**Town of Falmouth - Partnership with Coastal Systems Program**

**School for Marine Science and Technology**

**University of Massachusetts Dartmouth**

# Diagnostic Assessment of Nutrient Cycling in Mill Pond

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**Submitted to:**

**Town of Falmouth**

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## Acknowledgements

The authors acknowledge the contributions of the Massachusetts Estuaries Project for data that allowed for a long-term comparison of flow and nutrient conditions in Mill Pond. Without this comparison, understanding the watershed inputs and nutrient dynamics of Mill Pond would have been less certain. Instead, this data could bring certainty to our calculations of water flow and nutrient dynamics in Mill Pond to provide the appropriate recommendations for restoration.

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# 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 for the nutrient assessment of Mill Pond and the related assessment of the ecological health of the Mill Pond system. This report focuses on the results of the Diagnostic Assessment of Nutrient Cycling in Mill Pond conducted from August 2015 through March 2018 and the data collected during this assessment is also a component of a Master's Thesis (A. Unruh, 2018). 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. Further, the MEP found that some of the nitrogen load from the watershed above Rt. 28, which discharges initially to Backus Brook and Mill Pond before reaching Green Pond is removed during transport through the freshwater systems. However, the MEP evaluation did not assess the specific effect of nutrients on Mill Pond or determine the health of this basin. Mill Pond is a constructed freshwater pond, discharging to the head of the Green Pond Estuary, through a culvert under Rt. 28. Mill Pond receives freshwater through direct groundwater discharges and surface water discharge from an active cranberry bog. While the Town has been working on the restoration of the Green Pond estuarine system, more recently concerns have been raised about the declining ecological health of Mill Pond. This 16-acre freshwater pond is currently 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. These impairments are mainly the result of nutrient over-enrichment from its watershed sources transported by freshwater inflows. As such, it has been the subject of preliminary assessment efforts by SMAST scientists over the past 2 years with partial support from the Town of Falmouth.

# II. DATA COLLECTION AND MODELING APPROACH

The goal of the present study is to understand the role nutrients are having in driving the observed habitat impairment of Mill Pond as well as to determine appropriate management actions that can be implemented to affect restoration of this aquatic system. Data was collected to quantify:

- the nitrogen and phosphorus loads to Mill Pond from the various watershed sources as transported by surface water and groundwater,
- in-pond measurement of recycled nitrogen and phosphorus from sediments under aerobic and anaerobic conditions,
- dissolved oxygen conditions in the pond bottom waters and how that drives phosphorus recycling and controls water column phosphorus levels,
- distribution, density and nutrient content of aquatic plants pond-wide and
- water residence time and the major factors controlling it
- major controls on the annual cycle of nitrogen and phosphorus in pond waters.

Assessment of the sources and sinks of nitrogen and phosphorus to the pond allowed for the development of a detailed nutrient budgets for the Mill Pond system. Understanding the nutrient balance of the pond is the basis for formulating a list of likely management strategies and a comparison of their cost and practicality for restoring the water quality of this system. It is critical that any future management actions implemented in Mill Pond maintain or increase the ponds current nitrogen removal capacity for the benefit of the down-gradient Green Pond Estuary.

### *Data Collection*

Stream flow measurements and water sampling were conducted to determine the nitrogen and phosphorus loads entering and leaving Mill Pond beginning in August 2015. Sampling and flow measurements continued through April 2018 for the Diagnostic Assessment of Nutrient Cycling in Mill Pond based upon the prior works supplemented by additional needed data collection funded in part by the Town of Falmouth (2017). Sampling occurred weekly May through October and at least biweekly November through April. 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. Coupling the volumetric flow rate with the measured nutrient concentrations yields detailed nitrogen and phosphorus loading into and out of Mill Pond.

In-pond assessments of nutrient cycling from the sediments and associated production of di-nitrogen gas (Denitrification) were conducted in October 2016, May 2017, and June 2017. All sediment nutrient fluxes were assessed under aerobic conditions for nitrogen and phosphorus flux from the sediments and di-nitrogen gas production[1]. Additionally, the May 2017 cores were assessed for nutrient regeneration under anoxic conditions to allow projection of fluxes during the periods of anoxia in Mill Pond during the summer. The duration of Mill Pond anoxia was determined by deploying a YSI 6600 Multi-parameter Water Quality Monitor with optical dissolved oxygen, chlorophyll-a, and temperature sensors recording at 15-minute intervals, 30 cm above the pond bottom. Bi-weekly calibration samples for dissolved oxygen and chlorophyll were collected throughout the deployment period, June 14, 2017 to November 1, 2017.

Nitrogen and phosphorus loads from stormwater flowing into Mill Pond via the 2 identified stormwater outfall pipes were also measured. Stormwater pipes were located at an upper northeast location (off Prince Henry Avenue) and a northwest location (off Pontes Avenue). Stormwater related nutrient loads into these sections of the pond were assessed during two storm events: 1) August 7, 2017 and 2) September 8, 2017.

The bathymetry of Mill Pond was determined by manual depth measurements to the nearest centimeter and using a Garmin 76 handheld GPS unit to determine LAT and LON. A more manual

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[1] Denitrification in sediments is mainly through coupled nitrification-denitrification, where oxygen in overlying waters supports the nitrification step. When the bottom waters are devoid of oxygen (anoxic) nitrification ceases resulting in much lower or no denitrification.

approach was required for the bathymetry survey owing to shallow depths and dense vegetation that made use of acoustic devices problematic. The bathymetric survey of Mill Pond was completed in June 2016. Coordinates and depths were compiled into x-y-z coordinated systems to produce a bathymetric map and for the determination of pond volume to support calculation of pond residence time.

A vegetation survey was conducted by CSP-SMAST scientists in May 2017 to determine the types of plants and coverage in the pond. 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. An aquatic vegetation assemblage map was produced by digitizing the locations of the dominant plant communities colonizing Mill Pond.

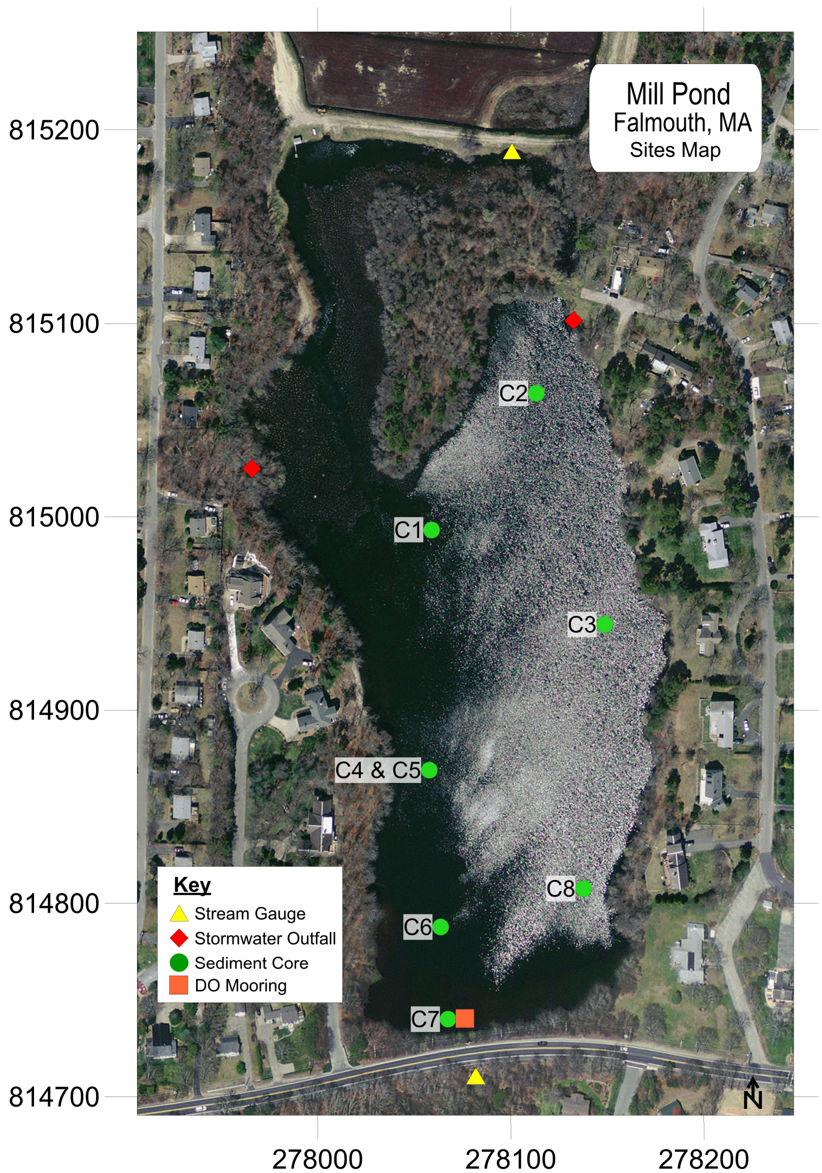


Figure II-1. Location of stream gauges, stormwater discharge pipes, sediment coring sites, and YSI 6600 Water Quality Monitoring (DO) mooring.

*Box Model*

A box model was constructed to understand the nutrient dynamics in the pond during an annual hydrologic cycle. Water and nutrient inputs and outputs were measured for one annual cycle. Sources of water included stream flow-in, groundwater, precipitation, and storm water discharges. Sinks of water include stream flow-out, evaporation, and cranberry bog irrigation. The model was calibrated by assessing the mass balance of water volume and salt load. Once the model was calibrated, nitrogen and phosphorus loads were input to the model, resulting in a mass of nitrogen and phosphorus into and out of the pond with the difference being that load either attenuated or generated by the pond. Since nitrogen and phosphorus are non-conservative parameters (they are consumed or generated by biological and chemical processes), these nutrients will not appear balanced in the budget. In many studies, the processes responsible for nitrogen attenuation are generally attributed to microbial processes that occur in the sediments. For this study, the parameters related to in-pond nitrogen attenuation by sediments was quantified through measurement of sediment nutrient flux, di-nitrogen production, and sediment burial throughout the year. The nitrogen and phosphorus loads associated with these processes were input to the model to “close” the nitrogen/phosphorus budget. Thus, quantifying the nutrient dynamics of Mill Pond.

# III. RESULTS

*Mill Pond Water Quality Conditions*

Understanding the Mill Pond water quality conditions and critical nutrient for management is vital to choosing an appropriate management solution. State regulation, 314 CMR 04, defines dissolved oxygen and temperature conditions suitable for Class B surface waters. Class B waters are used for fish habitat, other aquatic and wildlife habitat, migration, reproduction, and growth, secondary contact recreation, and crop irrigation. These waters shall maintain a minimum dissolved oxygen concentration of 5.0 mg/L for 16 hours of any 24-hour period and never drop below 3.0 mg/L. Temperature shall remain less than 28.3˚C, never rising more than 1.7˚C due to discharge (e.g. cranberry bog). In Class B waters where, natural background conditions of dissolved oxygen are lower and temperature higher, both parameters shall not exceed the natural background conditions.

Concerned citizens of East Falmouth have noted that during the warm summer months Mill Pond becomes thickly vegetated and the water develops a rotten-egg smell (hydrogen sulfide) that is particularly strong at the outflowing stream, under Rt. 28. These observations are consistent with a highly eutrophic pond (nutrient enriched). As part of the health assessment of Mill Pond dissolved oxygen, total chlorophyll-a pigments, total phosphorus, and secchi depth (water clarity) were used to determine the Carlson Trophic Status of Mill Pond during the growing season (oligotrophic, mesotrophic, eutrophic, or hypertrophic). From June through October, dissolved oxygen conditions were below 5.0 mg/L and the Carlson Trophic Status parameters (secchi, total phosphorus, and chlorophyll-a pigment) indicate that Mill Pond is eutrophic. This is supported by the Cape Cod Ponds[2] standards for highest water quality, which indicates a freshwater pond is impaired when TN, TP, and chlorophyll-a concentrations exceed 310, 10, and 1.7 µg/L, respectively. Due to the poor water quality, a full assessment of Mill Pond is necessary to develop an appropriate management plan to restore this impaired system.

In most freshwater systems, additions of phosphorus will cause phytoplankton blooms or increased macrophyte growth (limiting nutrient). Occasionally, nitrogen can be limiting or co-limiting with phosphorus. A nitrogen-limited system will have blooms or increased macrophyte growth when nitrogen is added to the system. Co-limited systems are limited by both nutrients, which may change seasonally. Identifying the limiting nutrient of the pond is important for developing appropriate management solutions, as phosphorus-limited systems needs phosphorus management and nitrogen-limited need nitrogen management. The nutrient limitation of Mill Pond was determined by determining the effect of additions of inorganic nitrogen, phosphorus, nitrogen + phosphorus and no additions on phytoplankton production. Production was determined from net oxygen production in incubations of pond water. The treatments were incubated in Mill Pond at 0.5-meter depth for 12-hours. Winkler bottles with dissolved oxygen concentrations higher than initial were presumed to have net oxygen production hence photosynthetic activity related to the nutrient addition. The assessment revealed that Winkler bottles with control (no nutrient addition), P addition, N addition, and N+P addition had increased dissolved oxygen concentrations. The N+P addition showed the greatest photosynthesis, with phosphorus next and nitrogen also showing some increase but less than the phosphorus addition. Photosynthesis in the control was from available nutrients in the pond water. The lower oxygen in the dark incubation is mainly the result of respiration of phytoplankton in the pondwater. The higher oxygen production in the N + P addition likely results from the uptake of P and the availability of additional N as the background N pool is depleted. This pattern has been seen in other similar experiments in Oyster Pond and Cockeast Pond and the explanation is consistent with the second highest production being in the P addition, which appears to have become nitrogen limited with such a large addition of P. Ultimately, these results are consistent with phosphorus being the primary nutrient that needs to be controlled, as also found in other ponds throughout Cape Cod.

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[2] Eichner, E. M., T. C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, B. Smith, M. Fenn. 2002. Cape Cod Pond and Lake Atlas. Cape Cod Commission. Pp. 22-23.

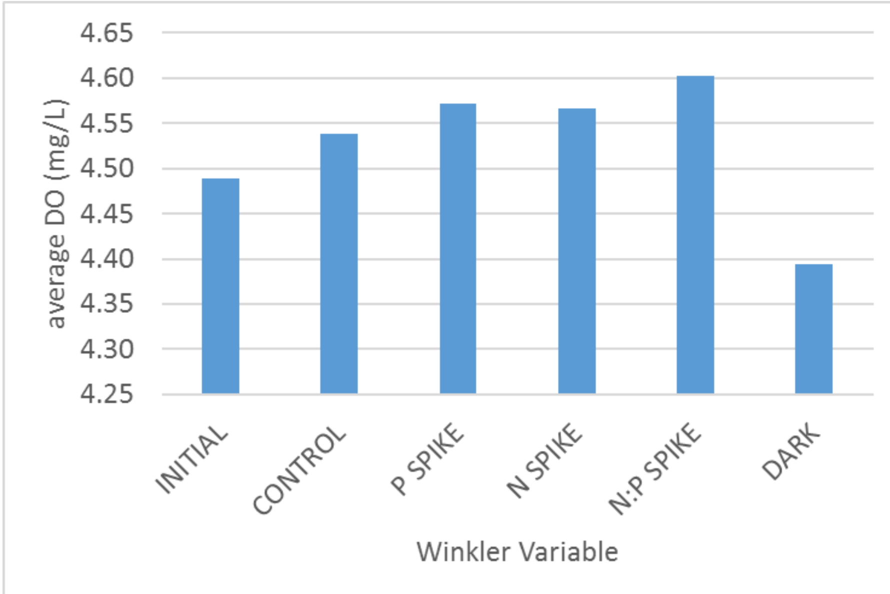


Figure III-1. N versus P limitation experiment. Initial treatment is the dissolved oxygen in the Winklers at the start of the experiment. Control (no additions), P addition, N addition, N+P addition, dark incubation, waters were incubated in Mill Pond for 12 hours at 0.5 meter depth. Dissolved oxygen concentrations over initial conditions indicate oxygen production by photosynthesis.

### *Mill Pond Watershed Land-use and N and P Loading*

The sub-watershed to Mill Pond had a land-use analysis at the time of the MEP assessment of the Green Pond watershed (2001)[3]. The MEP found that the Mill Pond sub-watershed was primarily built out, but it is possible that land-use based loads may have changed from 2001 to 2016. Therefore, the MEP land-use loading analysis was updated to confirm that present (2016) nutrient loads to Mill Pond via direct groundwater inflow are accurate (the surface water inputs were directly measured as part of the present study. Land-use and parcels in the Backus Brook GT10, Backus Brook LT10, and Mill Pond subwatersheds were reviewed for new development that may have occurred since the completion of the MEP analysis and added into the land-use loading model (*Appendix A – Mill Pond Sub-watershed*). There are 11 and 7 new residential builds in the Backus Brook LT10 and Mill Pond sub-watersheds, respectively. The new builds account for a 1% nitrogen load increase from 4242 in 2001 to 4344 kg unattenuated N/year in 2016.

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[3] Howes, B.L., J.S. Ramsey, S.W. Kelley, R.I. Samimy, D.R. Schlezinger, E. Eichner. 2005. Massachusetts Estuaries Project: Linked Watershed-Embayment Management Modeling to Determine Critical Nitrogen Loading Thresholds for Great Pond, Green Pond and Bournes Pond, Falmouth, MA. Final Report to MA Department of Environmental Protection and USEPA, 162 pp. Published by MassDEP.

Using the 2001 land-use nitrogen loading to the watershed model, the inflow and outflow nitrogen loads of Mill Pond are 2138 and 1585 kg attenuated N/year, respectively. The nutrient assessment of 2005-2007 validates these loads, which measured average inflow and outflow nitrogen load as 2464 and 1416 kg N/year, only 13% higher and 11% lower than the modeled, respectively, attributable to inter-annual differences in hydrology. For the current 2015-2017 study, the updated land-use nitrogen loading to the watershed model using 2016 land-use data from the Town of Falmouth generated inflow and outflow nitrogen loads to Mill Pond of 2185 and 1627 kg attenuated N/year, respectively. These modeled nutrient loads did not compare that well with the measured average inflow and outflow nitrogen loads of 1462 and 961 kg N/year respectively, in-flowing load being 33% lower than modeled and out-flowing load being 41% lower than the modeled nutrient loading values. This difference in modeled versus measured load is almost entirely from differences in groundwater contributions to Mill Pond as 2013-2016 had May-October precipitation almost half of average levels. During the 2015-2017 study period, the average groundwater elevations were significantly lower, resulting in lower stream flows and nutrient loads as well as lower nutrient loads from direct groundwater discharge to Mill Pond. In contrast, the 2005-2007 nutrient assessment, average groundwater elevations were very similar to the long-term average groundwater elevation in this area. Since the nitrogen concentration of the inflowing water remains nearly the same, less groundwater discharge would result in a lower nitrogen load in the short-term. Due to the differences between the modeled and measured nitrogen load, the measured nitrogen load was flow corrected for comparison purposes. Flow correction is the ratio of land-use modeled to measured flows at the Mill Pond output stream (1.01 in 2005-2007 and 0.77 in 2015-2017). Using this ratio, 2015-2017 measured inflow and outflow nitrogen loads were flow corrected to 1908 and 1254 kg N/year, 13% and 23% lower than the modeled, respectively (**Table III-1**). While these do not represent the actual loads, the flow corrected loads are useful for comparative purposes to understand the nutrient dynamics of Mill Pond and the magnitude of inter-annual variation. The flow corrected loads reveal 24% and 10% difference in the respective 2005-2007 and 2015-2017 inflow / outflow measured loads.

The notable difference observed in the inflow load is likely due to irrigation practices followed by the operator of the cranberry bog immediately up-gradient of Mill Pond, which directly affects the measured flows during both timeframes. Bog operation both pumps water from Mill Pond and returns water to Mill Pond confounding the inflow volume measurements. As such, the measured inflows needed to be corrected for the recycling of water (and associated nutrients). Water inflow volumes relied significantly on the modeled water inflows as this was considered more appropriate by the technical team for calculating water flow and ultimately nitrogen load into Mill Pond. The measured stream outflow volume and nutrient loads were unaffected by the recycling.

