophyte nutrient content percentages. This data was used to calculate the dry macrophyte weight removed from Mill Pond.

The average C: N ratio is 18 and N: P is 25. This system is both N and P limiting. Based on 100% removal of macrophytes from Mill Pond, including Backus Brook, the estimated concentration of N and P in the macrophytes was 453 kg of N and 10 kg P. The macrophytes grow from March to October and as they decay can release N and P back into the water column when oxygen levels are low. Plants like the yellow water Lilly restrict wind mixing[5] within the water column and limit oxygen distribution. As Mill Pond is 80% covered by macrophytes, harvesting was an option to reduce N and P levels up-gradient of Green Pond and within Mill Pond.

The Mill Pond harvest occurred in mid to late October but was not completed synchronically as water was removed for use in the up-gradient cranberry bog. This was done in the fall to maximize biomass (P removal).

The mass of N and P held by the aquatic plants, removed by the harvest, pond-wide in summer, is estimated to be approximately 21.38 kg nitrogen and 0.506 kg phosphorus. Assumptions made by the 2018 Feasibility Study 2018 predicted that the N and P in all of the plants totaled to 450kg of N and 10 kg P that could be removed. This was based on an area that included the harvesting of Backus Brook, which did not occur. By removing this area from the predicted area of harvest the pond area dropped from 63,924 m^2 to 56,234 m^2 and the total N and P that could be removed became 292kg of N and 7kg of P. During the plant harvest of 2020 the dry weight of plant material removed totaled to 10,776 kg biomass harvested. 8% of Mill Pond was harvested based on the 2018 Feasibility Study. Based on this information the theoretical kg N harvested was 23kg, 0.52 kg P, and 321 kg C. What was measured by the CSP team was a removal was approximately 21.38 kg nitrogen, 0.506 kg phosphorus, and 331.3 kg of carbon.

Differences in analysis included previous studies rinsing off some plants that by request were not rinsed for this analysis. The 2018 Feasibility Study's dry/wet ratio was 7% compared to this analysis which was 8%. This could be attributed to the rinsing of materials off the plant during the 2018 analysis. The previous samples had a high biomass and %N. 2020 samples were harvested in October and had lower wet biomass which translates to less dry biomass and less N per m^2.

[4] Gong, X., Xu, Z., Lu, W., Tian, Y., Liu, Y., Wang, Z. ... & Li, Z. (2018). Spatial patterns of leaf carbon, nitrogen, and phosphorus stoichiometry of aquatic macrophytes in the arid zone of northwestern China. Frontiers in plant science, 9, 1398.

[5] https://your.kingcounty.gov/dnrp/library/water-and-land/weeds/BMPs/fragrant-water-lily-control.pdf

VI. TASK 5 – ANALYSIS OF N AND P MASS REMOVAL BY HARVEST, 2020

Macrophyte harvest began in early October 2020 where plants were pulled from Mill Pond using a harvester (see FigureVI-1), dewatered (left to drain) overnight, and loaded into trucks to be weighted at Cape Cod Aggregates Corp. From these trucks subsamples were collected and weighted for wet weight in the field. These were then dried and ground to be analyzed. These samples were processed for % nitrogen and % phosphorus content at the time of macrophyte harvesting (see Task 4 for analysis details). The total removal of wet plant material from Mill Pond, during harvest, was 10,777kg. The wet weight ratio is 12.1 and the harvested dry weight removed was calculated as 890.7kg.

Dried harvest samples were received from the lab in early November 2020 and were processed along with the others. These activities follow the approach in the Diagnostic Feasibility Study (Unruh et. al. 2018). The plants averaged 37.2% carbon, 2.4% nitrogen and 0.05% phosphorus (percent of dry weight). **The mass of N and P held by the aquatic plants that were removed by harvest is estimated to be approximately 331.3 kg carbon, 21.4 kg nitrogen, and 0.516 kg phosphorus. This represents only 6.3 days of N input and 3.4 days of P input from Backus Brook to Mill Pond measured in summer of 2020. It must be concluded that harvesting would need to be more extensive and repeated annually to have the possibility of having any impact on the eutrophic conditions in Mill Pond.**

Figure VI-1. Macrophyte Harvest equipment and subsample.