Table III-1. Nitrogen load to the 2001 and 2016 watershed changed by only 1% and is represented as the unattenuated load – modeled. Attenuated nitrogen loads were both predicted by the models and measured in-field. Major differences in modeled and measured attenuated nitrogen loads is caused by differences in groundwater (GW) elevations. Rainfall infiltrating the ground affects the groundwater elevations and increases stream flows from direct input. Rainfall prior to 2005 was greater than the rainfall prior to 2015, driving the major differences in as indicated above, adjusted measured flows were used for comparison of modeled and measured nitrogen loads and 2005-2007 and 2015-2017 nitrogen loads.

| | 2001 Long-term modeled | 2005 - 2007 measured | 2005 - 2007 flow-corrected measured | 2016 Long-term modeled | 2015 - 2017 measured | 2015 - 2017 flow-corrected measured |
|---|---|---|---|---|---|---|
| **Total Rainfall (inches)** | 53 | 43 | 43 | 53 | 46 | 46 |
| **Rainfall ≥ 0.2 (inches)** | 40 | 32 | 32 | 40 | 35 | 35 |
| **Feet to GW level** | 6.43 | 5.75 | 5.75 | 6.43 | 7.30 | 7.30 |
| **Unattenuated - modeled** | | | | | | |
| **MP Inflow (kg/yr)** | | 3210 | | | 3275 | |
| **MP Outflow (kg/yr)** | | 4242 | | | 4344 | |
| **Attenuated N Loads - modeled and measured** | | | | | | |
| **MP Inflow (kg/yr)** | 2138 | 2464 | 2418 | 2185 | 1462 | 1908 |
| **MP Outflow (kg/yr)** | 1585 | 1416 | 1390 | 1627 | 961 | 1254 |
| **Attenuation** | | | | | | |
| **By Water Shed[1]** | | 33% | | | 33% | |
| **By Pond[2]** | | 56% | | | 61% | |
| **By Watershed + Pond[3]** | | 67% | | | 71% | |

**Notes:**
**1. Calculated using LU Model Inflow and Unattenuated Inflow**
**2. Calculated using LU Model Inflow, Unattenuated Inflow and Outflow, and Flow-corrected Outflow**
**3. Calculated using Flow-corrected outflow and Unattenuated Outflow**

By pairing inflows and outflows with sample nutrient concentrations to determine load in and out of Mill Pond and then subtracting flow out from flow in, this investigation revealed that the combined nutrient attenuation within the watershed and pond prior to discharging to the head of Green Pond for 2005-2007 and 2015-2017 removed 67% and 71% of the nitrogen load, respectively. The attenuation of nitrogen within Mill Pond alone was 56% and 61%, respectively (**Table III-1**). The congruence of in-pond attenuation over a decade indicates that changes in the watershed have not drastically affected the nutrient dynamics of Mill Pond.

### *Cranberry Bog Operation*

Currently water from Backus Brook passes through 52 acres of active cranberry bog before entering Mill Pond. Similar to other cranberry operations, the use of fertilizer is necessary to maintain the cranberries. Without the addition of fertilizer to replace the nutrients lost during harvest, productivity declines once the sediment pool of nutrients becomes depleted. As the water in Backus Brook moves through the bog channels it is potentially exposed to the addition of fertilizers that wash off of the bog during significant rainstorms that too closely follow the fertilization. In the case of Mill Pond, the bog operator uses a low P fertilizer ratio (18%/1%/18%, N/P/K) which was designed by the Cranberry

Experiment Station to meet bog needs at a lower dose than standard fertilizers and to reduce nutrient loss in bog outflows.[4]

The flow from Backus Brook into Mill Pond varies due to cranberry bog flooding practices. Usually, at the start of October, the bog operator places boards in the culvert, stopping flow into Mill Pond and allowing the bog to begin flooding. At the time of harvest, the bog operator also pumps a large volume of water from the pond to the bog. The bog remains flooded throughout the harvest and sometimes into November. In late October to early November the boards are removed, allowing the impounded water to flow into Mill pond again. Starting in December the bogs are flooded for the winter. In the last week of February, the boards are removed and flow into the pond resumes. During both periods when the bogs are being flooded, flow into the pond is greatly reduced, increasing the water residence time of Mill Pond. The reduced volumetric inflow results in parcels of water entering the pond at the time of board emplacement which are not flushed out until after the boards are removed. Conversely, once the boards are removed, flows become very high (for a short period), making the water residence time very short, about 1 day and flushing out the pond. When Backus Brook flow is unaffected by the water control boards in the culvert, the water flows freely into the channel running between bog and pond. During these prolonged periods water withdrawals from this channel to the pond are occasionally made by irrigation pump for frost protection in April and May and cranberry irrigation in June – September pond water can also move into the channel/pump as well.

### *Stormwater Nitrogen and Phosphorus Loading*

Nutrient loads from storms can significantly affect the water quality of small ponds, due to the high nutrient concentrations of runoff from roads and other impervious surfaces. The amount of nitrogen and phosphorus loading from stormwater runoff depends on the amount of rain in a storm, elapsed days since the previous storm and total rainfall in significant storms (>0.20") in the year. Mill Pond receives stormwater from two outfall pipes. The pipe outlets are in the northwest and northeast corners of the pond, near Prince Henry Avenue and Pontes Avenue, respectively (**Figure II-1**). Flow and nutrient concentration measurements were collected during two storm events (August 8 and September 7, 2017). The sampled storms were selected based on expected rainfall of a small (0.20" to 1") and large storm event (> 1"). Generally, it is expected to see more nitrogen and phosphorus loading with large storms, however, the nitrogen and phosphorus load per storm is also affected by the intensity of the storm (velocity of water flow) and days since previous rain storm. Based on the ten-year average precipitation for small and large storm events, stormwater contributes, on average, 4.1 kg N and 1.1 kg P / year to Mill Pond (**Table III-2**).

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[4] This new low nutrient fertilizer is recommended by CSP-SMAST in flow through bog settings like Backus Brook as a Best Management Practice (BMP) and the grower has been using it already.

Table III-2. Flow weighted concentrations and loads separated by storm and stormwater outfall pipe. Total direct discharges of stormwater nutrient loads and volumes are presented for each measured storm and annually, based on the long-term significant rainfall average (events >0.2").

| **Summary of Mill Pond Falmouth Stormwater Assessment** | | | |
|---|---|---|---|
| | Storm | Storm | Annual |
| Collection Dates | 8/8/2017 | 9/7/2017 | precip ≥ 0.2 |
| Precipitation (in) | 0.48 | 1.22 | 34.3 |
| Days between Rain Events | 13 | 2 | - |
| **Storm Pipe: PA - Pontes Avenue** | | | **per year** |
| Flow [$m^3$] | 11 | 111 | 1866 |
| TN [mg/L] flow weighted | 2.4 | 0.8 | - |
| TP [mg/L] flow weighted | 0.5 | 0.3 | - |
| TSS [mg/L] flow weighted | 85 | 14 | - |
| TN Load [g] | 26 | 83 | 2094 |
| TP Load [g] | 5.4 | 28 | 580 |
| TSS Load [g] | 914 | 1575 | 55416 |
| **Storm Pipe: PHA - Prince Henry Avenue** | | | **per year** |
| Flow [$m^3$] | 25 | 87 | 2104 |
| TN [mg/L] flow weighted | 1.4 | 0.6 | - |
| TP [mg/L] flow weighted | 0.3 | 0.2 | - |
| TSS [mg/L] flow weighted | 36 | 11 | - |
| TN Load [g] | 36 | 50 | 2035 |
| TP Load [g] | 8.2 | 18 | 553 |
| TSS Load [g] | 904 | 989 | 47328 |
| **Total Load (PA + PHA)** | | | **per year** |
| Flow [$m^3$] | 36 | 198 | 3970 |
| TN Load [kg] | 0.062 | 0.133 | 4.1 |
| TP Load [kg] | 0.014 | 0.047 | 1.1 |
| TSS Load [kg] | 1.8 | 2.6 | 103 |

### *Surfacewater Flows and Nutrient Loads Into and Out of Mill Pond*

Surface water inflow and outflow from Mill Pond is the main source and sink of nitrogen and phosphorus in the nutrient mass balance of the pond. Surface water inflow / outflow volume and mass transport of nitrogen and phosphorous was determined based on flow and stage measurements, as well as water quality sampling undertaken up-gradient and down-gradient of Mill Pond in Backus Brook. Flow measurements were merged with nutrient concentrations obtained from the water sampling program to calculate N and P load into and out of Mill Pond.

Flow into Mill Pond comes from Backus Brook, a ground water fed stream that runs through an active cranberry bog before entering Mill Pond. The flow from Backus Brook into Mill Pond varies due to cranberry bog flooding practices (*Cranberry Bog Operation*). To refine the amount of water (from Mill Pond) used for flooding and irrigation to more accurately determine the nitrogen and phosphorus loads into Mill Pond from Backus Brook, associated with bog operations, flow rates and pump run times are needed. Unfortunately, communication with the cranberry bog operator was established late in the study so that these data are not available at this time, but the operator was very forthcoming as to examine approaches to further reduce nutrient discharges for the restoration of the pond. . Therefore, alternate methods were developed to quantify the stream inflow volume (see below).

The first method used to quantify stream inflow was through the measurement of stream velocity and stage to create a stage-discharge relationship (rating curve). Discharge from Backus Brook to Mill Pond was measured just below the culvert where water flows over a control board and into a channel that flows directly into the Mill Pond. A stream gauge was deployed from August 2015 to April 2018, measuring stream stage every 10 minutes. A total of 108 direct measures of volumetric flow were also made during this deployment period. These flow measurements correlated with stream stage. Traditionally, a single rating curve is applied to a channel to predict stream flow. However, due to cranberry bog operation, boards were added or removed over the year for cranberry harvest and winter flooding of the bogs. The number of boards directly affects the flow into the channel through the culvert. In addition, the irrigation and flooding practices are affected using a pump house located further down the channel to draw water out of the channel, also affecting stage in the channel. The irrigation and flooding practices, pull water from the channel as needed for cranberry bog operations with the effect that some water measured through the culvert might be pumped back to the bog before it reaches the pond (*Appendix C*). These practices complicated the development of the rating curve and the application of a single rating curve to this channel. Therefore, to accurately quantify the volume of water entering Mill Pond, multiple rating curves were constructed based on specific periods, differentiated by annual harvest, summer irrigation practice, and winter flooding practice. Although, this is not a traditional method for determining volume of water on a long-term basis, the manipulation of flow required this approach. The use of different rate curves based upon bog operations allowed accurate measurements of flow as each discrete "rating curve" captures the specifics of the manipulated flow condition and in the aggregate, the overall flow characteristics of the system. This method of flow prediction closely matches the 108 directly measured flows (**Figure III-2**). Changes in flow from Backus Brook to Mill Pond occur most noticeably during harvest and winter flood, with irrigation activity affecting the late spring and summer flows (**Figure III-2**). This method accurately quantifies the stream flow from Backus Brook into the pond channel, but is not solely representative of the water and associated nutrient loads entering Mill Pond, due to the cranberry bog irrigation and flooding practices.

The second method used to quantify stream inflow was through the comparison of flow characteristics generated through the comprehensive assessment of Green Pond during completion of the MEP nutrient threshold analysis, graduate dissertation research (Samimy, 2013), and the current Mill Pond nutrient assessment. During the MEP assessment, stream flow and nitrogen concentrations measurements collected in 2005-2007 were used to calibrate the MEP land-use model. The congruence of the 2005-2007 measured flows with modeled flows indicated accurate model prediction for contributing area flow (**Table III-3**). The 2005-2007 measured inflow was 11% greater than the modeled, while the measured outflow was only 2% greater than the modeled. In 2015-2017, the measured inflow was 20% less than the modeled long-term inflow, with the outflow being about the same, 24% less. Differences in annual flows are attributed to interannual variations in regional precipitation and groundwater levels. Hydrologic conditions in 2005-2007 were close to the long-term average conditions used in the MEP land-use model. In contrast, the 2015-2017 hydrologic conditions were much different, generating lower flows than the long-term average conditions used in the model. To examine interannual differences the ratios of inflow and outflow volume were determined for each available time period. The ratio of outflowing to inflowing water is 1.02 (2005-2007), 1.06 (2015-2017), and 1.12 (MEP Long-Term). Similar ratios of outflowing to inflowing water indicate that the surface water inputs and groundwater inputs compared to the surface water output has not changed dramatically in the last decade. The small differences in these ratios are likely the result of the irrigation and flooding practices of the bog. The congruence of outflow to inflow ratios, means that a flow correction for the inflowing stream can be calculated using the MEP water balance (part of the land-use model) which excludes water recycling in bog operations. Since the inflow stream in both 2005-2007 and 2015-2017 studies is affected by cranberry bog operation, the outflow stream is used for the flow correction calculation. The flow-corrected inflow is calculated as:

Flow-corrected Inflow = Measured Inflow * (Measured Outflow/MEP Outflow from Water Balance)

Since the pond is in steady state, the flow-corrected inflow can be used as an accurate representation of the water and associated nutrient load entering Mill Pond, unaffected by the cranberry bog operations.

Discharge from Mill Pond to Backus Brook was measured just below Rt. 28 as the water flowed out of the concrete culvert, into the short channel entering the headwaters of the Green Pond Estuary. A recording stream gauge was deployed from August 2015 to April 2018, measuring stream stage every 10 minutes. A total of 107 flow measurements were made during this deployment period. These flow measurements correlated well with water level yielding a high quality single rating curve. This method of flow prediction closely matches the flows measured in the field (**Figure III-3**).

The predicted inflow (flow-corrected) and outflow was merged with nutrient concentrations to determine the load of N and P entering / exiting Mill Pond (**Table III-4**). Over the two-year period, an average of 62 and 1441 kg $yr^{-1}$ phosphorus and nitrogen, respectively, entered Mill Pond via surface water flow. After biological activities within the pond ecosystem, 47 kg P $yr^{-1}$ and 961 kg N $yr^{-1}$, was discharged from Mill Pond via surface water outflow.

Table III-3. Comparison of flow and nitrogen characteristics relative to the inflow / outflow streams of Mill Pond for data sets collected for long-term modeled flow (30 years), 2005-2007 measured flow and nutrient, and 2015-2017 (drought years) measured flow and nutrient studies.

| Stream Discharge Parameter | Backus Brook to Mill Pond | | Mill Pond to Green Pond | | Stream OUT/IN Discharge Ratio | Data Source |
|---|---|---|---|---|---|---|
| Days of Record | 730 | | 730 | | 730 | |
| Flow Characteristics | | | | | | |
| Stream Average Discharge 2005-2007 (m3/day) - measured | 6880 | | 7029 | | 1.02 | (1) |
| Stream Average Discharge 2015-2017 (m3/day) - measured | 4979 | | 5286 | | 1.06 | (2) |
| Contributing Area Average Discharge (m3/day) -modeled | 6186 | | 6899 | | 1.12 | (3) |
| Nitrogen Characteristics | | | | | | |
| | 2005-2007 | 2015-2017 | 2005-2007 | 2015-2017 | | |
| Stream Average Nitrate + Nitrite (mg N/L) | 0.507 | 0.489 | 0.154 | 0.159 | | (1), (2) |
| Stream Average Total N Concentration (mg N/L) | 0.920 | 0.900 | 0.594 | 0.546 | | (1), (2) |
| Nitrate + Nitrite as Percent of Total N (%) | 55% | 54% | 26% | 31% | | (1), (2) |
| Total Nitrogen (TN) Average Measured Stream Discharge (kg/d) | 6.75 | 5.23* | 3.88 | 3.44* | | (1), (2) |
| TN Average Contributing Area Attenuated Load (kg/d) | 5.86 | 5.98 | 4.34 | 4.46 | | (3) |
| TN Average Contributing UN-attenuated Load (kg/d) | 8.79 | 8.98 | 11.62 | 11.90 | | (3) |
| Attenuation of Nitrogen in Watershed + Pond (%) | | | 67% | 71% | | |

(1) 2005-2007 from Roland Samimy Dissertation Data Set
(2) 2015-2017 from Mill Pond Nutrient Assessment gauge site data. *Flow corrected for comparison
(3) from 2001 and 2016 MEP GGB land use database for 2005-2007 and 2015-2017, respectively

Although the comparison of the flow characteristics generated through the three assessments reveals significant differences in annual flows (hydrologic variability), the nitrogen concentrations in / out of the pond were relatively constant (**Table III-3**). The concentration of stream flow water into Mill Pond is the same in 2015-2017 as it was in 2005-2007. Differences in annual flows can be attributed to observed variations in regional precipitation and groundwater levels. However, it should be noted that in each analysis of flow the ratio of outflowing to inflowing water was relatively constant (1.02, 1.06, and 1.12). Similar ratios of outflowing to inflowing water indicate that (1) the inflows and outflows have been accurately quantified and (2) additional surface water inputs and groundwater recharge (%) have occurred nor is there a new unquantified discharge pathway for pond water. The small differences in these ratios are likely the result of the irrigation and flooding practices of the bog.

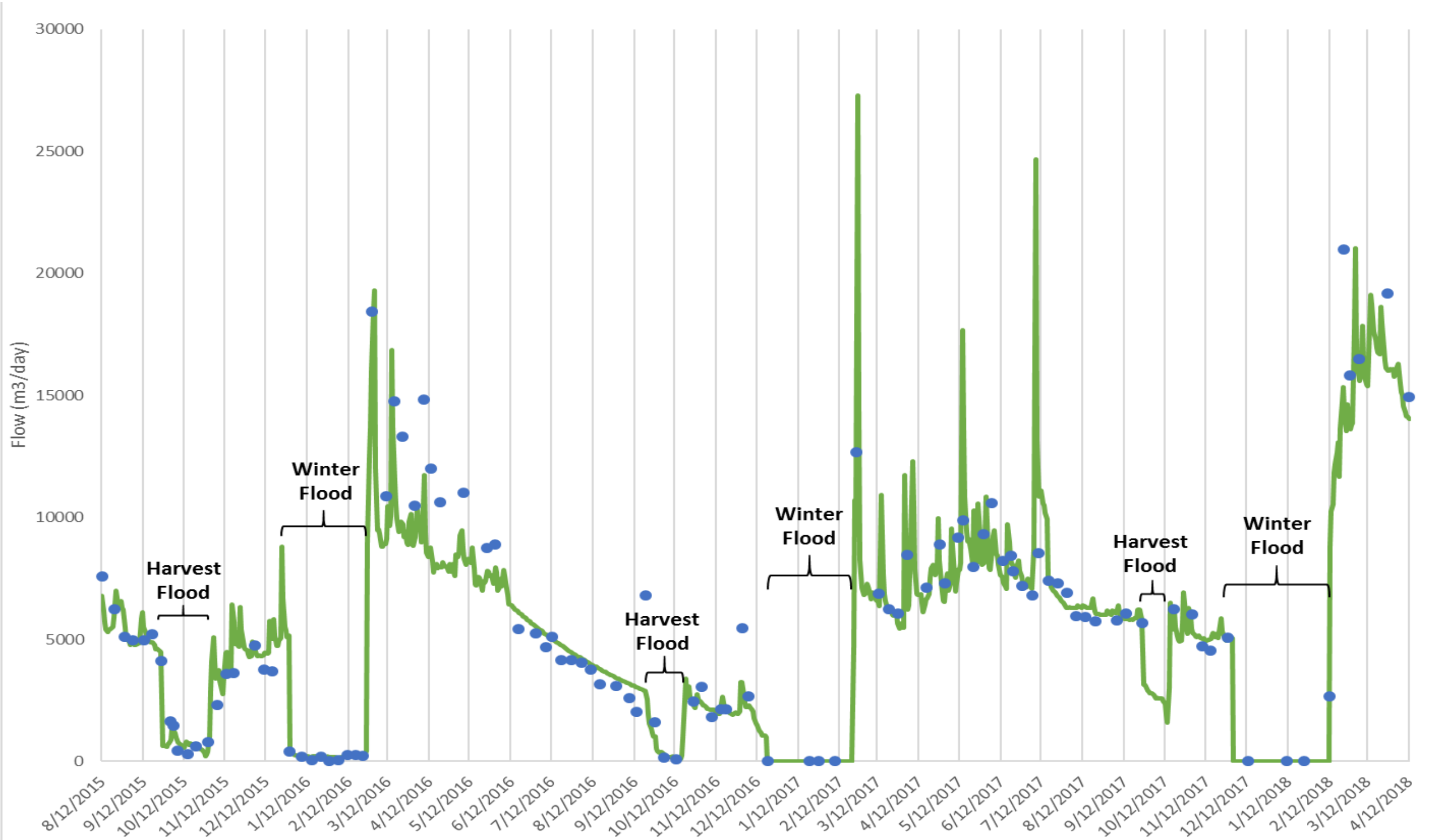


Figure III-2. Measured versus predicted flow at the inflowing stream of Mill Pond. Measure flows depicted by blue circles. Predicted flow represented by green line. Proximity of the green circle to the blue line indicates that the prediction of flow is representative of what was measured in the field. Note: Cranberry bog irrigation practices affected the stage in the channel and/or caused additional flow through the culvert. Therefore, this stream flow should be viewed as a qualitative representation of the flow in the channel, the quantitative determination of water volume that entered Mill Pond used the adjustment for water withdrawals and discharges by the bog.