The mid-water DO sonde was redeployed to capture any effects on watercolumn DO of the plant harvest (Figure VI-2). The majority of the plant harvest was conducted October 8th and 9th of 2020 with delays in total plant removal due to flooding of the bogs for harvest. The remaining vegetation, at the head (i.e., MP8 & MP9), was removed October 24th and 27th. Dewatering of the plants was conducted overnight and then the plants were weighted in the field using a CAMRY Waterproof Digital Commercial Computing Scale, as well as each truck full of plant matter was taken and weighted at Cape Cod Aggregates Corporation for determination of total plant removal and subsequent N and P removal.

During the harvest period there was a similar decline in oxygen as occurred in the following month. Therefore, it is not possible to directly assign the decline to the harvesting operation. It is likely that this is due to the late season temperature decline and watercolumn destratification.

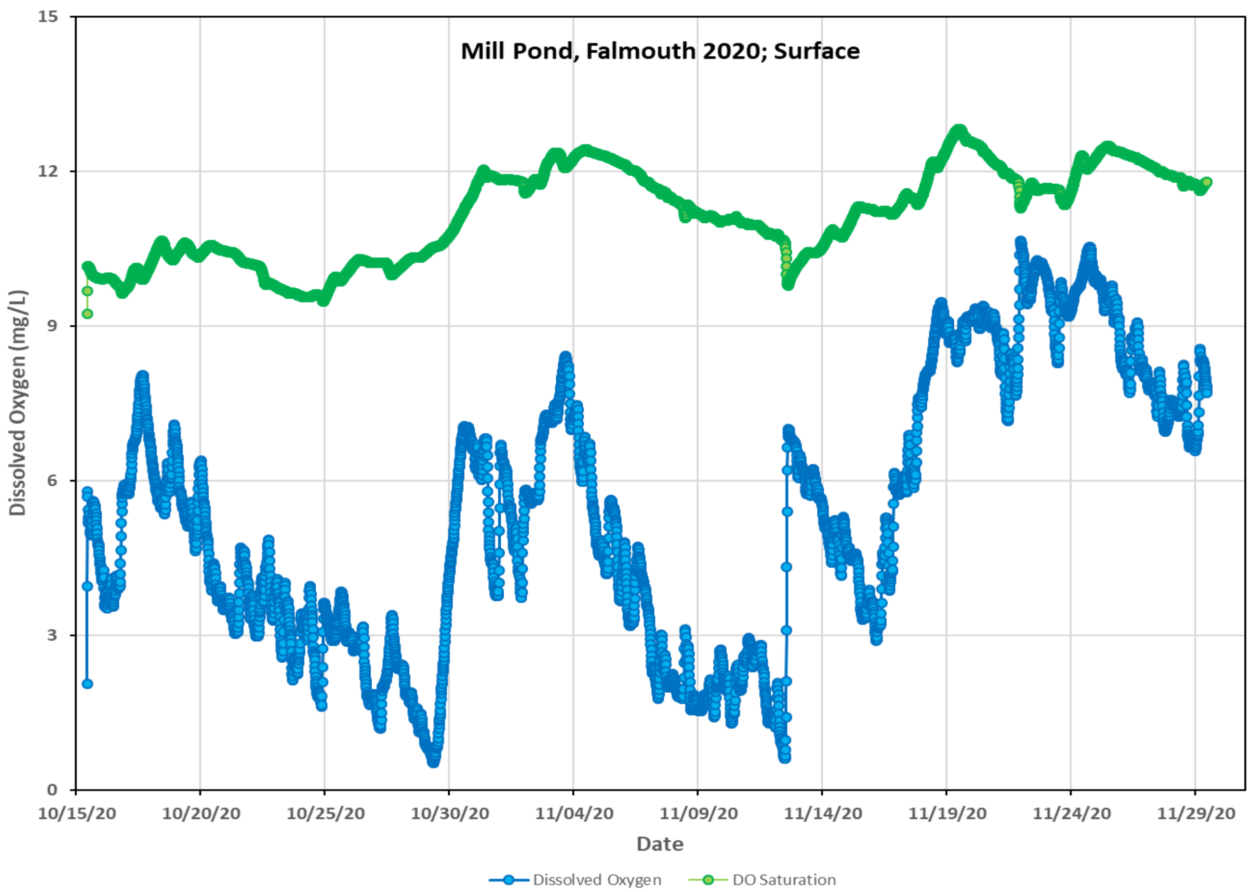


Figure VI-2. Time-series of dissolved oxygen levels in the water column of Mill Pond at the Basin Site (Figure III-3), during the harvest period. The upper green line shows the oxygen level at atmospheric equilibrium, while the blue line shows the actual DO concentration.