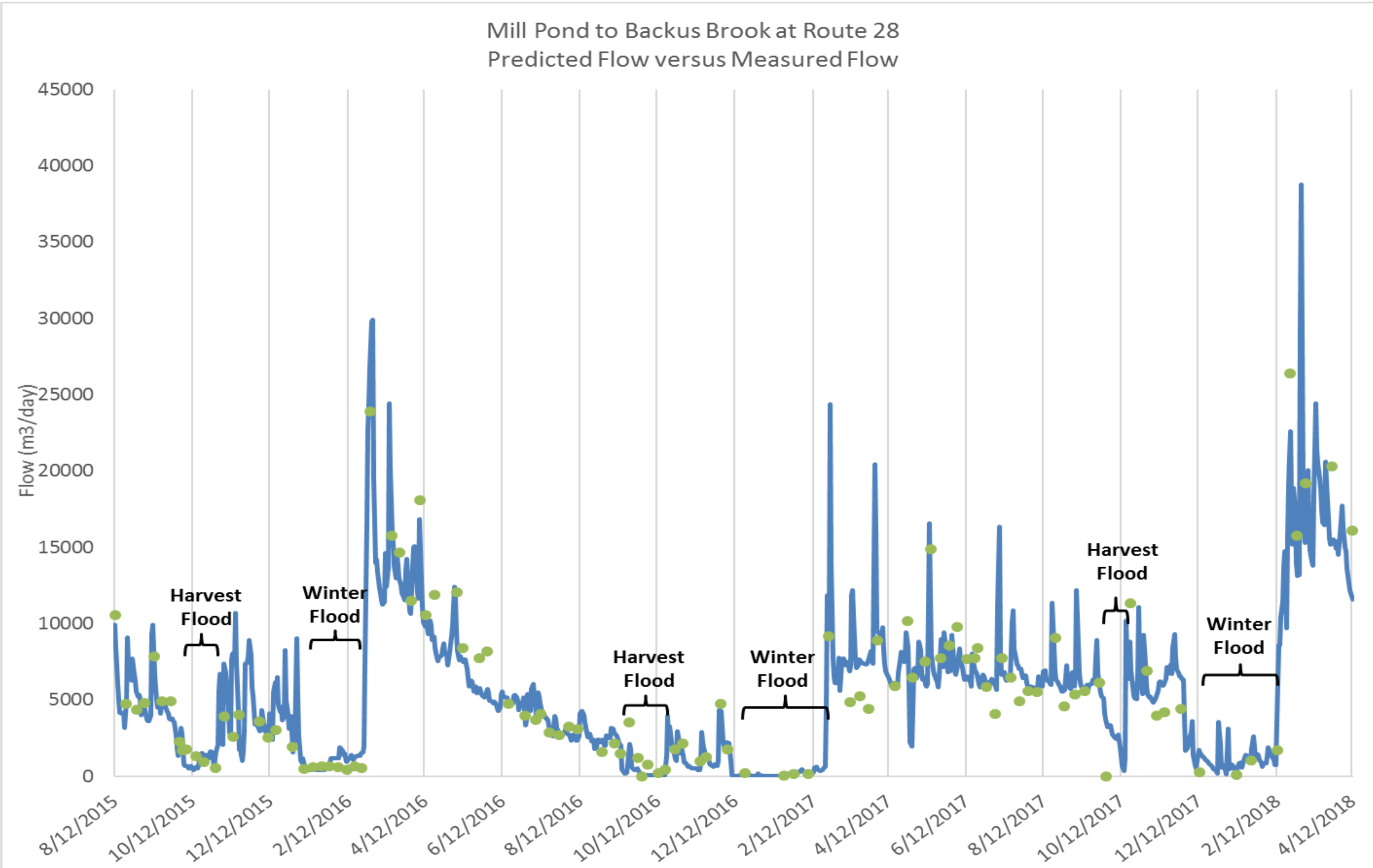


Figure III-3. Measured versus predicted flow at the outflowing stream of Mill Pond. Measured flows depicted by green circles. Predicted flows represented by blue line. Proximity of the green circle to the blue line indicates that the prediction of flow is representative of what was measured in the field. This stream flow is a quantitative representation of all the water flowing from Mill Pond.

Table III-4. Mill Pond inflow / outflow water flows and nutrient loads based on averaged daily load, separated by annual harvests (beginning of October) and averaged over the two-year sampling period. MP IN and MP OUT is the measured stream flows and associated loads. MP IN-corrected is the flow corrected for bog operations and associated loads. MP IN-corrected is not affected by cranberry bog operations, whereas MP IN includes bog operations and therefore, is not an accurate representation of nutrient load entering Mill Pond (it is included only for reference).

| Stream | 12 month Period | Average Volume m3/d | Salt kg/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 | Oct 2015 - Sept 2016 | 4735 | 191 | 0.09 | 0.22 | 0.13 | 2.34 | 2.47 | 1.29 | 3.75 | 4.26 | 5.95 | 0.51 |
| MP IN -corrected | Oct 2015 - Sept 2016 | 4607 | 185 | 0.09 | 0.21 | 0.13 | 2.25 | 2.37 | 1.26 | 3.63 | 4.12 | 5.76 | 0.49 |
| MP OUT | Oct 2015 - Sept 2016 | 5139 | 198 | 0.04 | 0.14 | 0.07 | 0.96 | 1.03 | 1.43 | 2.46 | 2.89 | 3.73 | 0.43 |
| | | | | | | | | | | | | | |
| MP IN | Oct 2016 - Sept 2017 | 4967 | 216 | 0.07 | 0.15 | 0.14 | 2.41 | 2.60 | 1.37 | 3.93 | 4.47 | 6.48 | 0.54 |
| MP IN -corrected | Oct 2016 - Sept 2017 | 4164 | 199 | 0.06 | 0.14 | 0.13 | 2.22 | 2.40 | 1.27 | 3.64 | 4.13 | 5.98 | 0.50 |
| MP OUT | Oct 2016 - Sept 2017 | 4644 | 206 | 0.04 | 0.12 | 0.08 | 0.65 | 0.70 | 1.30 | 2.12 | 2.37 | 3.25 | 0.38 |
| | | | | | | | | | | | | | |
| MP IN | 2 yr average | 4851 | 203 | 0.08 | 0.19 | 0.14 | 2.37 | 2.53 | 1.33 | 3.84 | 4.37 | 6.21 | 0.52 |
| MP IN -corrected | 2 yr average | 4386 | 192 | 0.07 | 0.18 | 0.13 | 2.23 | 2.38 | 1.26 | 3.63 | 4.13 | 5.87 | 0.50 |
| MP OUT | 2 yr average | 4891 | 202 | 0.04 | 0.13 | 0.08 | 0.81 | 0.86 | 1.36 | 2.29 | 2.63 | 3.49 | 0.41 |

*Sediment Nitrogen and Phosphorous Cycling*

Analysis of sediment phosphorus and nitrogen recycling (influx {uptake} / efflux {release}) is critical to the management of the pond, as nutrient regeneration from the sediments can be a significant source of nutrients to pond waters supporting phytoplankton production and aquatic plant growth through foliar uptake. Under aerobic conditions the sediment takes up (influx) oxygen, ortho-phosphate, total dissolved phosphorus, nitrite + nitrate, and releases (efflux) ammonium, total dissolved nitrogen, and di-nitrogen gas. During the warm summer months, the dissolved oxygen of the pond declines and the bottom water and surficial sediments become anoxic. Under hypoxic/anoxic conditions, the sediments become a source of iron, manganese, phosphorus, and nitrogen to the overlying water column. If the internal phosphorus load from the sediments in a pond is more significant than the external load from the watershed, then management of the benthic sediments is an appropriate management option.

Measurements of nutrient flux under anoxic conditions was undertaken in October 2016, May 2017, and June 2017 allowing for a more detailed understanding of the seasonal sediment dynamics. As expected, the data revealed that the sediment oxygen demand (SOD) is directly related to pond temperature, with the rate of sediment oxygen uptake (SOD) lowest in October (-29 mmol $O_2/m^2$/day)[5] and highest in June (-42 mmol $O_2/m^2$/day) (**Table III-5**). In the present study, sediment ammonium release was negatively correlated with increasing temperature. This is the result of ammonium uptake by the dense rooted macrophyte community which virtually covers the entire bottom of Mill Pond (submerged aquatic vegetation, SAV). In sediment flux experiments, it was noted that 23 of the 24 cores collected had SAV. The addition of plants to a sediment core, can greatly influence the water column nutrient concentrations, as plants take up inorganic nitrogen ($NH_4^+$ and $NO_x^-$) both through root and foliar uptake. Therefore, cores collected in June, containing actively growing SAV, have the lowest rate of $NH_4^+$ release (1016 µmol $N/m^2$/day) and highest uptake of $NO_x$ (-896 µmol $N/m^2$/day). Although all eight cores collected on October 27, 2016 have SAV, it is past the growing season, and $NH_4^+$ release (1471 µmol $N/m^2$/day) is less affected by SAV inorganic nutrient uptake than in May and June. Nitrite + nitrate ($NOx^-$) uptake by the sediments strongly correlates with temperature and SOD, with the June cores having the highest uptake rate (-896 µmol $N/m^2$/day) and October cores having the lowest (-35 µmol $N/m^2$/day). However, the $NOx^-$ uptake cannot solely be attributed to sediment uptake (denitrification), because macrophytes can also take up $NOx^-$.

Denitrification is a process that requires low oxygen conditions, a carbon source, denitrifying bacteria, and $NOx^-$ (for direct denitrification) and/or $NH_4^+$ (for coupled nitrification-denitrification or anammox). It is expected, based on the carbon rich, anoxic sediments, with an oxic water column, and high nitrate levels (>10uM $NOx^-$), di-nitrogen gas ($N_2$) production would be present at detectable levels in the Mill Pond sediments. This process has been observed in other Cape Cod Ponds, such as Filends Pond, a similar flow through pond in Barnstable, where approximately 365 kg $year^{-1}$ nitrogen removal by denitrification. Thus, it was expected that denitrification would be a major pathway for nitrogen

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[5] Negative (-) values represent uptake by sediments; positive (+) values represent flux from sediment to overlying waters.

attenuation in Mill Pond. However, it has been shown in vegetated salt marsh sediments that plants outcompete denitrifying bacteria for nitrogen, unless high levels of nitrate or oxygen/ammonium are available. It maybe that oxygen is limiting nitrification which limits denitrification as cores with the lower oxygen uptake have the strongest $N_2$—N rates. In Mill Pond sediment cores showed a high degree of variation in denitrification, due to the difficulty in collecting cores in dense macrophyte areas, the periodic low oxygen in bottom waters and surficial sediments inhibiting coupled nitrification-denitrification, possibly shifting denitrification into the shallower waters and those sediments with high levels of nitrate in overlying waters (direct denitrification). The result was that the sediment cores verified that denitrification was occurring at a range of rates in Mill Pond sediments, that pond-wide denitrification would also need to be based on system nitrogen mass balance measurements (see below).

Phosphorus release was significantly controlled by the level of oxygen depletion in bottom waters. Under aerobic conditions, phosphate (inorganic plant nutrient) binds to oxidized iron ($Fe^{3+}$) and is stored in the surficial sediments. In the sediments, phosphate can be used by macrophytes and some portion can be released to overlying waters. In contrast, under hypoxic/anoxic conditions the bound phosphate in the iron-phosphate complex is released resulting in a pulse of phosphorus to the overlying waters. In Mill Pond where there is high uptake of phosphate by the rooted plants (and also phytoplankton) and phosphorus is in high demand, it appears $PO_4^{3-}$ and TDP uptake by the cores is likely due to both the binding of phosphate by iron at the sediment surface and plant uptake. During each of the flux studies under oxic conditions phosphate was clearly being “taken up” by the sediment system from the overlying water. The uptake of phosphorus is higher at higher temperatures, except for the June 21, 2017 flux ($PO_4^{3-}$and TDP uptake rates of 51 and 67 µmol P/$m^2$/day, respectively), which was less than the May 30, 2017 uptake rates (93 and 106 µmol P/$m^2$/day, respectively). This is likely due to the oxygen depletion of bottom waters in June (**Figure III-6**). Therefore, cores collected on June 21, 2017 had experienced low oxygen conditions, although the core headspace was oxygenated before incubation. However, this oxygenation was likely insufficient to fully oxygenate the sediments for maximum $PO_4^{3-}$ and TDP uptake at temperature.

Since through much of the summer (after mid-June) Mill Pond has hypoxic/anoxic bottom waters, so it was necessary to conduct incubations under hypoxic/anoxic conditions. Cores were collected in May 2017 and held under anoxic conditions for ~3-months. Under anaerobic conditions, ortho-phosphate and ammonium is released from the sediments into the overlying water. The rate of the $PO_4^{3-}$ release is highest in the beginning and decreases over time, whereas $NH_4^+$ levels are mostly constant throughout the anaerobic period. $PO_4^{3-}$ release is a combination of chemical release and remineralization by the microbial community. The initial high rates of $PO_4^{3-}$ release results from the dissolution of the iron-phosphorus complex with a lower level of continuing remineralization lasting for about a month. The $PO_4^{3-}$ release under hypoxic/anoxic conditions after the initial month was primarily from continuing remineralization without chemical binding. The highest rate of release occurred in the chemical release phase (116 µmol P/$m^2$/day). The lowest rate of release occurred under hypoxic/anoxic conditions (11 µmol P/$m^2$/day). The rate of anaerobic ammonium release is 1676 µmol N /$m^2$/day.

Table III-5. Sediment flux rates under aerobic conditions occurred in October 2016, May 2017, and June 2017. Influx to sediments is represented as negative rates* and efflux from the sediments to the overlying water is represented as positive rates. Flux of oxygen into the sediments and exchanges of ammonium ($NH_4$), nitrite + nitrate ($NO_x^-$), total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), and ortho-phosphate ($PO_4^{3-}$).

| Oct-16 Aerobic Core ID | SOD Rate (mMoles/m2/d) | SOD S.E. | NH4 Rate (uMoles/m2/d) | NH4 S.E. | PO4 Rate (uMoles/m2/d) | PO4 S.E. | NO3 Rate (uMoles/m2/d) | NO3 S.E. | TDN Rate (uMoles/m2/d) | TDN S.E. | TDP Rate (uMoles/m2/d) | TDP S.E. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C1 | -37 | 2 | 2099 | 263 | -16 | 6 | -23 | 9 | 2036 | 376 | -47 | 24 |
| C2 | -42 | 1 | 639 | 90 | -13 | 4 | -28 | 10 | 543 | 453 | -12 | 9 |
| C3 | -23 | 1 | 4044 | 436 | -31 | 7 | -17 | 10 | 3982 | 392 | 0 | 0 |
| C4 | -27 | 3 | 636 | 81 | -34 | 9 | -31 | 7 | 1675 | 753 | -16 | 20 |
| C5 | -32 | 1 | 894 | 60 | -25 | 6 | -97 | 8 | 876 | 363 | -21 | 10 |
| C6 | -18 | 2 | 1015 | 100 | -29 | 4 | -48 | 30 | 1080 | 330 | -26 | 3 |
| C7 | -27 | 3 | 1548 | 147 | -10 | 3 | -12 | 7 | 2038 | 361 | -9 | 15 |
| C8 | -23 | 1 | 892 | 105 | -15 | 4 | -19 | 14 | 1144 | 365 | -22 | 12 |
| AVERAGE | -29 | 2 | 1471 | 160 | -22 | 5 | -35 | 12 | 1672 | 424 | -19 | 12 |

| May-17 Aerobic Core ID | SOD Rate (mMoles/m2/d) | SOD S.E. | NH4 Rate (uMoles/m2/d) | NH4 S.E. | PO4 Rate (uMoles/m2/d) | PO4 S.E. | NO3 Rate (uMoles/m2/d) | NO3 S.E. | TDN Rate (uMoles/m2/d) | TDN S.E. | TDP Rate (uMoles/m2/d) | TDP S.E. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C1 | -46 | 4 | 573 | 24 | -94 | 24 | -699 | 162 | -145 | 476 | -131 | 27 |
| C2 | -47 | 3 | 831 | 138 | -82 | 3 | -454 | 59 | 1093 | 327 | -102 | 13 |
| C3 | -49 | 2 | 2056 | 176 | -99 | 5 | -586 | 46 | 2034 | 698 | -109 | 18 |
| C4 | -32 | 1 | 1161 | 39 | -124 | 4 | -550 | 48 | 666 | 111 | -109 | 20 |
| C5 | -25 | 0 | 443 | 108 | -70 | 5 | -409 | 16 | 1412 | 324 | -78 | 15 |
| C6 | -21 | 0 | 298 | 63 | -93 | 8 | -211 | 10 | 672 | 703 | -94 | 16 |
| C7 | -27 | 1 | 837 | 47 | -116 | 20 | -335 | 24 | 1152 | 117 | -140 | 20 |
| C8 | -39 | 2 | 4439 | 419 | -68 | 10 | -499 | 28 | 4361 | 876 | -87 | 20 |
| AVERAGE | -36 | 2 | 1330 | 127 | -93 | 10 | -468 | 49 | 1406 | 454 | -106 | 19 |

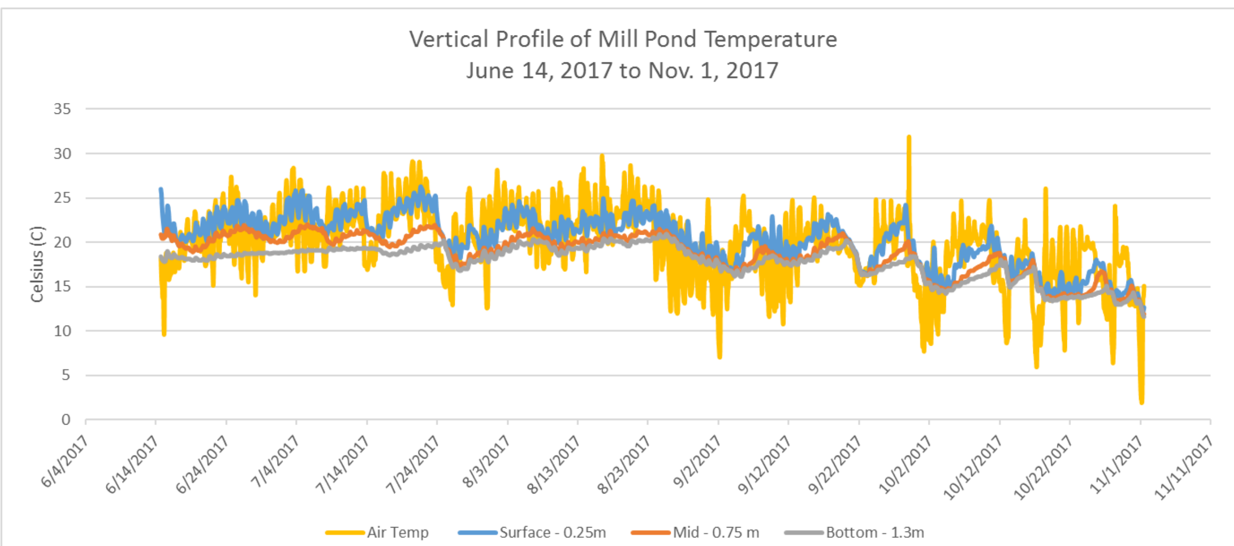
| Jun-17 Aerobic Core ID | SOD Rate (mMoles/m2/d) | SOD S.E. | NH4 Rate (uMoles/m2/d) | NH4 S.E. | PO4 Rate (uMoles/m2/d) | PO4 S.E. | NO3 Rate (uMoles/m2/d) | NO3 S.E. | TDN Rate (uMoles/m2/d) | TDN S.E. | TDP Rate (uMoles/m2/d) | TDP S.E. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C1 | -72 | 3 | 6403 | 419 | -40 | 11 | -1189 | 190 | 6209 | 477 | -68 | 28 |
| C2 | -41 | 1 | 1013 | 118 | -45 | 8 | -789 | 44 | 1579 | 552 | -33 | 7 |
| C3 | -40 | 2 | 1177 | 179 | -70 | 8 | -946 | 139 | 669 | 33 | -82 | 15 |
| C4 | -38 | 2 | -329 | 12 | -37 | 6 | -832 | 41 | -1827 | 236 | -38 | 9 |
| C5 | -36 | 2 | 691 | 91 | -51 | 9 | -787 | 117 | 1999 | 378 | -40 | 7 |
| C6 | -36 | 2 | -610 | 26 | -58 | 5 | -791 | 46 | -1458 | 260 | -117 | 27 |
| C7 | -48 | 3 | -501 | 16 | -58 | 4 | -1032 | 6 | -3329 | 307 | -100 | 29 |
| C8 | -29 | 2 | 286 | 212 | -53 | 7 | -800 | 27 | 141 | 250 | -56 | 8 |
| AVERAGE | -42 | 2 | 1016 | 134 | -51 | 7 | -896 | 76 | 498 | 312 | -67 | 16 |

| May-17 Anaerobic Core ID | | Anaerobic NH4 Rate (uMoles/m2/d) | Anaerobic NH4 S.E. | Chemical PO4 Rate (uMoles/m2/d) | Chemical PO4 S.E. | Anaerobic PO4 Rate (uMoles/m2/d) | Anaerobic PO4 S.E. | |
|---|---|---|---|---|---|---|---|---|
| C1 | | 2106 | 114 | 113 | 16 | 15 | 5 | |
| C2 | | 1217 | 65 | 136 | 18 | 22 | 6 | |
| C3 | | 1689 | 177 | 121 | 16 | 12 | 2 | |
| C4 | | 1766 | 183 | 107 | 16 | 11 | 5 | |
| C5 | | 2056 | 140 | 84 | 12 | 15 | 2 | |
| C6 | | 608 | 50 | 37 | 3 | 5 | 2 | |
| C7 | | 1263 | 103 | 84 | 9 | -1 | 5 | |
| C8 | | 2701 | 203 | 242 | 29 | 6 | 19 | |
| AVERAGE | | 1676 | 129 | 116 | 15 | 11 | 6 | |

*Temperature, Dissolved Oxygen Conditions, and Degree of Mixing in Mill Pond*

State regulation, 314 CMR 04, defines dissolved oxygen and temperature conditions suitable for Class B surface waters. Class B waters are used for fish habitat, other aquatic and wildlife habitat, migration, reproduction, and growth, secondary contact recreation, and crop irrigation. These waters shall maintain a minimum dissolved oxygen concentration of 5.0 mg/L for 16 hours of any 24-hour period and never drop below 3.0 mg/L. Temperature shall remain less than 28.3˚C, never rising more than 1.7˚C due to any man-made discharge. In Class B waters where, natural background conditions of dissolved oxygen are lower and temperature higher, both parameters shall not exceed the natural background conditions.