VII. TASK 6 – ANALYSIS OF IMPACT OF AERATION ON BOTTOMWATER OXYGEN AND DENITRIFICATION

A sediment denitrification analysis could not be completed on Mill Pond in summer 2020 as the aeration system did not significantly raise oxygen levels in the hypoxic bottom waters, so the funding was withheld. Two macrophyte studies were conducted by CSP staff.

The Diagnostic Assessment Nutrient Loading Assessment of Mill Pond (Unruh et al. 2018) did in-pond assessments of nutrient cycling from the sediments, in October 2016, May 2017, and June 2017.This looked at the biogeochemical fluxes between the sediments, water column, and fauna (in aerobic conditions), as well as the associated production of dinitrogen gas (denitrification[6]). The May 2017 cores were additionally assessed for nutrient regeneration under anoxic conditions to allow projection of fluxes during the periods of anoxia in Mill Pond during the summer. This data identified denitrification and NO_x uptake associated with the macrophyte community and minimally by the sediments. Denitrification is a microbial process that requires low oxygen conditions, a carbon source, denitrifying bacteria, and NO_x^- (for direct denitrification) and/or NH_4^+ (for coupled nitrification-denitrification or anammox)[1]. This work is continuing with UMass funding and will be available to the Town by summer 2022.

[6] Denitrification in sediments occurs in areas of low oxygen or anoxia, like the bottom waters of Mill Pond, but as it is through coupled nitrification-denitrification there needs to be oxygen in overlying waters to support the nitrification step. In Mill Pond this causes a reduction in denitrification.

III. RECOMMENDATIONS

Two major restoration approaches were piloted in Mill Pond between July 2020 and November 2020. The data collected in this study indicates that the harvest has relative success while the aeration unit did not improve water quality conditions.

Mill Pond is a surfacewater dominated pond. It receives 90% of its water volume from Backus Brook, which flows through several cranberry bogs and is groundwater fed from the overall watershed[1]. To reduce the external loads of nitrogen and phosphorus to the pond it is necessary to treat the surface water before it reaches the impaired ecosystem. Additional management strategies will be needed to address the impairments. These must be non-invasive, cost-effective, appropriately retrofitted to the system, and designed to improve downstream water conditions in Green Pond. With all these considerations in mind, the CSP technical team recommends implementing several measures to improve water quality in Mill Pond:

1. *Additional pond macrophyte management.* It does not appear that a second year of harvesting is in order at this time unless more of the pond can be harvested and a bit earlier in the season. Even so it would have to remove 10X the mass to have a discernable impact on the pond nutrient balances for N and P. However, harvesting could be important in the future if N and P external inputs can be significantly lowered, but it should be noted that the logistics of the harvesting operation encountered in 2020 would have to be addressed first. Of these most notable was the inability to harvest shallow areas and problems with submerged tree stumps. If this is to be examined, the N and P content of plants over the growing season provide herein will allow a solid estimate of what removals are possible, which should be determined prior to harvesting. This will allow a clear cost/benefit determination ($/Kg removed).

2. *Reducing the Sediment Phosphorus Regeneration and Improving Bottom Water Oxygen*[1]. DO surveys indicate that Mill Pond experiences anoxia in the bottom waters (levels lower than 5mg/L) throughout the summer into mid-fall. This is due to the decaying biomass in the sediments that take-up oxygen as they decay and cause a release of nutrients into the water column. While it is clear that aeration did not significantly affect the oxygen levels, hence denitrification in the pond sediments, the lack of effect was due to the specific technology deployed. Aeration may still be a viable approach if a properly sized unit were installed and run from spring through fall (i.e., the approach is viable; the 2020 specific technology was ineffective). It may also be possible to apply a phosphorus binding agent like Alum which has had wide use on Cape Cod and a long history in drinking water treatment.