The degree and duration of water column stratification was assessed in Mill Pond using a vertical array of three temperature recorders at a single location. In general, the pond is thermally stratified, with warmer surface waters as a result of high summer atmospheric temperatures and direct insolation and cooler bottom waters due in part to groundwater discharge (**Figure III-7**). Water column mixing occurs periodically during summer with significant drops in atmospheric temperature, cooling the surface water.




Summer stratification was found to temporarily breakdown during periods of cooler weather. For example, a 6-degree Celsius temperature drop on July 24 resulted in a vertical mixing event and destratification. However, within a day or two atmospheric temperatures returned to normal summer conditions, and the pond restratified. Similarly, from August 22 to September 1, the pond destratified nightly (**Figure III-4**).

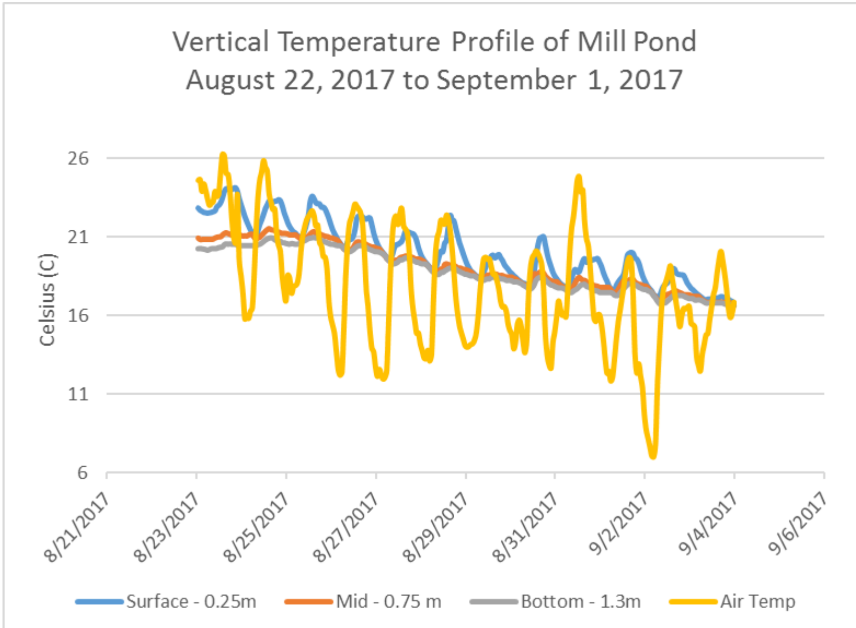
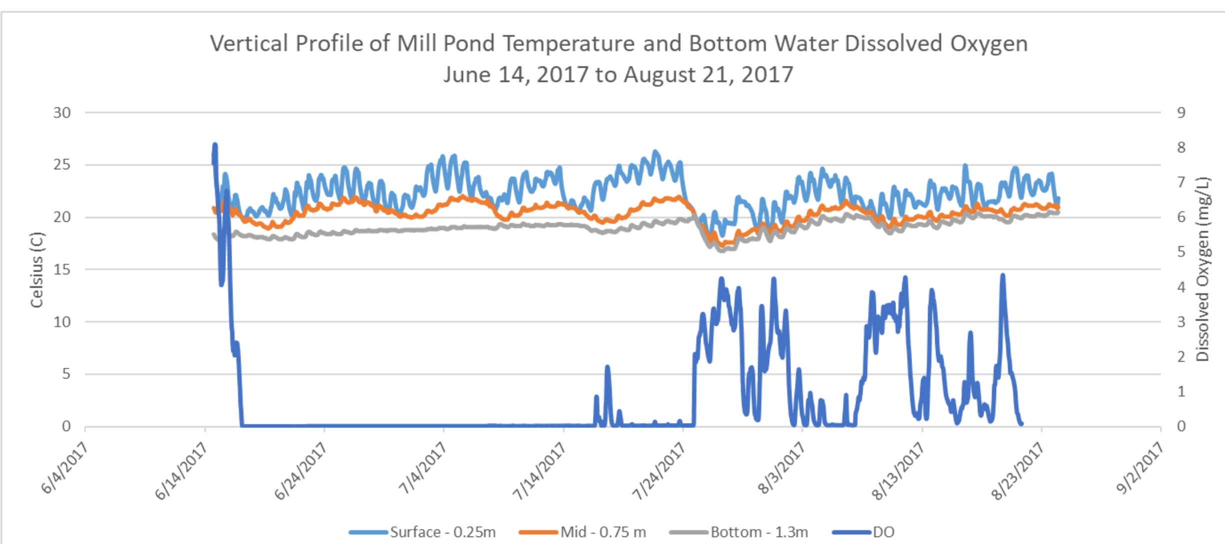



Figure III-5. Temperature profile from August 22 to September 1, 2017 reveals that the water column was isothermal each night, indicative of unstratified conditions. However, with warming of surface waters during the day time the pond becomes vertically unmixed.

As the surface water cools to temperatures less than the bottom water, it becomes heavier and sinks to the bottom and the pond destratifies. Oxygenated surface water oxygen then mixes with anoxic bottom water, increasing dissolved oxygen conditions of the bottom water (**Figure III-5**), affecting biogeochemical cycling in the sediments. This physical change in the pond can prevent the phosphorus release from the sediment by oxygenating the bottom water and possibly the sediment surface.



A YSI 6600 Multi-parameter Water Quality Monitor with optical dissolved oxygen, chlorophyll-a, and temperature sensors, was moored within Mill Pond and programmed to measure parameters every 15-minutes 30 cm above the bottom from June 14, 2017 to November 1, 2017, but the recorder failed August 21. However, bi-weekly calibration samples for dissolved oxygen and chlorophyll were collected from June through October. The available continuous record showed anoxia (*i.e.*, <0.5 mg/L) in the bottom water from June 16 to July 25 (39 days). After July 25, the pond destratified and bottom water oxygen concentrations increased slightly to 4 mg $O_2$/L, but still less than 314 CMR 04 State regulation (DO >5.0 mg/L). From July 25 to August 21 the oxygen conditions remained sub-standard, varying between oxic and hypoxic/anoxic (**Figure III-6**). The duration of Mill Pond hypoxia/anoxia after August 21 was roughly estimated using the biweekly calibration measurements (**Table III-6**), which indicate frequent periods of anoxia interspersed with hypoxic periods. The frequency of anoxia and brevity of hypoxia was insufficient to fully oxidize the surficial sediments, so that phosphorus release was more or less continuous until November 1, resulting in 138 days of bottom water anoxia. The length of bottom water anoxia relates to the release of phosphorus and ammonium from the sediments. The rate of ammonium released from the sediments is relatively constant throughout the anaerobic period. The rate and the number of days the pond is anoxic (138 days) determine the amount of ammonium released. Phosphorus release was determined by integrating the chemical release phase and the continuing anoxic microbial remineralization phase. Two rates, chemical (lasting 34 days) and anoxic (lasting 104 days) determine the amount of phosphorus released. The total mass of P released during the anoxic period (138 days) was very close to the total measured release during the anoxic incubation (120 day). The oxic, chemical, and anoxic nutrient flux rates are multiplied by the respective number of days to determine total nutrient regeneration load to Mill Pond (described in the *Nutrient Dynamic Assessment with Box Model*).

The level of total chlorophyll-a pigment indicates phytoplankton blooms in Mill Pond. These blooms appear to correlate with periods of lowest dissolved oxygen. As dissolved oxygen, readings reached 0.0 mg $O_2$/L on June 16 and August 5, there was a chlorophyll bloom in progress. Unfortunately, the chlorophyll measurements between June 24 and July 21 were confounded by the extremely high fluorescence, possibly due to the fluorescence of facultative anaerobes with accessory pigments or from benthic vegetation in the region of the sensor. Accurate measurements of total chlorophyll a pigment resumed after July 21 at which point, daily chlorophyll concentrations remain around 2-4 µg/L until a large bloom started on July 31, reaching 34 µg/L on August 5 (**Figure III-6**). Chlorophyll levels greater than 1.7 ug/L are typical of impaired aquatic systems.

Table III-6. Tabulated water quality data for the YSI 6600 Multi-parameter Monitor. Measurements of total depth, secchi depth, dissolved oxygen, temperature, chlorophyll-a, pheophytin-a were collected at the mooring biweekly. Winkler dissolved oxygen measurement of pond bottom water on July 10 is inaccurate due to sample collection error.

| Date | Time | Sample Depth (m) | Total Depth (m) | Secchi Depth (m) | Winkler DO (mg/L) | YSI 55 - DO (mg/L) | TEMP (C) | CHLA (ug/L) | PHEO (ug/L) | % Chla | T. PIG (ug/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 05/17/17 | 11:22 | 0.15 | 1.50 | 1.50 | NS | 9.4 | 17.7 | 1.6 | 0.5 | 76% | 2.1 |
| 05/17/17 | 11:15 | 0.50 | - | - | NS | 9.3 | 16.4 | NS | NS | NS | NS |
| 05/17/17 | 11:15 | 1.00 | - | - | NS | 10.3 | 14.8 | 2.3 | 1.9 | 54% | 4.2 |
| 05/17/17 | 11:15 | 1.25 | - | - | NS | 10.2 | 14.1 | NS | NS | NS | NS |
| 06/14/17 | 15:50 | 1.20 | 1.55 | ND | 7.4 | ND | ND | 3.17 | 4.61 | 41% | 7.79 |
| 07/10/17 | 12:05 | 0.15 | 1.60 | 1.25 | NS | 5.1 | 23.2 | 4.0 | 3.6 | 53% | 7.5 |
| 07/10/17 | 12:05 | 0.50 | - | - | NS | 5.0 | 22.1 | ND | ND | ND | ND |
| 07/10/17 | 12:05 | 1.00 | - | - | NS | <2.0 | 19.0 | ND | ND | ND | ND |
| 07/10/17 | 12:05 | 1.20 | - | - | 2.6 | <2.0 | ND | 3.97 | 3.55 | 53% | 7.52 |
| 07/10/17 | 12:05 | 1.50 | - | - | NS | <2.0 | ND | ND | ND | ND | ND |
| 7/24/2017 | 10:30 | 0.15 | 1.20 | 1.00 | NS | 2.2 | 20.8 | 3.5 | 4.1 | 46% | 7.6 |
| 7/24/2017 | 10:30 | 0.50 | - | - | NS | 2.3 | 20.8 | ND | ND | ND | ND |
| 7/24/2017 | 10:30 | 0.95 | - | - | 1.9 | ND | ND | 20.54 | 7.74 | 73% | 28.28 |
| 7/24/2017 | 10:30 | 1.00 | - | - | NS | <2.0 | 20.4 | ND | ND | ND | ND |
| 8/7/2017 | 10:04 | 0.15 | 1.24 | 1.00 | NS | 3.4 | 21.4 | 2.6 | 2.4 | 52% | 5.0 |
| 8/7/2017 | 10:04 | 0.5 | - | - | NS | 2.7 | 21.0 | ND | ND | ND | ND |
| 8/7/2017 | 10:04 | 0.95 | - | - | 2.8 | ND | ND | 2.4 | 3.5 | 41% | 5.9 |
| 8/7/2017 | 10:04 | 1.00 | - | - | NS | <2.0 | 20.5 | ND | ND | ND | ND |
| 8/21/2017 | 9:43 | 0.15 | 1.23 | 1.23 | NS | 3.7 | 22.1 | 0.7 | 1.6 | 32% | 2.4 |
| 8/21/2017 | 9:43 | 0.50 | - | - | NS | 3.3 | 21.7 | ND | ND | ND | ND |
| 8/21/2017 | 9:43 | 0.95 | - | - | 1.5 | <2.0 | ND | 4.24 | 4.05 | 51% | 8.29 |
| 8/21/2017 | 9:43 | 1.00 | - | - | NS | <2.0 | 20.1 | ND | ND | ND | ND |
| 9/6/2017 | 9:50 | 0.15 | 1.22 | 1.22 | NS | 6.3 | 20.4 | 3.0 | 1.3 | 69% | 4.3 |
| 9/6/2017 | 9:50 | 0.50 | - | - | NS | 5.9 | 18.5 | ND | ND | ND | ND |
| 9/6/2017 | 9:50 | 0.95 | - | - | 4.3 | 2.5 | 16.9 | 4.4 | 2.6 | 63% | 7.1 |
| 9/6/2017 | 9:50 | 1.00 | - | - | NS | ND | ND | ND | ND | ND | ND |
| 9/25/2017 | 14:20 | 0.15 | 1.20 | 1.20 | NS | 4.5 | 20.0 | 2.58 | 3.90 | 40% | 6.48 |
| 9/25/2017 | 14:20 | 0.95 | - | - | 2.1 | ND | ND | 3.67 | 4.62 | 44% | 8.29 |
| 9/25/2017 | 14:20 | 1.00 | - | - | NS | <2.0 | ND | ND | ND | ND | ND |
| 10/19/2017 | 9:00 | 0.15 | 1.20 | 0.40 | NS | ND | ND | 9.38 | 5.58 | 63% | 14.96 |
| 10/19/2017 | 9:00 | 0.90 | - | - | 1.2 | ND | ND | 9.95 | 4.21 | 70% | 14.16 |
| 11/1/2017 | 13:15 | 0.15 | 1.02 | 1.40 | NS | 8.48 | 12.8 | 1.70 | 3.21 | 35% | 4.90 |
| 11/1/2017 | 13:15 | 0.50 | - | - | NS | 7.51 | 12.3 | ND | ND | ND | ND |
| 11/1/2017 | 13:15 | 1.00 | - | - | NS | 7.55 | 11.9 | ND | ND | ND | ND |
| 11/1/2017 | 13:15 | 1.10 | - | - | 4.8 | ND | ND | 2.47 | 5.51 | 31% | 7.98 |

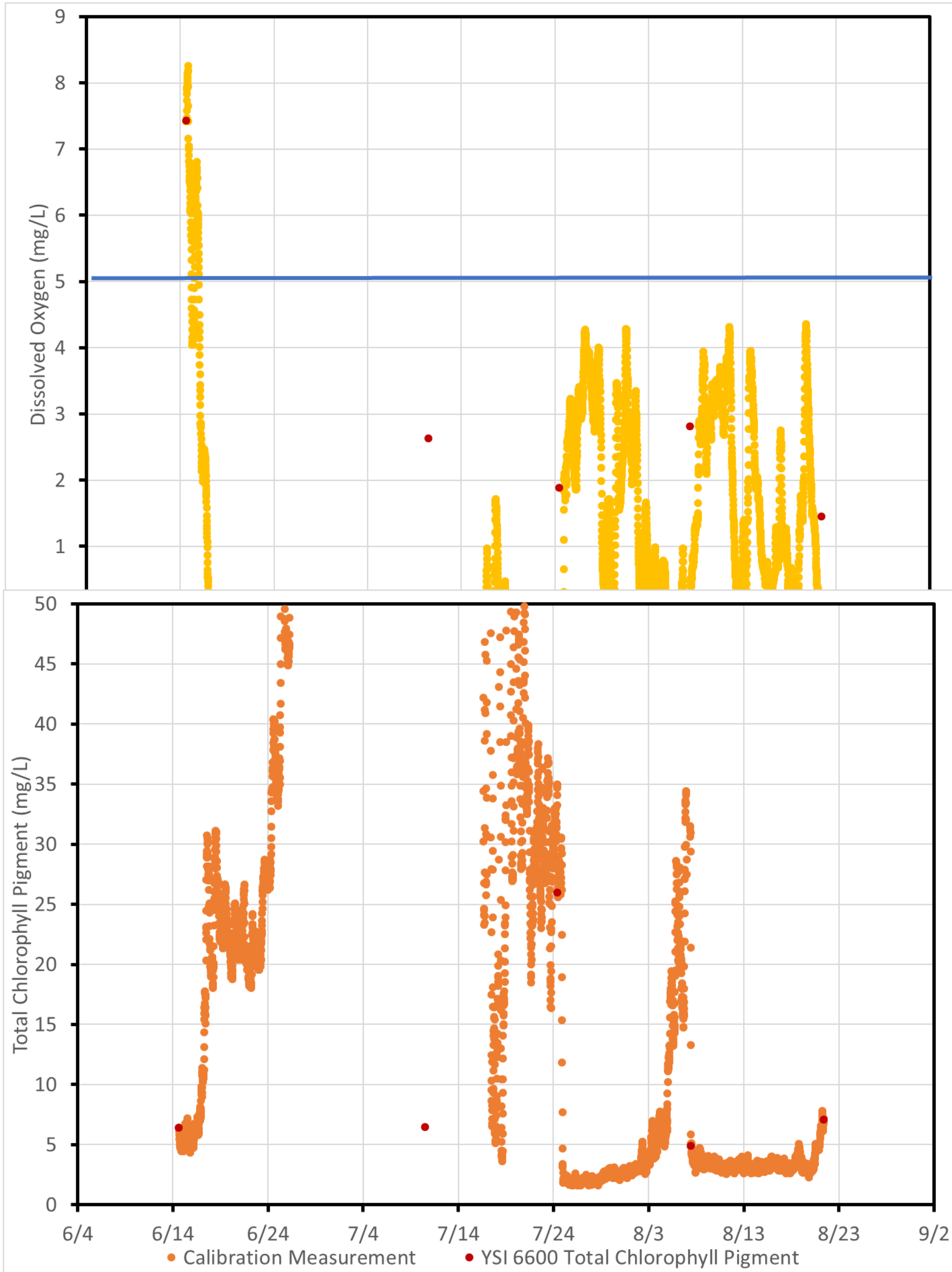



Figure III-7. TOP: Dissolved oxygen concentration (mg/L) of Mill Pond bottom water. The yellow line is the YSI 6600 DO record, red circles represent the in-field calibration measurements, and the horizontal blue line is the State regulation for minmum dissolved oxygen. BOTTOM: Chlorophyll-a concentrations (µg/L) of Mill Pond bottom water represented by the orange line. Red circles represent the in-field calibration measurements.

Dissolved oxygen (DO) concentrations measured at 0.5-meter depth at 18 locations around the pond found the highest concentrations near the inflow from the channel and along the West-side of the pond, with decreasing dissolved oxygen levels as the water moves toward the outlet. Lower DO was found along the eastern side of the pond than the western side (**Figure II-1**). Even with a high density of macrophytes, the pond sediments consume so much oxygen that the surface waters on the East-side of the pond become hypoxic/anoxic. The high rates of oxygen uptake by the sediments and plants/phytoplankton within the water column at night. In locations with the highest dissolved oxygen at 0.5 m depth, the dissolved oxygen at 1-meter was still less than 2 mg/L, indicating that the bottom water throughout the pond was hypoxic/anoxic. Also indicating that low dissolved oxygen in the Northeast section of the pond, could be related to the shallow depths.

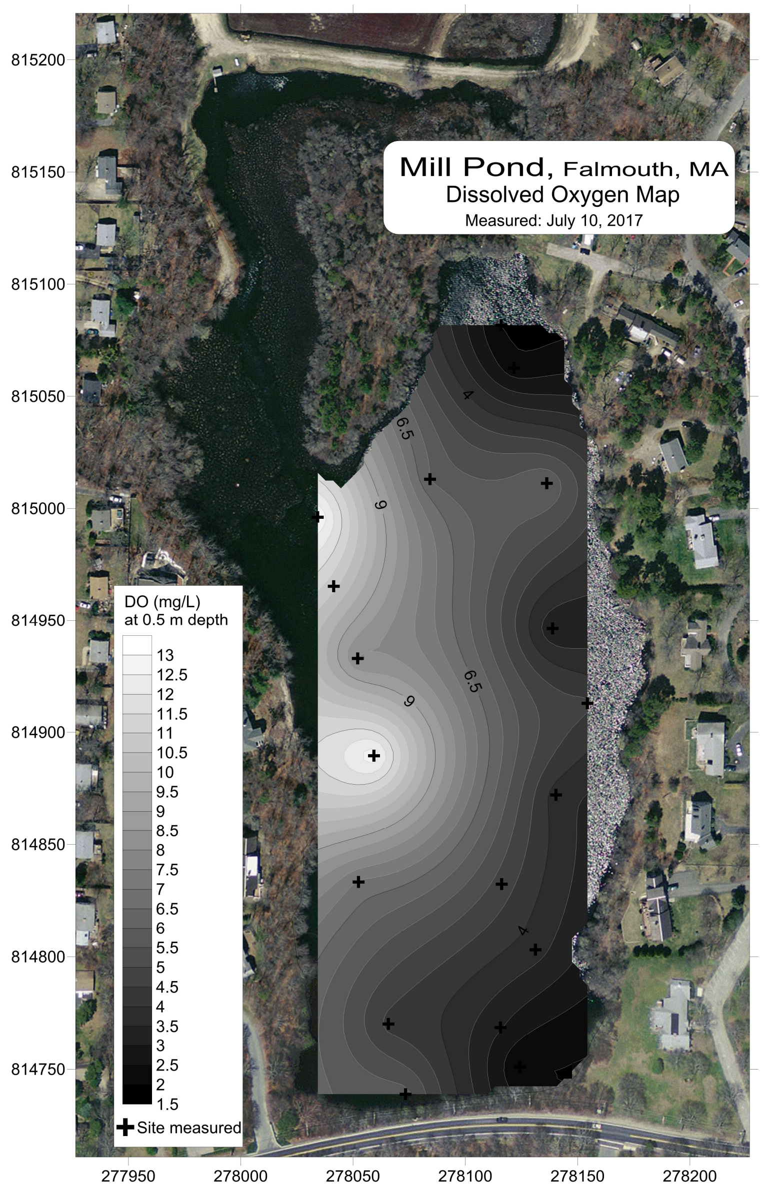



Figure III-8. Distribution of dissolved oxygen in Mill Pond at 0.5 meter depth determined from measurements at 18 locations (7/10/2017).

*Rooted Macrophyte and Bathymetric Survey*

Macrophyte distribution throughout Mill Pond was determined by identifying the macrophyte species in the pond and marking their location with GPS to create a distribution map. Locations of macrophytes were digitized and labeled accordingly using Geographic Information System (GIS) Mapping Software (**Figure III-9**). There are 10 dominant species of aquatic vegetation and one macroalgae in Mill Pond. Floating aquatic vegetation includes: watershield, yellow water lily, and watermeal. Submerged aquatic vegetation includes: bladderwort, milfoil, pondweed, and curly leaf pondweed. Emergent aquatic vegetation includes: Canada rush, bayberry bush, and sedges. The one type of macroalgae is filamentous green algae. Many of the submerged and floating aquatic vegetation cohabitate the same areas in the pond, making the plant density and biomass very high.

Plant density was assessed by SCUBA diver surveys at eight sites in May and June 2017. The average percent coverage is reported in **Table III-7**.

Table III-7. Aquatic vegetation total percent coverage at each of the 8 survey sites.

| Site | SAV % Coverage |
|---|---|
| MP1 | 95% |
| MP2 | 100% |
| MP3 | 100% |
| MP4 | 95% |
| MP5 | 95% |
| MP6 | 90% |
| MP7 | 80% |
| MP8 | 80% |

Macrophyte biomass was assessed in October 2017 by collecting aquatic vegetation inside a 0.25 square-meter quadrat placed at the sediment surface. All macrophytes were collected in each of three quadrats placed at two locations in the pond. The macrophytes were sufficiently rinsed off and patted dry for determination of wet weight, and then dried at 64 ˚C to constant weight for dry weight. The average wet and dried biomass per square meter was 11.1 and 0.98 kg/m$^2$, respectively. 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 36.6% carbon by weight, 2.8% nitrogen and 0.06% phosphorus (of dry weight). The nitrogen and carbon content were used to determine the total mass of C and N held within the vegetation per unit area of pond bottom (**Table III-8**). Using macrophyte density, biomass, nitrogen content, and surface area of the pond from bathymetric analysis, the mass of N and P held by the aquatic plants pond-wide in summer is estimated to be approximately 453 kg nitrogen and 9.8 kg phosphorus. The N:P ratio of the plants is approximately 102 N: 1P.

Table III-8. Concentration (%)and weight of nitrogen, carbon and phosphorus held in aquatic vegetation at the end of the growing season, per square meter.

| Location | Quadrat | Wet Biomass (g/m^2) | Dry Biomass (g/m^2) | %N Of Dry Biomass | %C Of Dry Biomass | %P Of Dry Biomass | g N/m^2 | g C/m^2 | g P/m^2 |
|---|---|---|---|---|---|---|---|---|---|
| **NE SHORE -** | **Q1** | 2472 | 175 | 2.6 | 32.8 | 0.03 | 4.5 | 57 | 0.047 |
| **NE SHORE -** | **Q2** | 2371 | 191 | 2.4 | 33.0 | 0.13 | 4.6 | 63 | 0.250 |
| **NE SHORE -** | **Q3** | 2911 | 206 | 2.7 | 38.9 | 0.03 | 5.6 | 80 | 0.063 |
| **NW SHORE** | **Q1** | 3025 | 344 | 3.9 | 38.6 | 0.07 | 13.3 | 133 | 0.242 |
| **NW SHORE** | **Q2** | 3183 | 315 | 2.5 | 37.5 | 0.05 | 7.7 | 118 | 0.147 |
| **NW SHORE** | **Q3** | 2686 | 243 | 2.8 | 38.8 | 0.07 | 6.7 | 94 | 0.170 |
| **Average** | | 2775 | 246 | 2.8 | 36.6 | 0.06 | 7.1 | 91 | 0.153 |

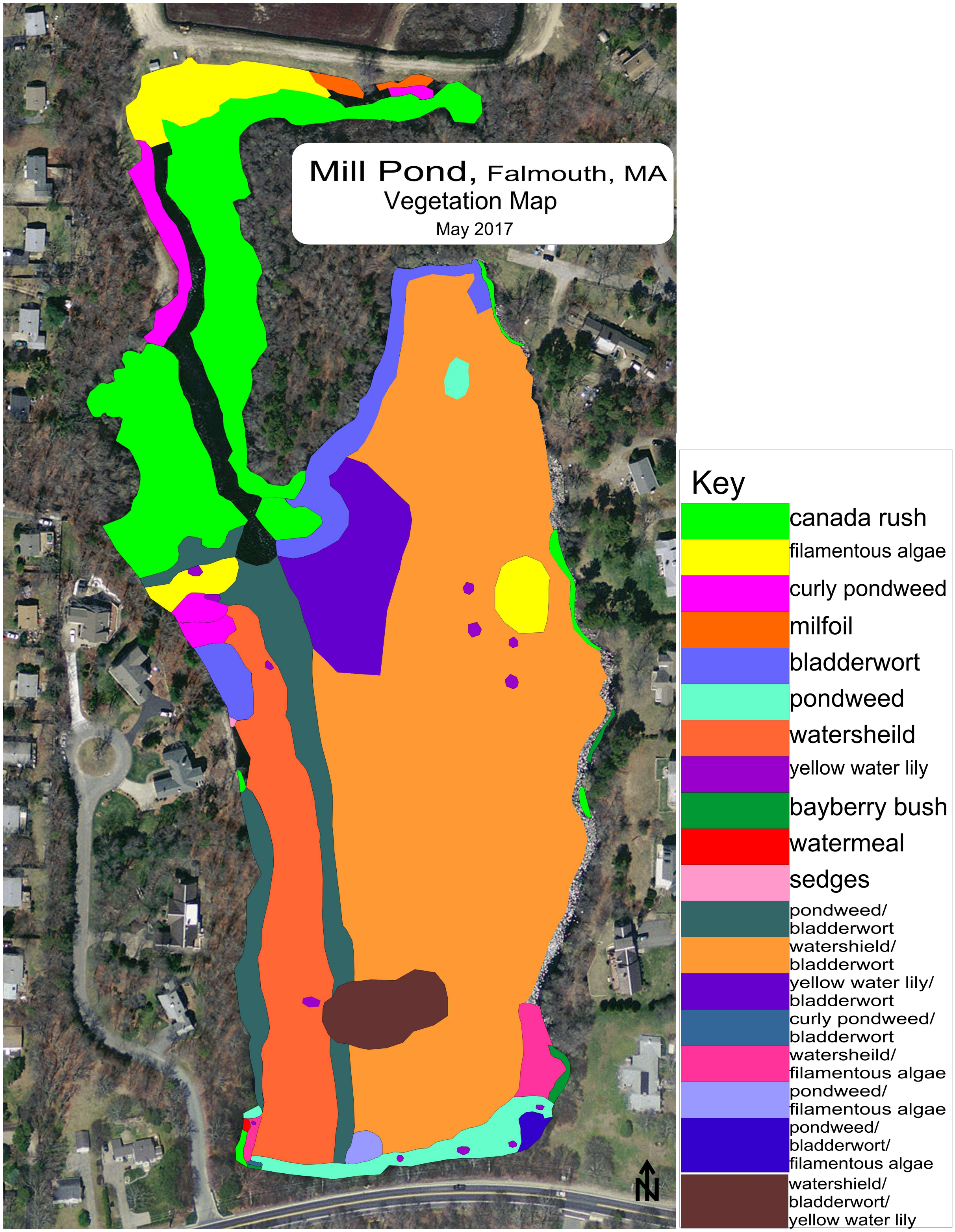



Figure III-9. Rooted vegetation map. Macrophyte and macrophyte assemblages greater than five sq. meters are depicted with color.

Due to shallow depths and dense vegetation, pond bathymetry was determined during a June 2016 survey using manual depth measurements to the nearest centimeter and a Garmin 76 handheld GPS unit for LAT LON. Over 400-point depth measurements were compiled into x-y-z coordinated systems to produce a detailed bathymetric map of Mill Pond (**Figure III-10**).

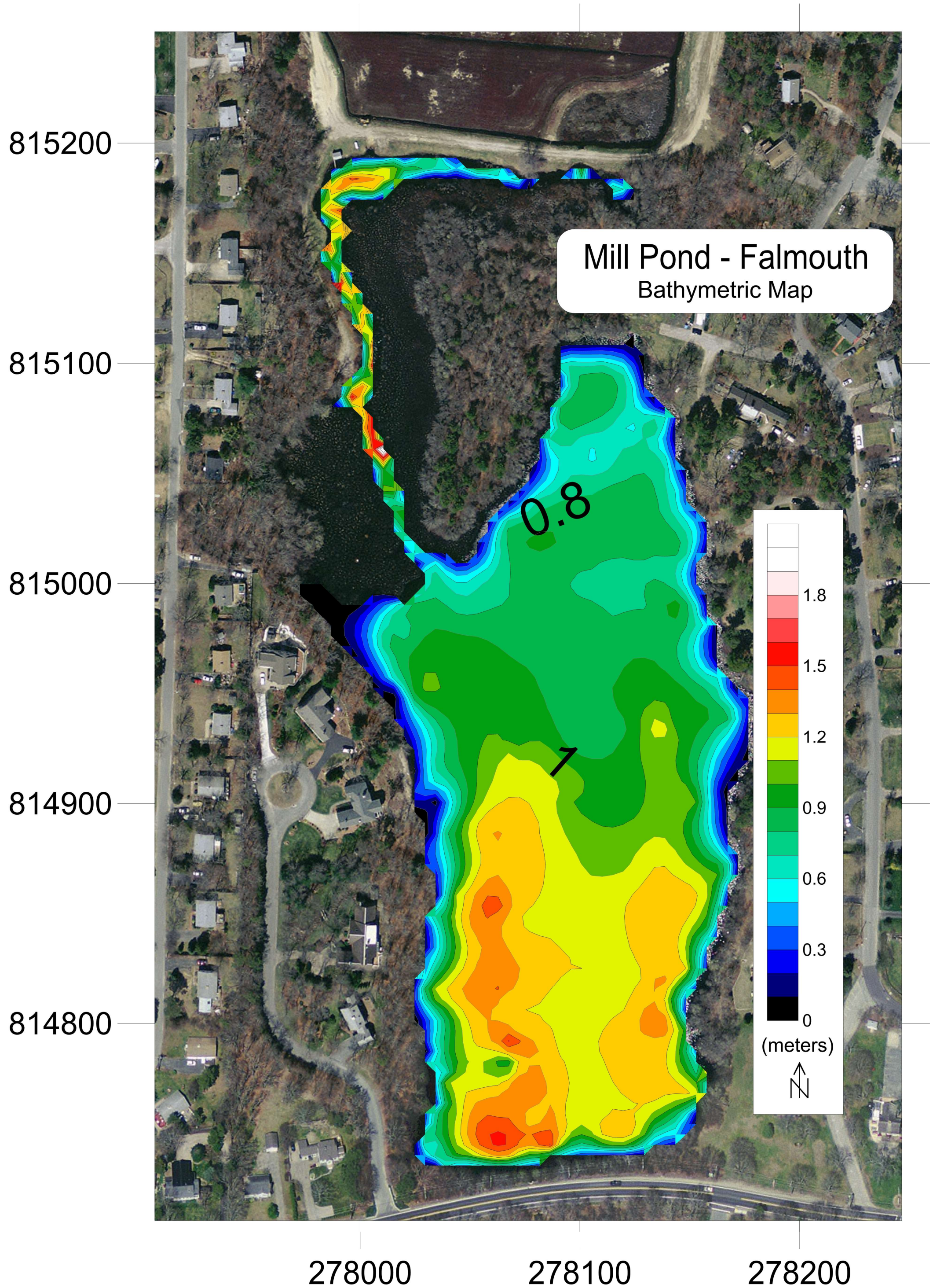



Figure III-10. Bathymetric Map of Mill Pond, representing the benthic morphology of the pond.

### *Determination of Water Residence Time in Pond*

Mill Pond is a 15.6-acre pond, dominated by surface water in and out flows. The bathymetric study revealed that pond has a volume of 36,050 $m^3$. During the 2015-2017 assessment, the pond average daily discharge was 4,891 $m^3$/day, resulting in an average annual water residence time of 7.4 days. However, water residence time during the summer is more critical to pond dynamics. In 2016 and 2017, the June – August residence time was 7.2 days and 5.3 days, respectively. The difference in these two summers is attributed to the interannual hydrological conditions, which reveal that 2016 was a dry year and 2017 was a wet year.

Due to cranberry bog irrigation and flooding practices and natural seasonal variations in the inflows, the flow in / out of the pond varies throughout the year, with the most noticeable variations occurring during harvest (October) and winter (December- February) floods (**Figure III-11**). To harvest the cranberries and protect the plants during the winter, the bogs are generally flooded. This requires the bog operator to place boards in the outflow culvert between the bog and Mill Pond. These boards stop almost 100% of the surface water flow from the bog into the pond. However, residual pond water, groundwater, and precipitation allow water to flow from Mill Pond into Backus Brook. During the period of study, the outflowing surface water flowed continuously, with lowest flows occurring in January, averaging approximately 550 $m^3$/day, going as low as 50 $m^3$/day on a single day. Highest flows occurred in March, averaging, 11,200 $m^3$/day, going as high as 30,000 $m^3$/day for a single day. Large variations in stream flow is the major determinant of residence time of water in the pond (Figure III-12). During the low flow period, January through mid-February, water entering when the boards are emplaced may not be discharged until the boards are removed restoring surface inflow (approximately 60 days). In contrast, during the high flow period in March, a parcel of water may move through the pond in as little as one day.

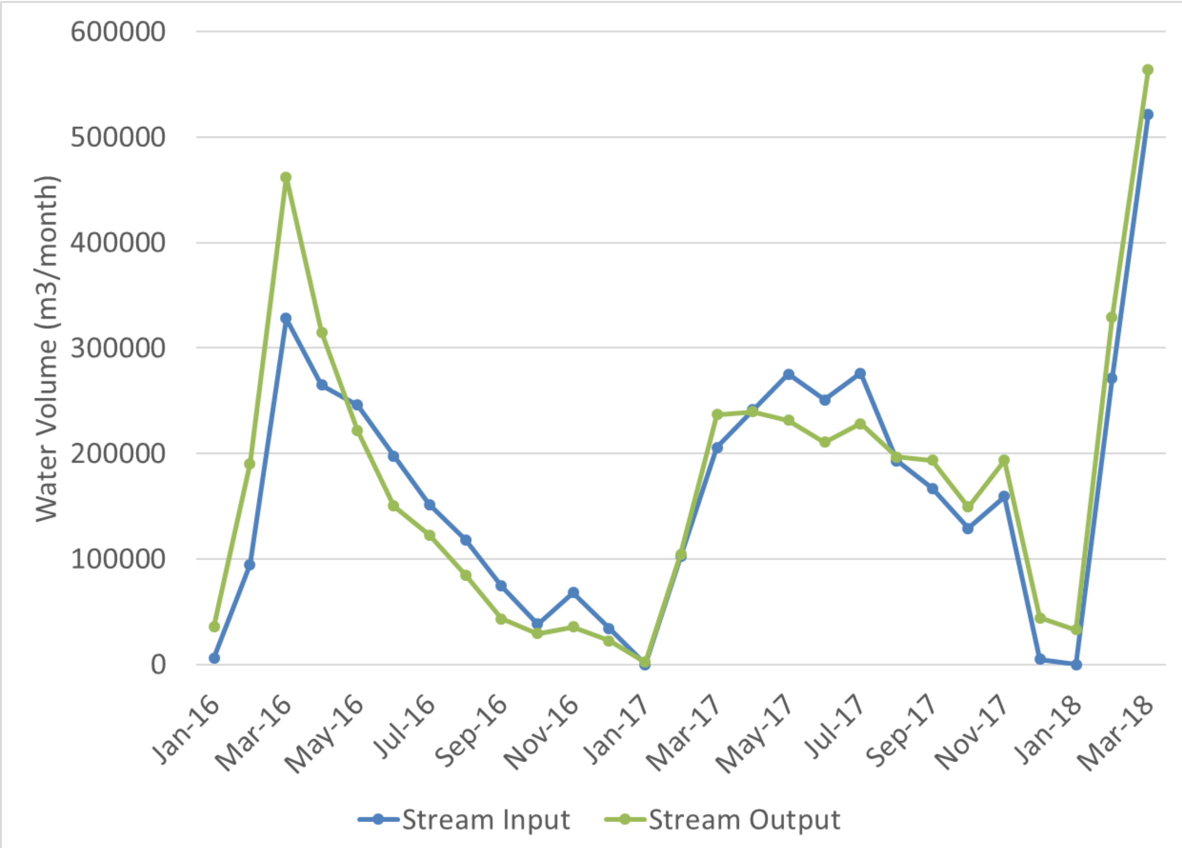



Figure III-11. Monthly water volumes of surface water inflow and outflow, showing the strong variation in flows over a year. Note: groundwater inputs are not included in the inflowing water volume.

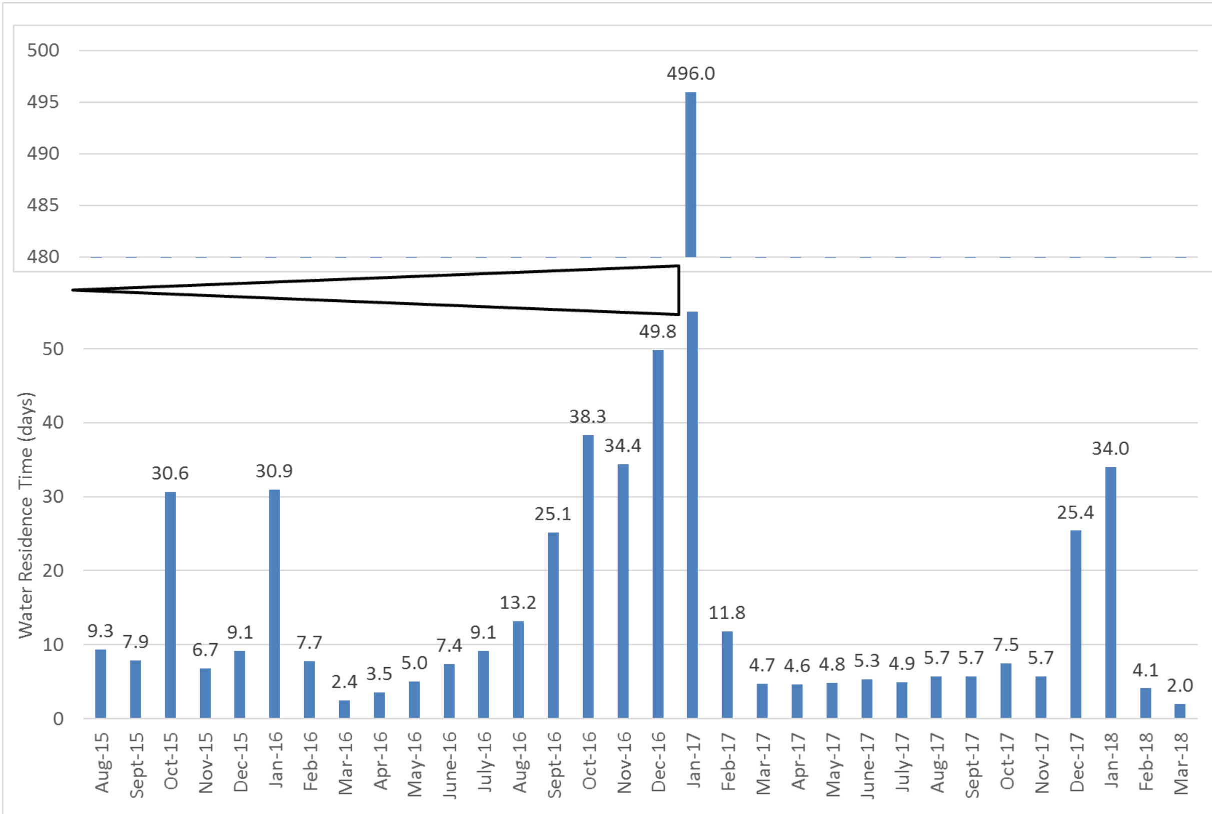



Figure III-12. Water Residence Time for each month of the current study. High water residences occur during harvest and winter flood, with the lowest residence time occurring in March and April after bog flood waters are released.

Irrigation practices were also found to increase the water residence time in the pond by changing the flow dynamics of the pond when water is pumped from the channel back to the bog for irrigation. This practice causes the input flows to appear higher than the outflows, as a result of the return of non-infiltrated irrigation water re-entering the pond (double counting) needs to be corrected for in the raw inflow data (**Figure III-11**). This flow dynamic typically occurs between April and September when bogs are irrigated for frost protection (April and May) and irrigation (June-September).

*Sediment Burial Analysis*

Nitrogen and phosphorus can be lost from pond waters through burial of organic matter from plants and phytoplankton in bottom sediments. Burial of N and P was assessed by Dr. Matthew Charette and Owen Filiault, in October 2016. They collected a single 50-centimeter core at the center of Mill Pond. The sediment was comprised of a silty surface gradually becoming sandier with depth (**Figure III-14**). At approximately 20 centimeters, there was a thick sand layer. Water content was greatest in the fine sediment layers in the top 20 cm of the sediment column (**Figure III-13**).

137-Cesium and 210-Lead profiles were used to determine the rate of sediment accretion and the associated mass of N and P over recent decades. Profiles of 137-Cesium typically show two cesium peaks, each peak relating to a very specific atmospheric Cesium event. The larger peak identifies mid-1960s nuclear tests and the smaller peak is from the Chernobyl nuclear accident in 1986. Profiles of 210-Lead generally show highest levels near the sediment surface where it is deposited and declines with depth due to decay. 210-Lead is deposited on Earth's surface at a constant rate, and immediately begins to decline through radioactive decay at a known rate (Appleby & Oldfield, 1978). The sediment core collected from Mill Pond varied from these general patterns in 137-Cesium or 210-Lead (**Figure III-16** and **Figure III-15**). Based on handling procedures the elevated 137-Cesium peak and a spike in 210-Lead at the bottom of the core are likely due to the bottom of the core being contaminated with surface sediment when it was harvested and capped.

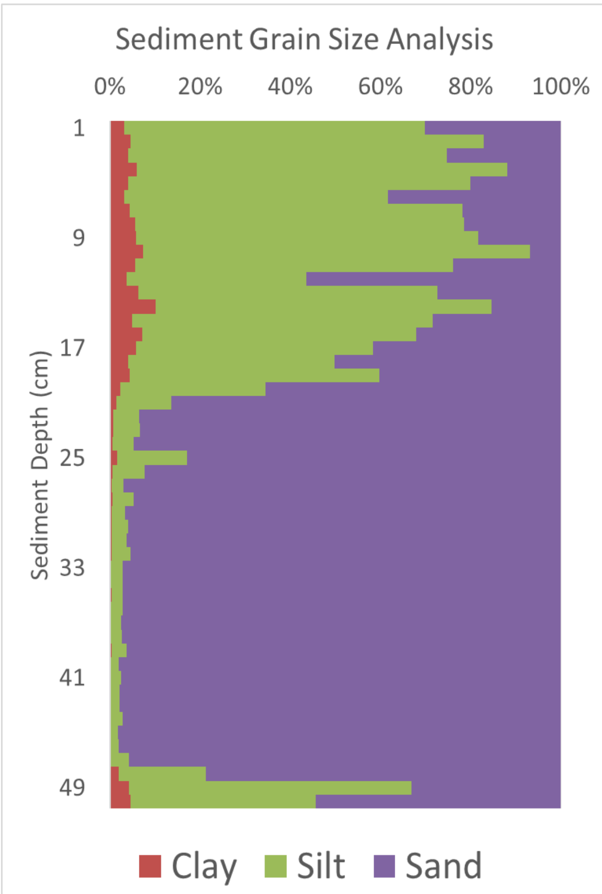



Figure III-14. Sediment grain size assemblage at depth. Figure provided by Matt Charette (WHOI).

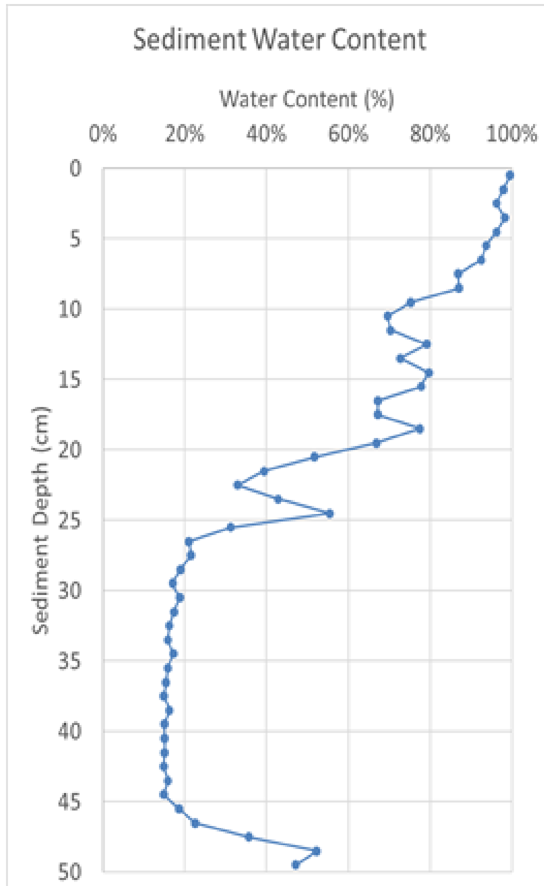



Figure III-13. Sediment water content at depth. Figure provided by Matt Charette (WHOI).

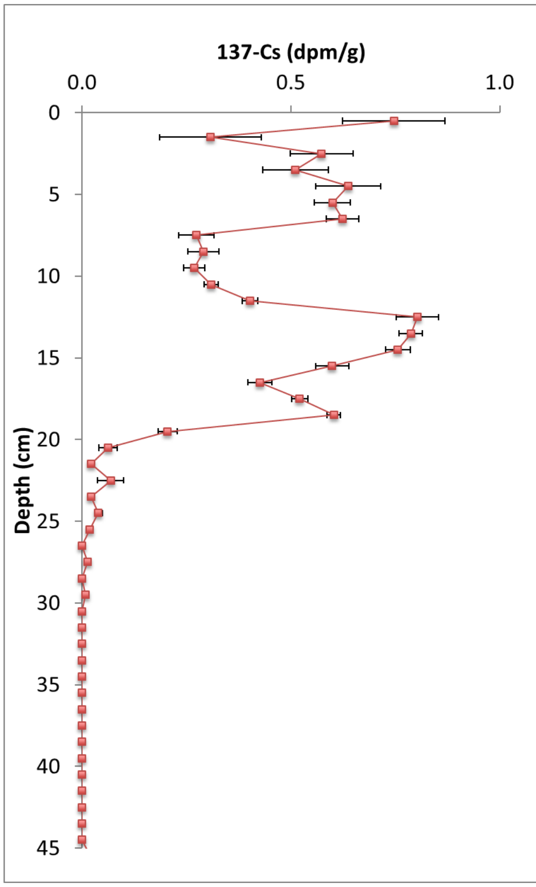



Figure III-16. 137-Cesium at depth. Modified from figure provided by Matt Charette.

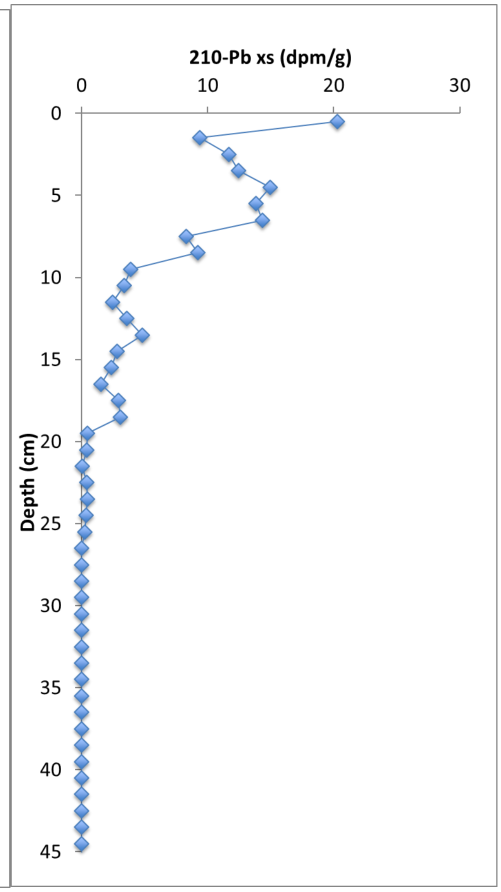



Figure III-15. 210-Lead at depth. Modified from figure provided by Matt Charette.

For the sediment accretion calculations, given the likelihood of contamination at the bottom of the core from handling, only data from the upper 45 cm was used. The recent rate of sediment accretion was determined by the amount of sediment that has accumulated over lower 137-Cesium peak the bottom of the peak corresponds to ~1966, suggesting 20-centimeters of sediment had accumulated post 1966. This approximate accretion rate was used to calculate average nitrogen and phosphorus burial per year, assuming steady state. The average annual burial rate of nitrogen and phosphorus was determined to be approximately 921 kg N per year and 24 kg P per year over the entirety of Mill Pond.

### *Nutrient Dynamic Assessment with Box Model*

#### <u>Box Model Calibration</u>

A variety of numerical tools can be employed to better understand the dynamics of aquatic systems. In the case of an estuary, which is extremely dynamic due to tidal exchange, a time varying linked hydrodynamic/water quality numerical model would be needed to realistically represent changes in the system based on varying nutrient inputs and outputs to the system. In the case of fresh ponds, including Mill Pond, a simpler yet robust approach is to employ a "steady state" box model to represent the system as a function of set volumes of water in and out of the system as well as constituent loads in and out of the system. Regardless of which tool is utilized, the first step in using a numerical tool is calibration of the model.

To allow integration of the water flow and nutrient loading data and to aid in evaluating management alternatives, a box model was developed for Mill Pond, which was independently verified using salt (chloride) balance. If the pond is in steady state and all sources and sinks were measured and accounted for correctly, then the volume of water and mass of salt entering (+) and exiting (-) the pond should sum to zero. Two water and salt balances were created for two hydrologic years, October 2015 to September 2016 (2016) and October 2016 to September 2017 (2017).

Initially, the model was constructed using measured (inflow / outflow, stormwater, precipitation) and modeled (groundwater, evaporation) input and output terms. The box model developed using 2016 water values appeared to balance well (within 4%), whereas the model developed using the 2017 water values for flow did not balance as well (within 17%). Similar results were obtained using the conservative constituent (chloride). The salt balance was within -6% and 20% for the same 2016 and 2017 periods (**Table III-10**) when comparing mass of salt into the pond versus salt out of the pond.

**Table III-9**. Measured water inflow, water outflow, stormwater, and precipitation and modeled groundwater, and evaporation per day used for model calibration. Groundwater values are flow-corrected based on flow ratios discussed in *Mill Pond Water Quality Conditions*.

| Water Balance | 2016 ($m^3$/day) | 2017 ($m^3$/day) |
|---|---|---|
| **Vstream input** | 4735 | 4967 |
| **Vgroundwater*** | 531 | 480 |
| **Vprecipitation** | 182 | 235 |
| **Vevaporation*** | -89 | -89 |
| **Vstream output** | -5139 | -4644 |
| **Vstormwater** | 13 | 16 |
| **Vcranberry irrigation** | ? | ? |
| **Total Inputs** | 5462 | 5699 |
| **Total Outputs** | -5228 | -4733 |
| **Vsum** | 234 | 966 |
| **Balance** | 4% | 17% |
| Notes: * indicates modeled from MEP landuse database | | |

Table III-10. Measured salt mass at the inflow, outflow, stormwater, and precipitation and modeled groundwater, and evaporation per day used for model calibration.

| Salt Balance | 2016 (g/kg) | 2017 (g/kg) |
|---|---|---|
| **Sstream input** | 190768 | 216111 |
| **Sgroundwater** | 13278 | 12001 |
| **Sprecipitation** | 4745 | 6122 |
| **Sevaporation** | 0 | 0 |
| **Sstream output** | -197204 | -205409 |
| **Sstormwater** | 315 | 390 |
| **Scranberry irrigation** | ? | ? |
| **Total Inputs** | 209106 | 234623 |
| **Total Outputs** | -197204 | -205409 |
| **Ssum** | 11902 | 29215 |
| **Balance** | 6% | 12% |

Further investigation revealed that the greater difference in water and salt balance found in 2017 than 2016 (**Table III-9**, **Table III-10**) were associated with water withdrawals/return associated with cranberry bog irrigation. Based on the results of the box model runs using 2016 and 2017 input terms, bog irrigation during 2016 appeared to have minimal water recycling (*i.e*., double counting of flows) as water removals did not return via the channel into the pond. Alternatively, bog irrigation in 2017 appears to have been significant and had significant water return to the pond. This interannual difference appears to result from groundwater levels returning after the drought years of 2013-2016 and the high rainfall summer of 2017 (2x precipitation May-September than drought summers). The result would be that the bog would be more consumptive in 2016, with little water returning to the pond compared to 2017, and it is this water return that appears to be causing the greater departure in box model output from observed data in 2017 (*Appendix C*).

Given the observations, it was possible to deal with the issues associated with irrigation return flow on the stream input measurements to provide a more accurate input term for the model. Using the measured (outflow, stormwater, precipitation) and modeled (inflow, groundwater, evaporation) input and output sources of water, a water balance unaffected by bog irrigation was developed. The result of correcting for return flow is that the 2016 and 2017 water budgets balance, within 2% and 3%, respectively (**Table III-11**).

The calibrated model (balanced for water volumes) was validated using the salt loads (specific conductance/salinity) for each water source and output). Salt is commonly used for this purpose, as it is conservative by nature (as opposed to nutrients). Salt is not transformed via biological processes the way nitrogen and phosphorus can be. Specific conductance as a measure of salt concentration was measured with stream inflow / outflow and stormwater volume measurements. The result compared very well with the water balance in the box model, salt balanced within 3 and -3% for 2016 and 2017, respectively **Table III-11**, **Table III-12**). This indicates that almost all the sources and sinks of water have been identified and the model is sufficient robust for examining nitrogen and phosphorus inputs and losses, as well as making initial predictions over the effects of hydrologic or nutrient loading modifications on pond nutrient levels and nitrogen attenuation rates.

Table III-11. Measured water outflow, stormwater, and precipitation and stream water inflows (adjusted for recycled irrigation water), groundwater, and evaporation per day used for model calibration.

| Stream Input Corrected Water Balance | 2016 ($m^3$/day) | 2017 ($m^3$/day) |
|---|---|---|
| **Vstream input*** | 4607 | 4164 |
| **Vgroundwater*** | 531 | 480 |
| **Vprecipitation** | 182 | 235 |
| **Vevaporation*** | -89 | -89 |
| **Vstream output** | -5139 | -4644 |
| **Vstormwater** | 13 | 16 |
| **Vcranberry irrigation** | ? | ? |
| **Total Inputs** | 5334 | 4896 |
| **Total Outputs** | -5228 | -4733 |
| **Vsum** | 107 | 163 |
| **Balance** | 2% | 3% |
| Notes: * indicates modeled from MEP landuse database | | |

Table III-12. Measured salt mass at the outflow, stormwater, and precipitation and modeled water inflow, groundwater, and evaporation per day used for model calibration.

| Stream Input Corrected Salt Balance | 2016 (g/kg) | 2017 (g/kg) |
|---|---|---|
| **Sstream input** | 185633 | 181179 |
| **Sgroundwater** | 13278 | 12001 |
| **Sprecipitation** | 4745 | 6122 |
| **Sevaporation** | 0 | 0 |
| **Sstream output** | -197204 | -205409 |
| **Sstormwater** | 315 | 390 |
| **Scranberry irrigation** | ? | ? |
| **Total Inputs** | 203971 | 199691 |
| **Total Outputs** | -197204 | -205409 |
| **Ssum** | 6767 | -5717 |
| **Balance** | 3% | -3% |

Nitrogen Mass Balance

The calibrated and validated model was used to determine the net movement of nitrogen in and out of the system as well as the relative importance of each source of nitrogen load. Nitrogen loads can come from external, internal, and recycled sources and are represented as such in **Table III-13**. Nitrogen loads defined in the analysis of surface water flow in / out, stormwater, land-use, groundwater, and precipitation as well as sediment regeneration, denitrification, and burial were used to determine the nitrogen mass balance of Mill Pond (net in or out).

Comparing the nitrogen load into Mill Pond to the load leaving the pond results in an estimate of how much N-load is attenuated (reduced) in transit through the pond system. Based upon the lower total nitrogen load (1055 kg $yr^{-1}$) discharged from Mill Pond in 2016 compared to that which entered Mill Pond from surface water inflow, its watershed (direct ground discharge) and precipitation (2553 kg $yr^{-1}$), the integrated attenuation in passage through Mill Pond in 2016 prior to discharge to the Green Pond estuary was 59% (i.e. 59% of nitrogen input to Mill Pond does not reach the Green Pond estuary). Nitrogen attenuation in passage through Mill Pond was even higher in 2017, with only 866 kg $yr^{-1}$ of the 2429 kg $yr^{-1}$ entering the pond being discharged to Green Pond, an overall attenuation of 64%. These attenuation rates compared well to that measured previously by the Massachusetts Estuaries Project (MEP, 2004) using a less refined approach which yielded a 67% attenuation rate.

As a cross check on the measure of N-attenuation, if all the nitrogen attenuation is taking place through biogeochemical process within Mill Pond, the sum of the attenuation processes (e.g. burial, denitrification) should equal the attenuated load discussed above. Burial accounts for 365 kg N removed per year. Based on a validated water budget and measurement of all input sources and the output nutrient concentrations reveal an uptake of 967 and 1,157 kg nitrate + nitrite and ammonia ($NO_x$, $NH_4^+$) in the pond. This uptake is directly translated into nitrogen gas through denitrification. Although direct measurement of sediment denitrification measured during three aerobic fluxes, revealed minimal nitrogen removal. Overall, burial and denitrification amounted to a net loss of 1332 kg N $yr^{-1}$, comparable to the 2016 attenuation, which was determined to be 1,498 kg N $yr^{-1}$, a 12% difference. Similarly, in 2017, the burial and denitrification amounted to 1,522 kg N $yr^{-1}$ with the attenuated load of 1,563 kg N $yr^{-1}$, a 3% difference. Moreover, some of the "missing" nitrogen maybe associated with the irrigation practices followed by the operator of the up-gradient bog. Recall, in 2016 (drought year) water being used for cranberry bog irrigation may not have returned to the pond (*Appendix C – Potential Flow Dynamics of Backus Brook to Mill Pond and Bog Irrigation*), supported by the decreasing flows throughout the summer (**Figure III-2** and **Figure III-3**). Whereas in 2017 (wet year) part of the water used for irrigation returned to the pond, supported by the measured inflow being much higher than measured outflow, deemed double counted water (**Table III-4**). Nonetheless, the attenuation of Mill Pond in both years is comparable at 59% and 64% N attenuation in 2016 and 2017, respectively (**Figure III-13**) and is consistent with the integrated measure of attenuation determined by the MEP in 2004 (67% attenuation).

Table III-13. Nitrogen Mass Balance of the respective sources and sinks of nitrogen into and out of the pond. Attenuation processes responsible for nitrogen attenuation. Recycled nitrogen loads based on the nitrogen contained within aquatic vegetation or regenerated from the sediments.

| Nitrogen Mass Balance | 2016 | | 2017 | |
|---|---|---|---|---|
| | (kg/yr) | % of inputs | (kg/yr) | % of inputs |
| **Input Loads:** | | | | |
| **Nstream input** | 1514 | 59.3% | 1368 | 56.3% |
| **Ngroundwater*** | 962 | 37.7% | 962 | 39.6% |
| **Nprecipitation*** | 73 | 2.8% | 94 | 3.9% |
| **Nstormwater** | 5 | 0.2% | 6 | 0.2% |
| **Total Inputs** | 2553 | | 2429 | |
| **Output Loads:** | | | | |
| **Nstream output** | -1055 | - | -866 | - |
| **Nevaporation*** | 0 | - | 0 | - |
| **Ncranberry irrigation** | ? | - | ? | - |
| **Total Outputs** | -1055 | | -866 | |
| **Pond Attenuation of N:** | 1498 | 59% | 1563 | 64% |
| **Attenuation Processes:** | | **% of atten. N** | | **% of atten. N** |
| **Nburial** | -365 | 24% | -365 | 23% |
| **Ndenitrification**** | -967 | 65% | -1157 | 74% |
| **Total Attenuation** | -1332 | | -1522 | |
| **Recycled Loads:** | | | | |
| **Nsediment regeneration** | 184 | | 184 | |
| **Nplant** | 453 | | 453 | |
| **Total Recycled** | 637 | | 637 | |

Notes: * indicates modeled from MEP landuse database
** estimated from nitrate+nitrite uptake in the pond

The most significant sources of external nitrogen load to Mill Pond comes from stream inflow (58%) and groundwater (38%), with precipitation (3.5%) and stormwater outfall pipes (0.2%) making up less than 5% of the external nitrogen load. Nitrogen regeneration from the sediments is a significant source of recycled nitrogen, totaling 184 kg N / year. The anoxic period during the summer increases the rate of sediment ammonium release, also increasing the mass of bioavailable nitrogen for plant and phytoplankton uptake. Ultimately, we find that the in-pond nitrogen mass is related to both the external and internal inputs Figure III-17). However, there is a stronger correlation between the outflowing nitrogen to the in-pond nitrogen mass (r = 0.82) than the inflowing nitrogen to the in-pond nitrogen mass (r = 0.61). This indicates that in-pond attenuation and regeneration processes affect the nitrogen mass that entered the pond, and therefore more closely resemble the nitrogen mass leaving the pond.

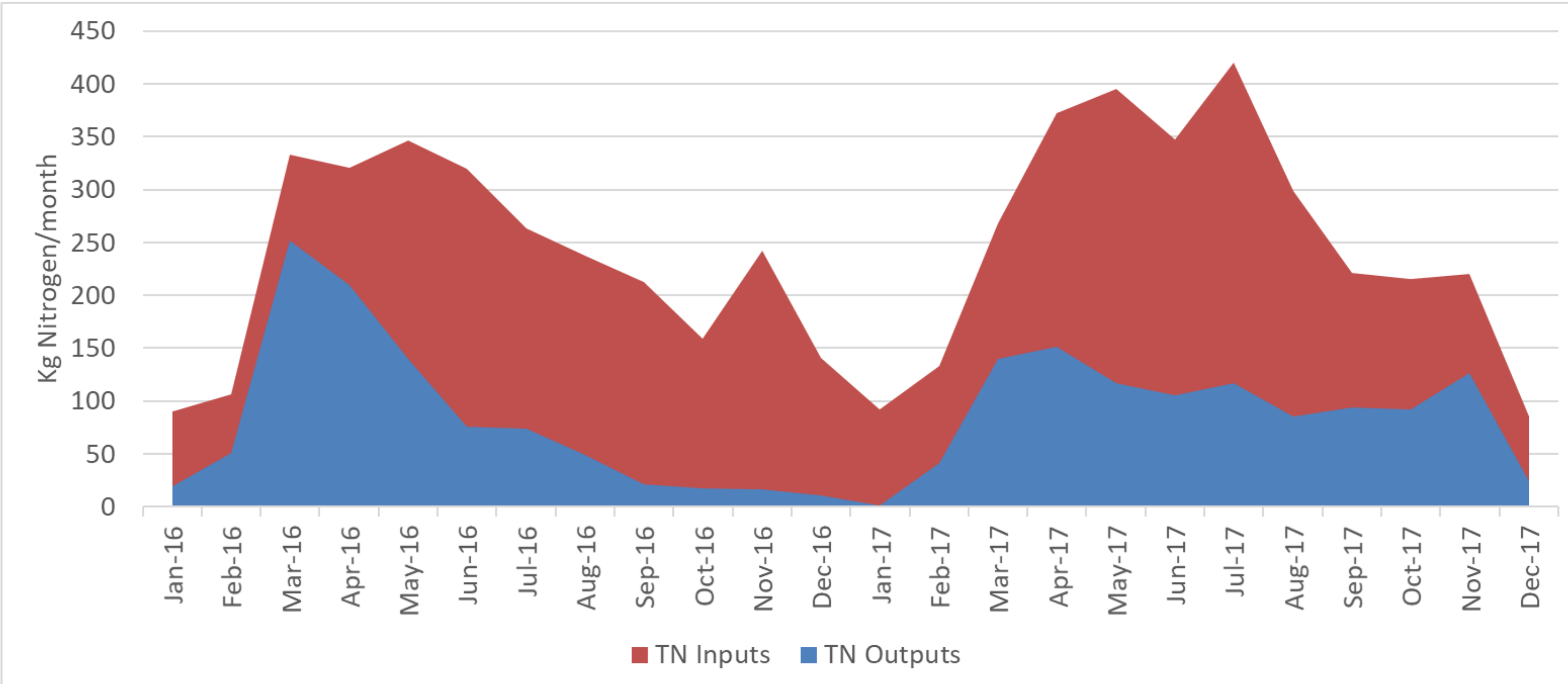



Figure III-17. Nitrogen dynamics of Mill Pond. The nitrogen mass of inputs (flow-corrected stream, groundwater, precipitation, and stormwater) and outputs (stream outflow) are in kg/month based on the flows and associated concentrations of each variable.

## Phosphorus Mass Balance

Phosphorus loads to Mill Pond were determined as a component of the analysis of surface water flow in / out, stormwater, sediment regeneration, and burial. P-loads associated with each potential source/sink were assessed together to determine the phosphorus mass balance of Mill Pond. Similar to nitrogen, phosphorus loads can come from external, internal, and recycled sources and are presented as such in **Table III-14**.

Phosphorus moves very slowly with groundwater (e.g., 0.01-0.02 ft/d)[6], so the primary additions to surface water bodies tend to be direct discharges from stormwater runoff or stream inflows. Groundwater inputs tend to be limited to sources directly abutting the water body with variations in most residential settings depending on the age and distance of septic system leach fields, use of lawn fertilizers, and treatment of roof runoff. Measured phosphorus loads to Mill Pond comes primarily from the stream inflow and two stormwater pipes discharging into the pond, so other factors need to be estimated. There are approximately 40 houses within 100 m of the pond with many of the houses constructed in the 1950's. Using estimated phosphorus travel times and without detailed review of leach field distances, lawn size, or building sizes, these houses would contribute approximately 21 kg P year to Mill Pond via groundwater and another 0.5 kg P year would be added by precipitation/dry fall. More refined land use characterization would help to refine these estimates. Based on the monitoring completed during this project, the stream flowing into Mill Pond added 81 kg P in 2016 and 50 kg P in 2017, while the stormwater discharges added 1.4 kg P in 2016 and 1.7 kg P in 2017. Stream inputs would include cranberry bog P inputs. Collectively, these estimates and measurements sum to 100.2 kg P added to Mill Pond in 2016 and 70.3 kg P added in 2017.

Within the pond, phosphorus would be buried and regenerated from the sediments, altered, retained, and released by the plants, and some portion would flow out. Stream measurements showed that 53 kg P flowed out of the pond in 2016, while 42 kg flowed out in 2017. While these loads are different, the proportions of P inputs retained in the pond was approximately the same in the two years (48% in 2016 and 40% in 2017). This relationship suggests that processes impacting P sediment release and plant P uptake adjusted within the ranges seen in the two years to the changes in inputs and the variations in streamflow.

Review of sediment core incubations showed P release during the summer from anoxic sediments could be a significant addition, but this was relatively balanced by P uptake from aerobic sediments. As noted in the continuous monitoring, anoxic conditions began deeper in the pond in mid-June and lasted until late-July. Given the DO profiles measured during this period approximately half of the pond bottom could have been anoxic throughout this period, which would have been sufficient to release all the iron-bound P (*i.e.*, chemical release P). This release was 7.8 kg P, but some portion of this P would have been

[6] Robertson, W.D. 2008. Irreversible Phosphorus Sorption in Septic System Plumes? *Ground Water*. 46(1): 51-60.

returned to the sediments through the settling of particles and some portion flowed out of the pond since the residence time was estimated at approximately 7 days. The core incubation results also showed that little P would be released after the chemical release phase was completed; the average anaerobic P release was approximately 25% (2.2 kg P) of the chemical release phase. Finally, the core incubations showed that the sediments had roughly the same uptake rate as release rate when the sediments were aerobic. Collectively, the cores results suggest that the anoxic portions of the pond sediments would have been releasing P at roughly the same rate as the aerobic portions and that the area of each would have been similar. In the May and November profiles, aerobic conditions existed throughout the water column; this suggests that sediments throughout the pond would have been adsorbing P between at least December and April. Of course, all of this would have varied in real time due to changes in water inputs (*i.e.*, both precipitation and upstream bog releases), water outputs, and how much of the sediment surface was exposed to anoxia as winds altered the portion of the water column that was anoxic. Additional variations would occur depending on the rate of plant growth and sediment processes around the plant roots.

All of these P loads and removals were incorporated into box model calculations. The particulate phosphorus was calculated using the total phosphorus concentration minus the dissolved ortho-phosphate concentration which can very slightly overestimate the concentration. Phosphorus particle settling was estimated as 41 kg P in 2016, and 26 kg P in 2017. These are reasonable estimates for use in the box model to determine the main processes for phosphorus attenuation in the pond. Phosphorus loading in 2017 was significantly lower than 2016, with the pond attenuating an estimated 48 and 28 kg P in 2016 and 2017, respectively. Changes in phosphorus loading are probably related to changes in, specifically related to the cranberry bog operation. Ultimately, we find that the in-pond phosphorus mass is related to both the external and internal inputs (Figure III-18). However, there is a stronger correlation between the outflowing phosphorus to the in-pond phosphorus mass (r = 0.99) than the inflowing to the in-pond phosphorus mass (r = 0.84). This indicates that in-pond attenuation and regeneration processes affect the phosphorus mass that entered the pond, and therefore more closely resemble the phosphorus mass leaving the pond.

Table III-14. Phosphorus Mass Balance of the respective sources and sinks of phosphorus into and out of the pond (external loads). Sources and sinks of phosphorus occurring within the pond (internal loads). Recycled phosphorus loads based on the phosphorus contained within aquatic vegetation.

| Phosphorus Mass Balance | 2016 | | 2017 | |
|---|---|---|---|---|
| | (kg/yr) | % of inputs | (kg/yr) | % of inputs |
| **Input Loads:** | | | | |
| **Pstream input** | 77 | 77.2% | 47 | 67.1% |
| **Pgroundwater*** | 21 | 21.0% | 21 | 29.9% |
| **Pprecipitation*** | 0.5 | 0.5% | 0.5 | 0.7% |
| **Pstormwater** | 1.4 | 1.4% | 1.7 | 2.4% |
| **Total Inputs** | 100 | | 70 | |
| **Output Loads:** | | | | |
| **Pstream output** | -53 | - | -42 | - |
| **Pevaporation*** | - | - | - | - |
| **Pcranberry irrigation** | ? | - | ? | - |
| **Total Outputs** | -53 | | -42 | |
| **Pond Attenuation of P:** | 48 | 48% | 28 | 40% |
| **Attenuation Process:** | | **% P atten.** | | **% P atten.** |
| **Pburial** | -24 | 51% | -24 | 86% |
| **Total Attenuation:** | -24 | | -24 | |
| **Recycled Loads:** | | | | |
| **Psediment uptake** | -60 | | -45 | |
| **Pplant** | 9.8 | | 9.8 | |
| **Total Recycled** | -50 | | -35 | |
| Notes: * indicates modeled from MEP landuse database | | | | |

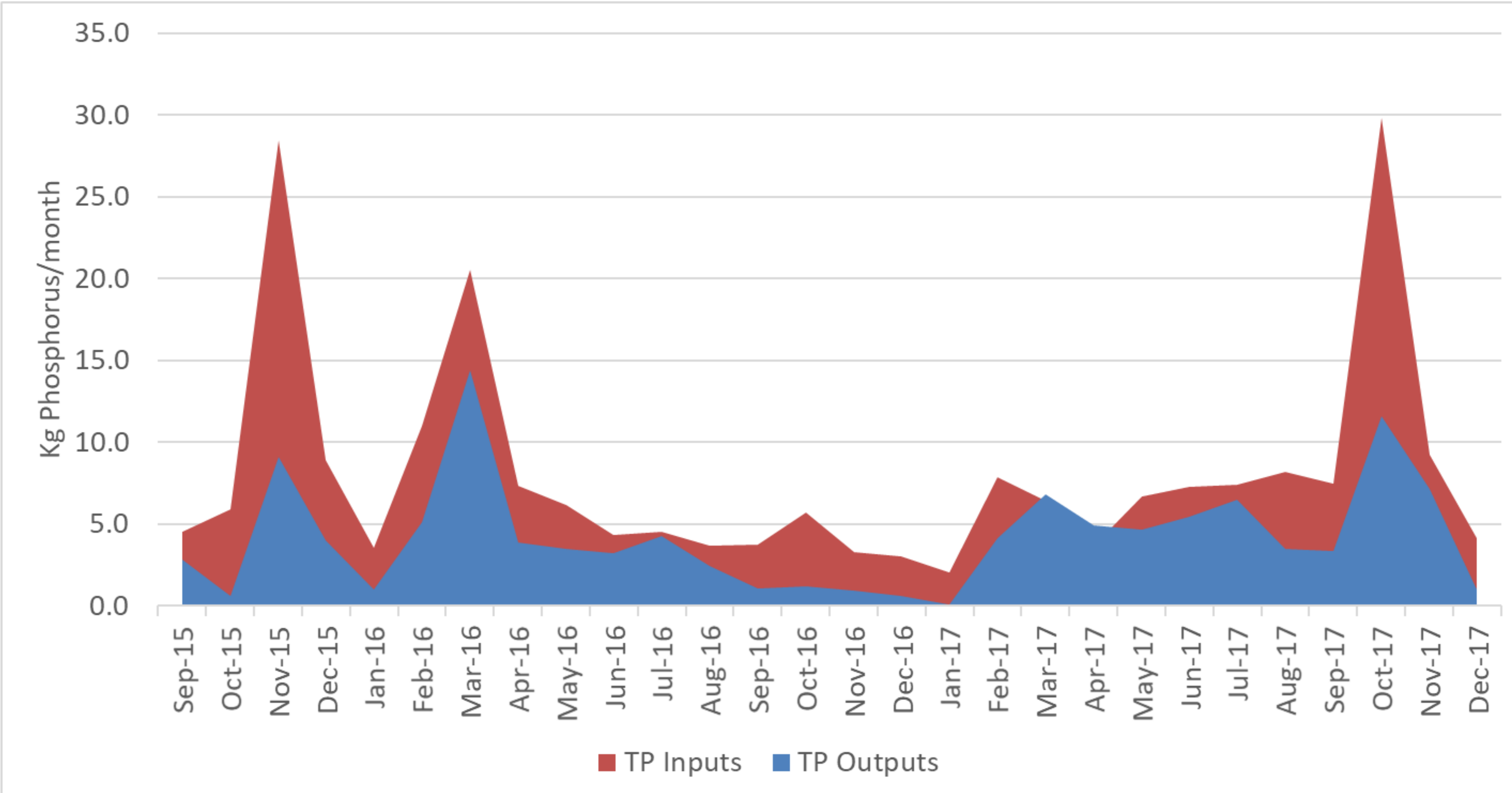



Figure III-18. Phosphorus Dynamics of Mill Pond. The phosphorus mass of inputs (flow-corrected stream, groundwater, precipitation, and stormwater) and outputs (stream outflow) are in kg/month based on the flows and associated concentrations of each variable.

# IV. RECOMMENDATIONS

Mill Pond is a surface water dominated pond, receiving 90% of its water volume from Backus Brook, which flows through several cranberry bogs and is groundwater fed from the overall watershed. The annual stream inputs from Backus Brook are approximately 58% and 70% of the external nitrogen and phosphorus loads, respectively, to Mill Pond. The high concentration of nitrogen and phosphorus loading from anthropogenic activities has led to the significant impairment of the Mill Pond ecosystem. Due to high nutrient loading (N & P), Mill Pond is an eutrophic system, exceeding the Cape Cod ecoregion limits for freshwater ponds (TP ≤ 10 µg $L^{-1}$, TN ≤ 0.31 mg $L^{-1}$, chlorophyll-a ≤ 2.1 ug $L^{-1}$), causing persistent low dissolved oxygen and extreme algae and plant growth. Aquatic vegetation and algae have been able to thrive in the nutrient rich waters, covering approximately 95% of the pond sediment and water surface. Further, the cranberry irrigation and flooding operation periodically reduces the amount of flushing that occurs in Mill Pond, by reducing the flow of water through the pond. Slow moving water allows for increased particle settling and longer contact time at the sediment-water interface, increasing the opportunity for denitrification to occur, but also allowing the plant community extended access to available nutrients. In the case of Mill Pond, the high organic matter settling (~900 kg organic carbon) and high density of dead macrophyte material causes a high biological oxygen demand when it begins to decompose. During warmer months, when lower groundwater levels and lower stream flows often lengthen the residence time of water in the pond, more rapid warming of shallow waters causes intermittent temperature stratification and creates conditions for significant loss of dissolved oxygen in deeper waters. The low dissolved oxygen conditions in pond bottom waters results in noxious odors, release of phosphorus and ammonium from the sediments, a hypoxic/anoxic environment that is unsupportive for most organisms (particularly fish), and prevents denitrification from occurring in the sediments. The flushing time of Mill Pond is most important during the critical warmer months, June – September. This assessment revealed that cranberry irrigation during a dry summer (2016), will reduce the flow of water through the pond, increasing water residence time and lowering the pond level. However, in a wet summer (2017), the irrigation practices caused relatively little change in the flow of water through the pond, so water residence time and water levels stayed relatively consistent throughout the year. Based on the results of this investigation, Mill Pond is phosphorus-limited and management of the phosphorus load during critical summer months (June - September) is required. As part of the management strategy, it will be important to maintain or increase the high level of nitrogen attenuation in the pond for the health and restoration of Green Pond.

The impaired water quality in Mill Pond reflects both external and internal inputs of nutrients with Backus Brook stream input being the largest contribution. Management strategies to address the impairments must also address community acceptance, costs, and any potential downstream impacts on Green Pond. With all these considerations in mind, the CSP technical team recommends implementing several measures to improve water quality in Mill Pond:

*(1) Potential Changes in Upstream Cranberry Bog Operations*. Changes in cranberry bog operations upstream of Mill Pond have the potential for significant improvement to the pond water quality. As noted in the nitrogen and phosphorus budgets, Backus Brook is the primary source of both nutrients to Mill Pond. Given that cranberry bogs are often located along streams, strategies to address downstream transfer of nutrients have been reviewed at several bogs. A preferred option to preventing particle and plant debris transport into Mill Pond is to construct a 0.25+ acre detention pond

above the Mill Pond culvert, allowing plant debris, and particulates to settle out before entering Mill Pond, reducing the particulate N and P loads possibly 192 and 40 kg $yr^{-1}$ respectively (Figure IV-1). This management alternative has been discussed with the bog owner, who is supportive of this option. CSP scientists also observed a lack of flushing during the harvest and winter bog floods, so it is recommended that boards placed for the floods be placed to exactly the height necessary to complete cranberry harvest and preserve the plants during winter. This adjustment would allow greater flow from the bog to the pond during the harvest and winter flood periods, thus helping flush the pond. Discussions with the bog owner indicated that this would be possible, but that the improvement in flushing would be dependent on the specific annual flows. Other recommendations included: a) alternating between "low P" and "no P" fertilizers to help reduce the P export from the bog (should have relatively little impact to the bog operation or harvests), b) removing the flood boards one at a time over a couple days to keep water velocities low and prevent scouring and mobilization/export of fine particles in the bog channels, and c) placing a metal grate between the bog and pond to catch debris and prevent the transport of plant detritus to Mill Pond (will require regular seasonal cleaning). Overall, these recommendations were discussed with the bog owner and he indicated a willingness to adjust some of the practices within his operation as part of a plan to improve the health of Mill Pond.

*(2) Pond Macrophyte Management.* As the macrophytes grow from March to October, they take up approximately 453 kg of nitrogen and 10 kg of phosphorus. This organic nitrogen and phosphorus is shifted to the sediments when the macrophytes die. As the macrophytes decay, the bacterial community consumes the oxygen in the overlying waters and if oxygen is sufficiently low, the macrophyte-associated nutrients are released back into the water column. Given the large macrophyte biomass currently growing in the pond each summer and the biological oxygen demand it represents, it is recommended that a macrophyte harvesting program be considered as an part of an adaptive management approach to lowering phosphorus levels of Mill Pond. Harvesting would likely occur only occasionally, and could be reduced once phosphorus levels drop sufficiently. This type of approach is currently used by the Town of Brewster (C. Miller pers. Comm.) and the Mill Pond approach could use guidance and protocols from their use. Permitting would likely have to further refine the implementation details. As the Town of Brewster has its own plant harvester, CSP staff have begun investigating this option for Mill Pond and potential access to the harvester. While the ultimate solution will require reducing nutrient inputs, macrophyte harvesting can accelerate the process. It should be noted that macrophyte harvest should be completed in the late summer/early fall to maximize biomass/P removal and conform to any time of year restrictions that might apply to Mill Pond for fish passage. If the macrophyte harvesting is performed during cranberry harvest when the water residence time of the pond is usually longer than 7 days, it will allow maximum deposition of any resuspended particles, preventing transport downstream to Green Pond. Additionally, the pond level will be low due to water usage for bog flooding, allowing for easier removal of macrophytes. Macrophytes nutrient removal can be measured by analyzing the plant material removed. If only conducted every few years new macrophyte growth will continue to take up nitrogen, carbon, and phosphorus in the sediments resulting in further "stored" phosphorus removals, potentially leading to higher pond dissolved oxygen levels over time which will have a major positive impact on reducing summer phosphorus loading to the water column. In addition, improving the sediment environment will also help improve nitrogen removal by denitrification, which would improve Green Pond to the extent it increases current nitrogen attenuation.

*(3) Reducing Sediment Phosphorus Regeneration and Improving Bottom Water Oxygen.* The regular anoxia in the bottom waters of Mill Pond is reflective of impaired conditions, including being well less than the MassDEP minimum for warm surface waters [5 mg/L; 314 CMR 4.05(b)]. Anoxia is due to the large amount of decaying biomass in the sediments and the anoxia creates conditions that favor the regeneration of nutrients into the water column, as well as the potential for nuisance conditions, such as release of hydrogen sulfide gas (*i.e.*, rotten egg smell). Measurements during the current effort indicated that the anoxic conditions contributed to the seasonal re-release of 10 kg of phosphorus and 184 kg of nitrogen into the Mill Pond water column. The re-release was the second largest phosphorus source to Mill Pond after the upstream additions from Backus Brook. Potential ways to address bottom anoxia in freshwater Cape Cod ponds typically include aeration/enhanced mixing, Alum applications, or dredging. These approaches are typically considered together with estimates of costs, discussion of implementation details, and regulatory permitting. As an example, an aerator would add oxygen to the bottom waters to address the biological oxygen demand in the sediments and higher DO concentrations would minimize the chemical conditions that cause the regeneration of nutrients. Use of aerators in freshwater ponds typically remove between 1/3 and 2/3 of regenerated phosphorus; performance will be dependent on the details of the aerator design and characteristics of the pond. Details of the aeration system could be developed through a public procurement and permitting process; there are a number of designs for aeration systems. Issues to address typically include pure oxygen or air addition, source of power (shoreline or solar), and community acceptance of impacts (*e.g,* costs, noise, and visual impacts, such as surface machines, shoreline generators or water surface disturbance). Alum (aluminum sulfate) application to pond sediments has also been found to be effective in lowering phosphorus levels in the 10 Cape Cod ponds/lakes where it has been used (e.g. Ashumet Pond, Hamblin Pond, Long Pond, etc.). Alum is used in ponds that might experience anoxia as it forms an insoluble precipitate that binds with phosphorus under both oxic and anoxic conditions. As opposed to iron which only works in oxic environments. In Mill Pond an alum treatment would reduce the phosphorus sediment regeneration by 70%, and a single application should last for approximately 10 years. The aerator also holds the phosphorus in the sediments but must be maintained for ~6 months per year forever. Either method should work in the case of Mill Pond, the only difference is the operating and maintenance expenses. Overall, an in pond action (aeration or alum) combination with proposed reductions in input sources e.g. cranberry bog management changes and in pond plant harvesting should provide a solid basis to restore Mill Pond. Implementation of management alternatives needs to have ongoing monitoring to support adaptive management, since over time if source reductions are implemented and in pond options are implemented, the in-pond actions may be able to be reduced or stopped. For example, the Alum treatment might last 20+ years.

*(4) Removal of Dam at Route 28.* Per request, the removal of the dam at Route 28 was evaluated as a potential management option. The concept would be to remove the dam, draining the pond and creating a small freshwater wetland. Implementing this option, would remove the ecological problems that the pond is experiencing, by removing the pond itself, which may have public resistance, given the public's interest in restoring the pond to past water quality. However, the main issue to be examined is the impact of removing the dam on Green Pond water quality. Shifting from a pond to a freshwater wetland has uncertain impacts on nitrogen removal. Freshwater wetland can either remove nitrogen or be net contributors of nitrogen to outflowing streams. In this case, to Green Pond. There are numerous studies showing either freshwater wetlands as sinks or sources of nitrogen, as has been found in s.e. Massachusetts by the Massachusetts Estuaries Project. As a pond, Mill Pond is currently attenuating

64% of the watershed nitrogen flowing through it before it discharges to Green Pond. Removing this attenuation would increase the nitrogen load to the nitrogen enriched waters of Green Pond by up to 1,400 kg N yr$^{-1}$.This represents additional nitrogen that would have to be removed from the watershed to meet the Clean Water Act requirements (TMDL). This additional nitrogen removal may be less than 1400 kg N yr-1 to the extent that the freshwater wetland may take up some nitrogen, but it is highly unlikely that it will be as effective as the current pond. Therefore, resources will have to be made available to implement other nitrogen removal technologies (sewering, IA system, etc.) will be required, in order to reduce the nitrogen load to the existing nitrogen load from the Backus Brook sub-watershed to Green Pond. Given the uncertainties in future attenuation rates, public acceptance of a wetland vs pond and likely costs, removing the dam is a low priority option and cannot be recommended at the present time.


Figure IV-1 Recommended location for a detention pond above the Mill Pond culvert to prevent particle and macrophyte debris transport. Site is part of the existing bog system.

Table IV-1. Possible N and P reduction (% of total inputs), cost, benefit, and level of effort associated with the recommended management scenarios. All options will reduce phosphorus into Mill Pond, the exact amounts required further analysis, but all were selected to have at least a 5-10% P reduction. *Pond aeration systems are effective for N and P reduction during operation.

| Management Recommendations | Possible N and P Reduction % | Cost | Effort | Benefit |
|---|---|---|---|---|
| **Bog alternates b/w "low P" and "no P" fertilizers** | 5-10% | Low | Low | will provide some reduction of P load from bog |
| **Slow Release of Bog Flood Water** | 5-10% | Low | Low | **a)** prevent debris export from channels, **b)** nutrient pulse into pond |
| **Increase Flow during Harvest & Winter Floods** | 5-10% | Low | Low | **a)** Increase turnover and nutrient attenuation |
| **Grate b/w Bog and Pond** | 5-10% | Low | Medium | prevent N and P in plant debris export |
| **Construct Detention Pond** | 15-50% | Medium | High | catch plant and bog debris, particulates |
| **Macrophyte Harvesting** | 15% | High | High | **a)** reduce recycled nitrogen, **b)** phosphorus **c)** decaying macrophyte biomass in pond; improves use of pond for recreation |
| **Aluminum Application** | 70% P<br>0% N | Medium | Low | reduce sediment P release |
| **Pond Aeration System*** | 15-30% | Medium | Low | **a)** reduce noxious smell of low oxygen, **b)** reduce sediment P release, **c)** decrease sediment N release, **d)** increase denitrification |

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# V. APPENDIX

*Appendix A – Mill Pond Sub-watershed*

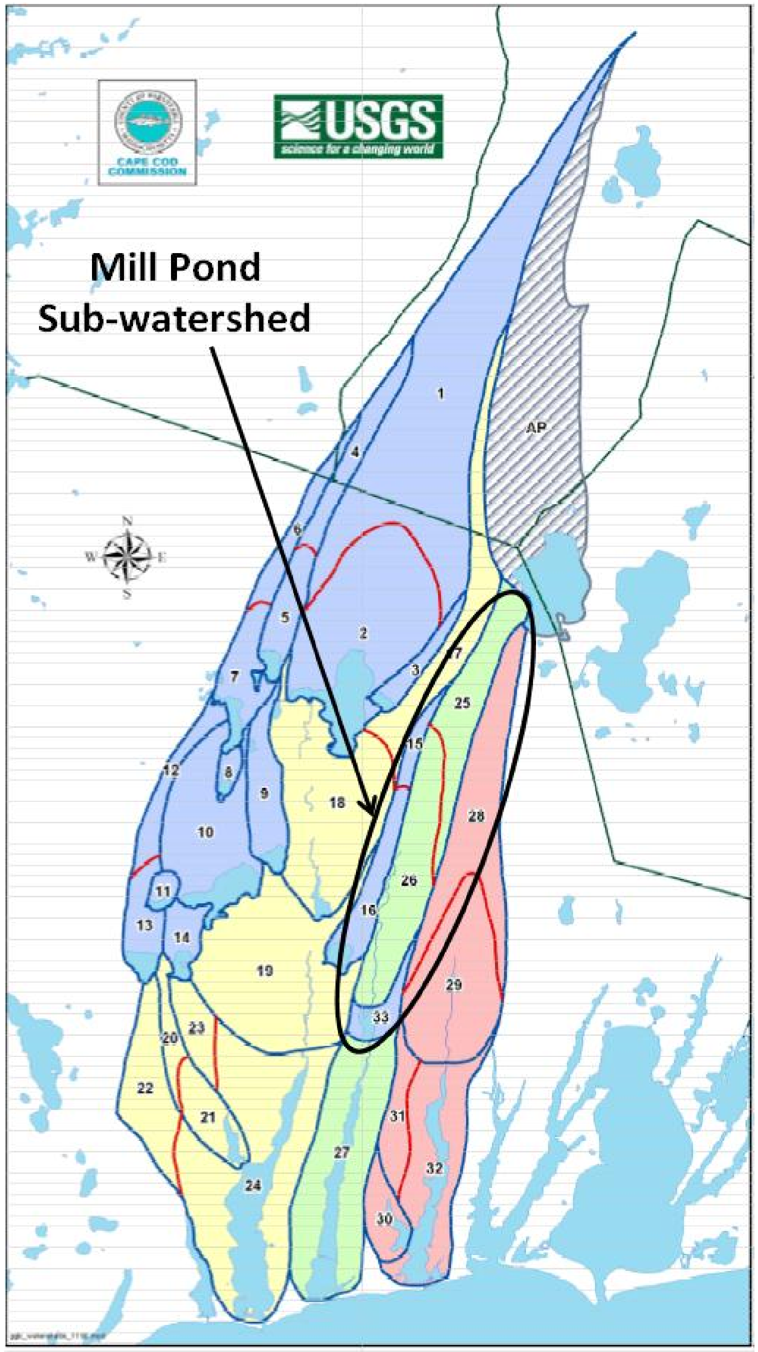
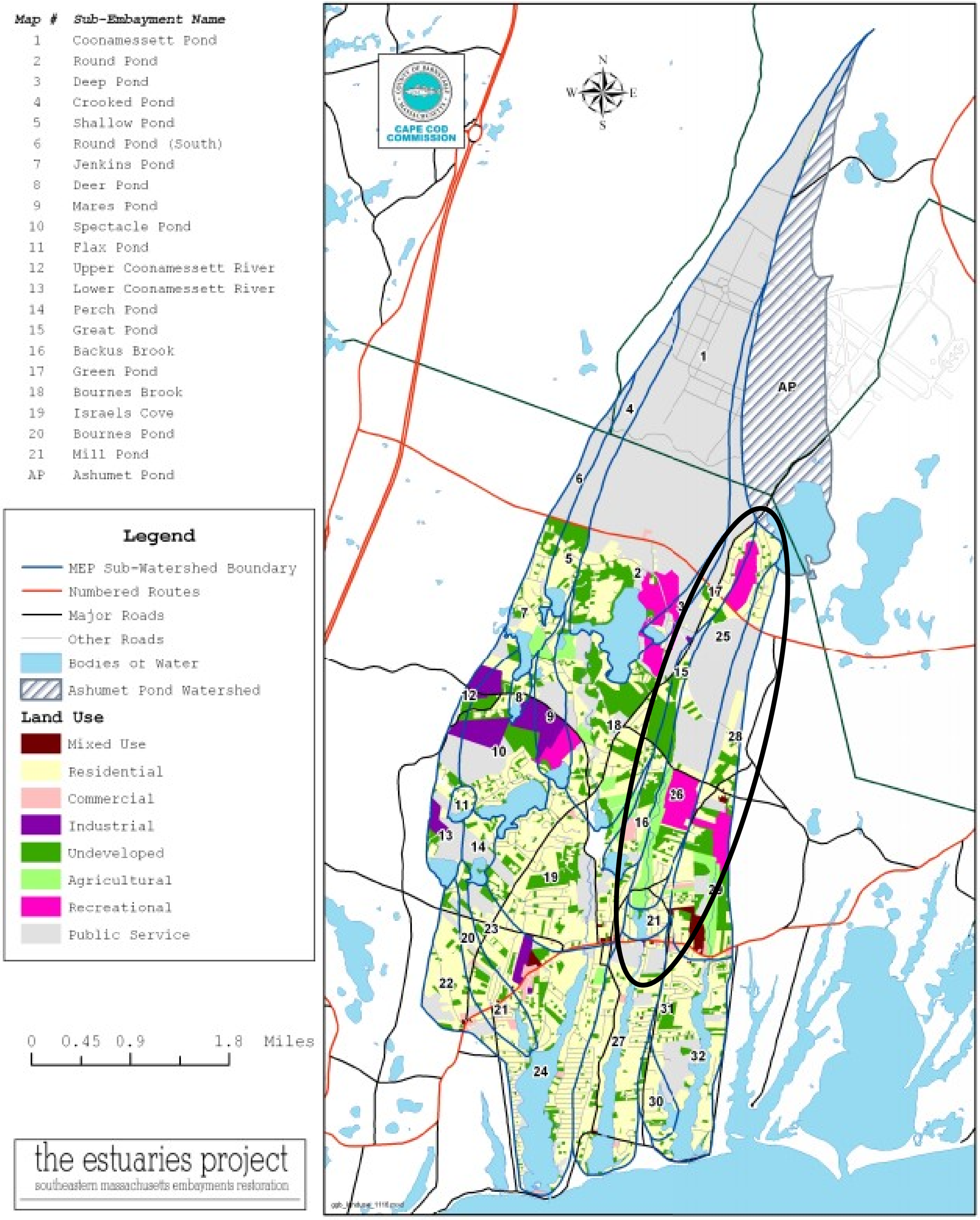
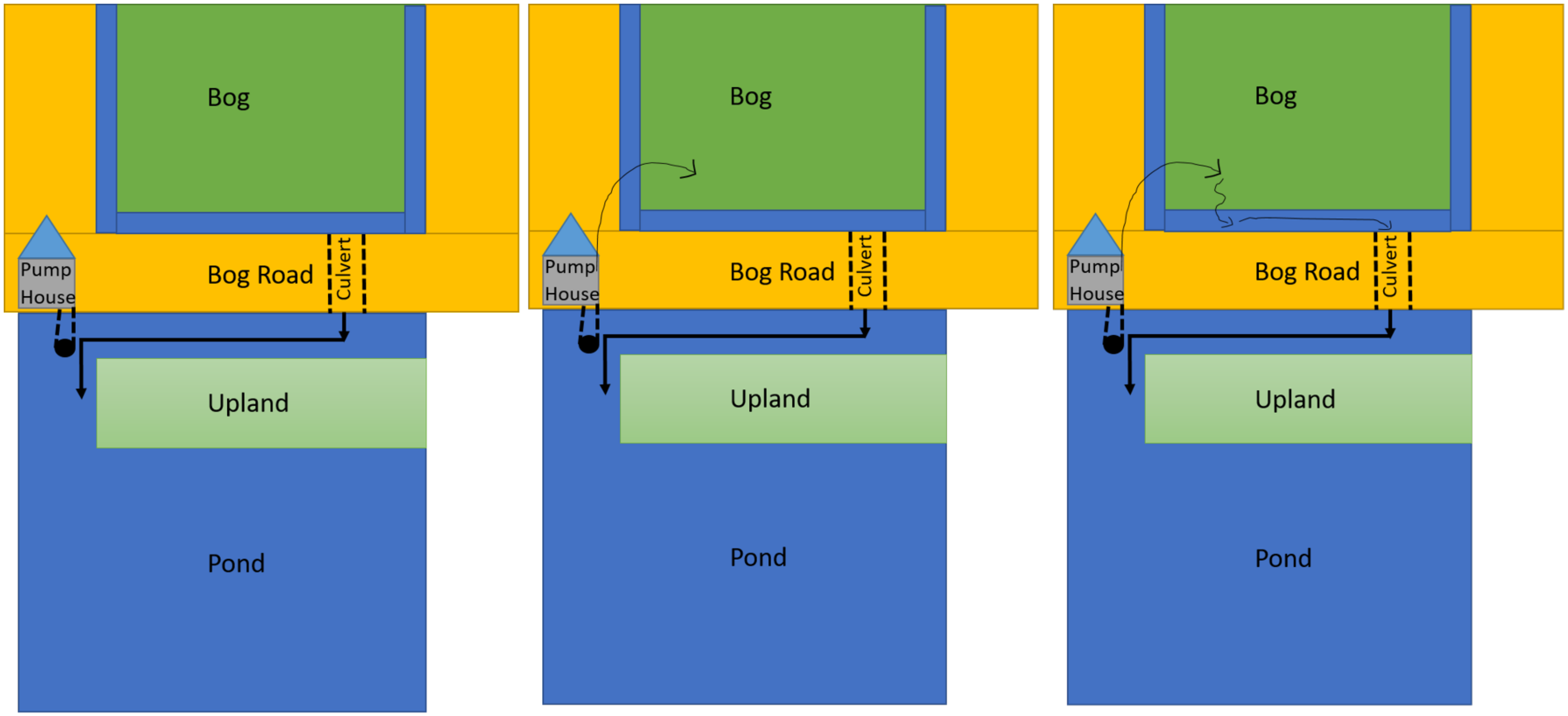



Figure V-1. Mill Pond and associated subwatersheds that will receive updated Land-use loading analysis: subwatersheds 25, 26, and 33.

*Appendix B – Mill Pond Sub-watershed Land-Use Map*



*Appendix C – Potential Flow Dynamics of Backus Brook to Mill Pond and Bog Irrigation*




Normal
Water flow when pump is not irrigating

Flow Constant and Stage Decreases
Irrigation decreases stage in channel and the water stays on bog

Flow Increase and Stage Decrease
Irrigation causes lower stage in channel and runoff from bog increases flow in culvert

Figure V-2. Schematic of possible flow dynamics for Backus Brook to Mill Pond stream flow.

*Appendix D – Project Schedule*

**Table V-1.** Project schedule.

| Task | Task Description | May | Jun | July | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | June |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **Update Mill Pond Watershed Land-use Loading** | | | | | | | | | | | | | **DONE** | |
| **2** | **Quantification of Surfacewater Flow and Nutrient Load In/Out of Mill Pond** | | | | | | | | | | | | | **DONE** | |
| **3** | **Determination of Water Residence Time in pond and Degree of Mixing** | | | | | | | | | | | | | **DONE** | |
| **4** | **Sediment Nitrogen and Phosphorous Regeneration / Loading plus Denitrification** | | | | | | | | **Biogeochemical Analysis** | | | | | **DONE** | |
| **5** | **Analysis of Dissolved Oxygen Conditions in Mill Pond** | | | | | | | | | | | | | **DONE** | |
| **6** | **Rooted Plant Survey** | | | | | | | | | | | | | **DONE** | |
| **7** | **Reporting and Project Management** | | | | | | | | | **Synthesis and Report - DONE** | | | | **Meetings** | |

*Appendix E – Letter and Survey to the Bog Operator*

UMASS-Dartmouth School for Marine Science and Technology

New Bedford, MA

**Diagnostic Assessment of Nutrient Cycling in Mill Pond**

Dear Bog Operator:

I am writing to you to ask if you would assist the Town of Falmouth and the University by providing information related to the feasibility of improving the ecological health of Mill Pond, the freshwater basin before the Backus Brook discharges to the head of Green Pond. I have provided a brief overview of the project below, but if you have any questions, please feel free to call the Coastal Systems Program at UMASS-Dartmouth School for Marine Science and Technology (508)-910-6325 or email at aunruh@umassd.edu.

The purpose of the study is to complete a Diagnostic Assessment of Nutrient Cycling in Mill Pond. Mill Pond is a constructed freshwater pond, immediately up-gradient of the head of the Green Pond Estuary. Mill Pond is a flow through pond receiving inflow via Backus Brook from the inland watershed and discharging through a culvert under Rt. 28. While the Town has been working for several years on restoration of the Green Pond Estuary, only recent concerns have been raised about the declining ecological health of freshwater Mill Pond. This 16 acre freshwater pond is currently exhibiting signs of severe habitat impairment (over-abundance of aquatic plant growth, bottom water anoxia and extremely poor water clarity) most likely due to nutrient over-enrichment, possibly related to historic inputs from the watershed which are stored in the pond sediments. As such, it has been the subject of preliminary assessment efforts by SMAST scientists over the past year.

As part of the preliminary assessment and citizen concerns, CSP-SMAST was asked by the Town of Falmouth to complete a study to understand the role new versus recycled nutrients are having in driving the observed habitat impairment as well as determine appropriate management actions that might be taken to affect restoration of this aquatic system. Specifically, the study will aim to quantify the nitrogen and phosphorus inputs to Mill Pond from its watershed (surface and groundwater) as well as in-pond measurement of recycling of nitrogen and phosphorus from sediment regeneration. In addition, dissolved oxygen conditions in the pond bottom water and how they may accelerate phosphorus release to pond waters and resulting distribution and density of aquatic plants are being assessed. These activities coupled with ongoing hydrologic monitoring will more fully define the sources and sinks of nitrogen and phosphorus to the pond thus allowing the development of a detailed nutrient budget and water balance for the Mill Pond system. These efforts all form the basis for formulating a list of management strategies and a comparison of their cost and practicality for restoring the water quality in this system. While improving Mill Pond, attempts will also be made to ensure that whatever management actions are undertaken that the pond maintains (or increases) its current nitrogen removal capacity to protect the down gradient Green Pond Estuary.

If you are willing to assist in these efforts, we are only asking that you take 15 minutes in answering the questionnaire below pertaining to your knowledge of bog maintenance.

The decision to participate in this research project is voluntary. You do not have to participate and you can refuse to answer any question. Your name will not be public unless you indicate otherwise on the Questionnaire. Thank you.

Coastal Systems Program (SMAST)

**Bog Maintenance Questionnaire for Mill Pond Falmouth, MA**

1. Do you want your participation and/or responses to remain confidential? Yes No
2. Will you be willing to provide any maintenance records for irrigation and/or fertilizer application?
3. How long has this been an active bog? ____________years
4. Do you know the history of Mill Pond construction/ use for bog irrigation?

Water Use Questions

1. Do you irrigate the whole bog system using Mill Pond water?
2. How often are the bogs flooded by boarding the culvert to Mill Pond? ______per year
3. Is there a record of when the boards are placed and pulled between the bog and pond?
4. Have boards been placed or pulled from the weir at the bottom of the pond next to RT. 28?
5. How often is water pumped from Mill Pond to the bog? _____per year
6. Do you irrigate the bogs the same way every year?
    a. 2015?
    b. 2016?
    c. 2017?
7. Do you know the flow rate of the water pump and tractor pump?

Fertilization

1. How much fertilizer is applied? ____________
2. Do you use low P fertilizer (N%/P%/K%)? _____________
3. Do you apply the fertilizer with irrigation?
4. Which time(s) of the year is it applied? (circle all that apply)
   Early Spring Late Spring Early Summer Late Summer Fall
5. Do you use approximately the same amount of fertilizer every year?

Bog Maintenance

1. How often are the bog ditches mowed? ______per year
2. Are they cleared of debris?

3. Would you be willing to use a grate between the bog and the pond to prevent transport of plant debris to Mill Pond?

Thank you very much and I appreciate the time you have taken to help me gather data for my thesis.

If you are willing to provide any or all maintenance records for the bog. Please send with this questionnaire to:

Amber Unruh
706 Rodney French Blvd.
New Bedford, MA 02744

Phone: 508-910-6325
Email: aunruh@umassd.edu

If you have any additional information that wasn't covered in the questionnaire, but you would like to provide, please do so here.

NOTES: