Santuit Pond Baseline Monitoring, Sediment Coring, and Nutrient Inactivation Dosing Study

Santuit Pond, Mashpee, Massachusetts

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Prepared For:

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1. Introduction

Santuit Pond is an approximately 176-acre Great Pond located entirely in the town of Mashpee, Massachusetts. The pond serves as the headwaters of the Santuit River, which originates as the outlet at the pond's southernmost end and flows south into Shoestring Bay. As with most of Cape Cod, Santuit Pond is located in an area of thick glacial outwash deposits. As a result, the pond is primarily groundwater-fed and has no permanent surface tributaries, although surface flows may reach the pond in the form of stormwater runoff.

Under the *Final Massachusetts Integrated List of Waters for the Clean Water Act 2018/2020 Reporting Cycle* (MassDEP 2021), Santuit Pond is listed as a Category 5 water body (i.e., needing a TMDL) and is impacted by the following impairments:

1. Fish passage barrier
2. Abnormal fish deformities, erosions, lesions, tumors
3. Chlorophyll-a
4. Harmful algal blooms
5. Nutrient/eutrophication biological indicators
6. High pH
7. Total phosphorus
8. Transparency/clarity

With the possible exception of the first two, these impairments are highly interrelated. For example, excessive total phosphorus is likely to result in eutrophication and harmful algal blooms, which likewise result in high concentrations of chlorophyll a. These impairments, in turn, reduce transparency and can lead to high pH levels. This suggests that the reduction of phosphorus concentrations in Santuit Pond could have cascading benefits to multiple impairments.

In the recently completed *Focused Feasibility Study of Santuit Pond* (ESS 2022) a number of in-pond management options were evaluated as means to improve water quality over the short term while watershed controls (septic and stormwater) come online to provide longer term reductions in nutrient loading. One of the primary recommendations was to investigate the potential benefits from nutrient inactivation (e.g., alum treatment) that targets internal release of phosphorus from the sediments.

Internal recycling of phosphorus through release of available sediment phosphorus fractions was previously documented in the 2010 *Santuit Pond Diagnostic Study* (AECOM). The key findings of that study related to internal loading were as follows:

- Despite shallow depths and frequent mixing, dissolved oxygen depletion still occurs in bottom waters. This allows release of phosphorus from sediments into the waters of Santuit Pond (internal loading).
- The total phosphorus load to Santuit Pond is approximately 380 kg/yr, which is equivalent to an annual in-pond phosphorus concentration of 80 µg/L. Most of this (78%) is from internal loading.
- Available fractions (i.e., iron-bound and loosely-sorbed fractions) of phosphorus in the sediment were found to be high (i.e., >300 mg/kg dry) in three of the four sediment core locations sampled.

While helpful, these observations are more than a decade old. Therefore, prior to recommending additional in-pond management, the SNEP Network, in concert with project partners (the Mashpee Wampanoag Tribe and Town of Mashpee), requested that TRC provide an update to on the current conditions in the pond, including but not limited to a reassessment of phosphorus in Santuit Pond sediments.

The overall goals of this Project were as follows:

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1. Collect water quality data to document an additional baseline data point and build upon existing information that indicates water quality issues in Santuit Pond; and

2. Collect sediment cores to establish an up-to-date dataset of phosphorus availability from Santuit Pond sediments and determine the optimal nutrient inactivation dosage to address excessive phosphorus loading.

The study approach, results, and recommendations are provided in the following sections.

2. Approach

TRC, accompanied by Dr. Keith Pilgrim of BEC Engineering & Geology, PC (BEC), visited Santuit Pond on June 10, 2022 to collect water quality data and sediment cores. Each element of the field program is described in more detail in the following sections.

2.1. Water Quality Baseline Monitoring

During the field sampling event, water quality samples were collected within one meter of the surface and bottom of the deepest part of Santuit Pond for a total of two samples at one location (Figure 1). Additionally, water quality profiles were measured in situ within the water column.

The geographic coordinates for each sampling location were recorded using a Differential Global Positioning System (DGPS) in the NAD83 Massachusetts State Plane Coordinate system.

Water quality samples were sent to qualified analytical laboratories for analysis of the following:

- Total Phosphorus – (two grab samples)
- Chlorophyll a – (two grab samples)

Additionally, the following parameters were field-measured using calibrated instruments:

- Secchi Disk Transparency – surface only
- Water Temperature – full vertical profile at 0.3 m increments
- Specific Conductance – full vertical profile at 0.3 m increments
- Dissolved Oxygen – full vertical profile at 0.3 m increments
- pH – full vertical profile at 0.3 m increments

For quality assurance purposes, duplicate samples and field measurements were collected at a minimum of a 10% rate.

2.2. Sediment Coring and Phosphorus Fractionation

Five sediment cores were collected using a gravity coring device (Willner-type coring device) modified to allow for the extrusion of sections from each core (Figure 2). Coring locations SCP1, SCP2, and SCP3 were targeted in areas that had previously been sampled as part of the 2010 *Santuit Pond Diagnostic Study* (AECOM 2010) while locations SCP4 and SCP5 were selected to provide a more representative distribution of samples from previously unsampled areas of the pond (Figure 1). The southern cove of Santuit Pond was excluded from sampling, as the Army Corps of Engineers is currently investigating this area for a potential dredge and fill habitat restoration project.

Once retrieved, each core was sliced on-site in 2 cm increments for the top 10 cm of sediment. Additional sections were taken from each core at 14 to 15 cm and 19 to 20 cm deep. The top layer of sediment is typically the most active layer, where phosphorus releases to the water column (internal phosphorus loading) while the deeper sediment provides an indication of background conditions. The ratio of the deep and shallow phosphorus concentrations provides information on the decay rate over time.

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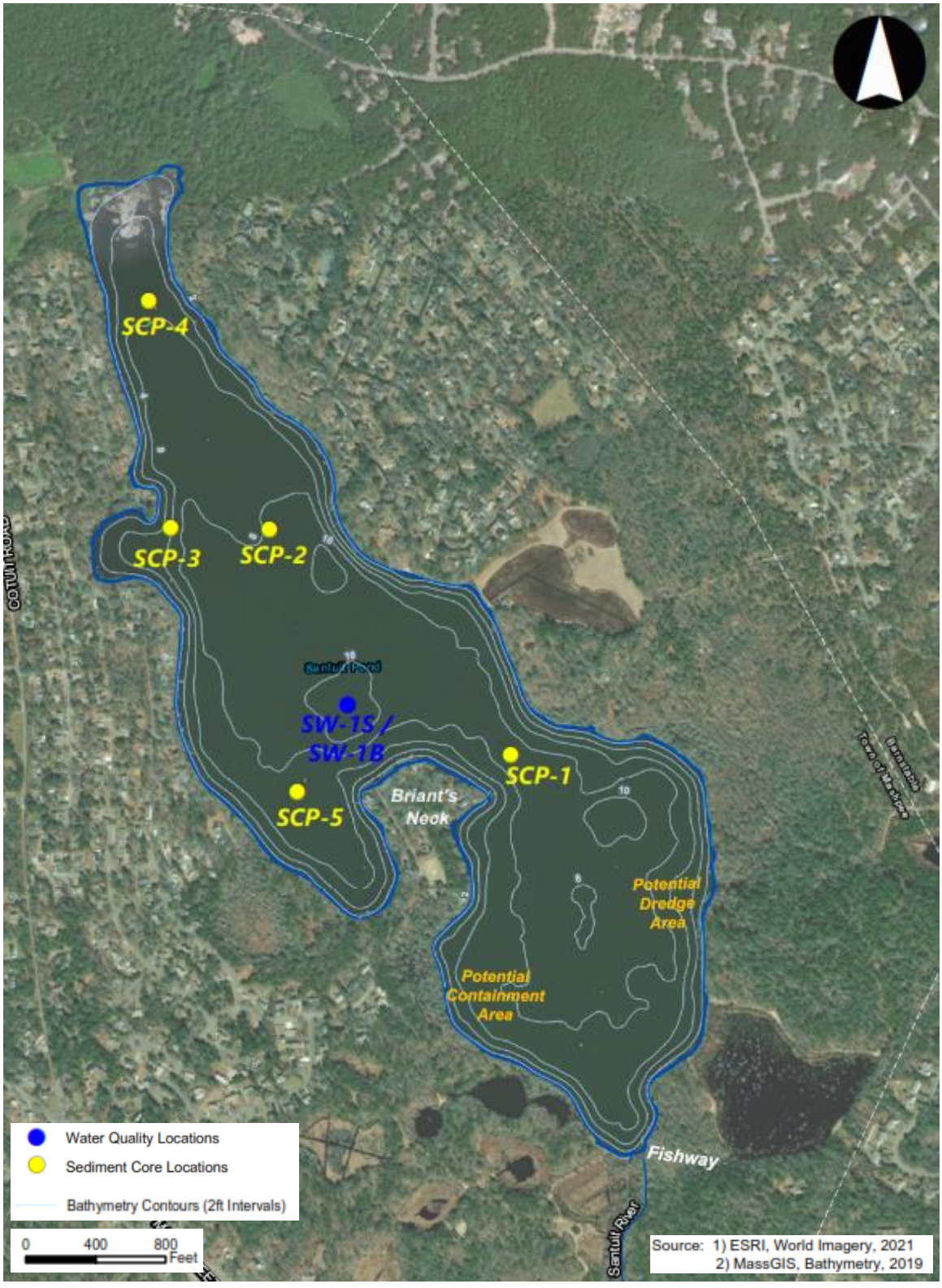

Figure 1. Sampling Locations

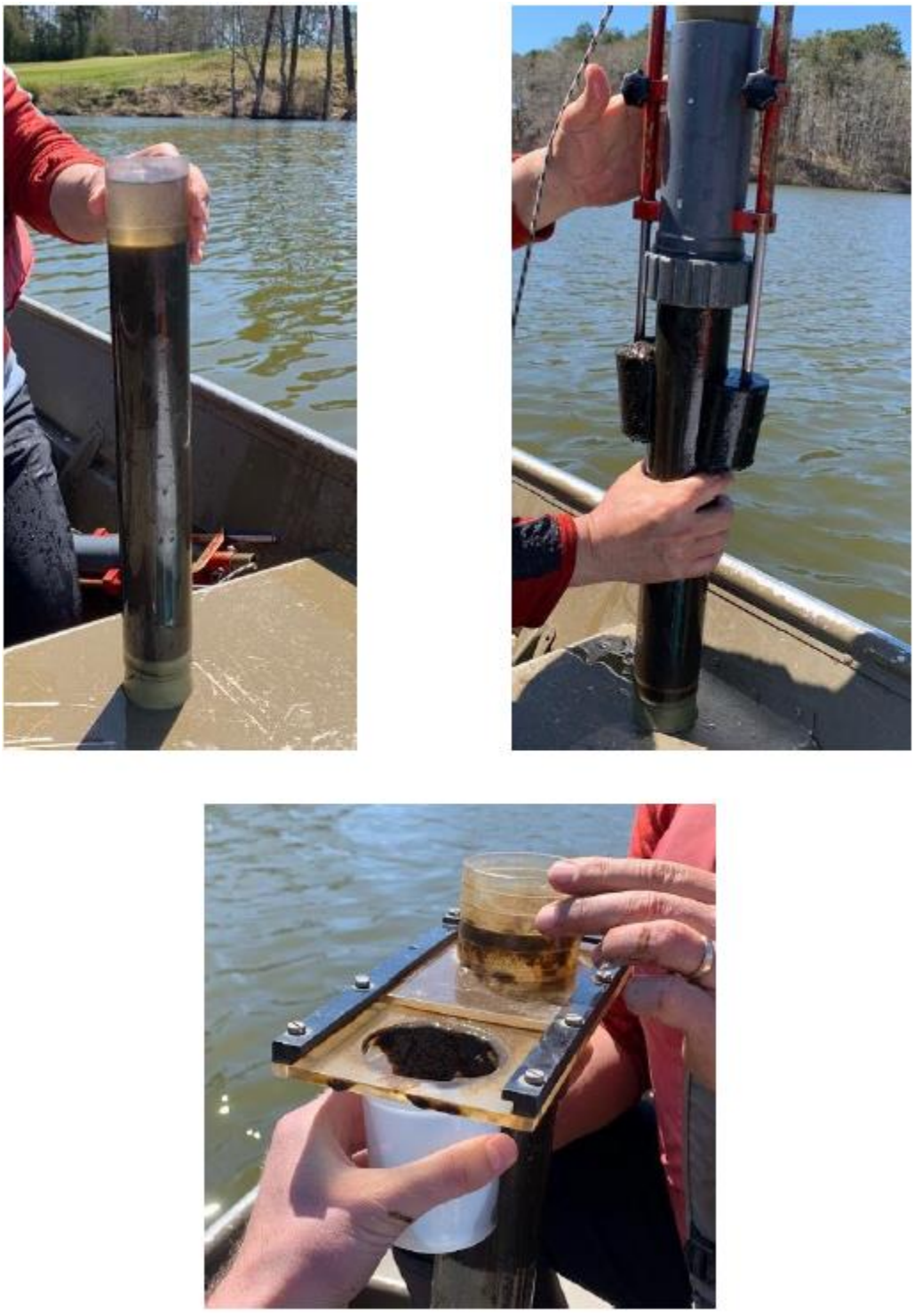

Figure 2. Willner-type Coring Device in Use
Clockwise from upper right: the coring device upon retrieval at the surface, the core slicing head used to section the core, and the full core showing the sediment-water interface.

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In total, 35 sections (i.e., 7 sections per core) were obtained. Sections were shipped on ice to the BEC phosphorus fractionation laboratory, where they were analyzed for different phosphorus forms or "fractions" according to the sequential fractionation method published by Psenner and Pucsko (1988). Phosphorus in bottom sediments is typically either bound to inorganic chemicals (e.g., calcium, manganese, iron, magnesium, and aluminum) or incorporated into organic matter (e.g., DNA, lipids, and phosphonates). Sequential fractionation makes use of acids, bases, reducing compounds, and an oxidizer to release these different types of phosphorus sequentially, and quantify the amount of phosphorus bound to iron and manganese (Fe-P), calcium and magnesium (Ca-P), and aluminum (Al-P), as well as the amount incorporated into organic matter (Org-P). The process is summarized in Figure 3.

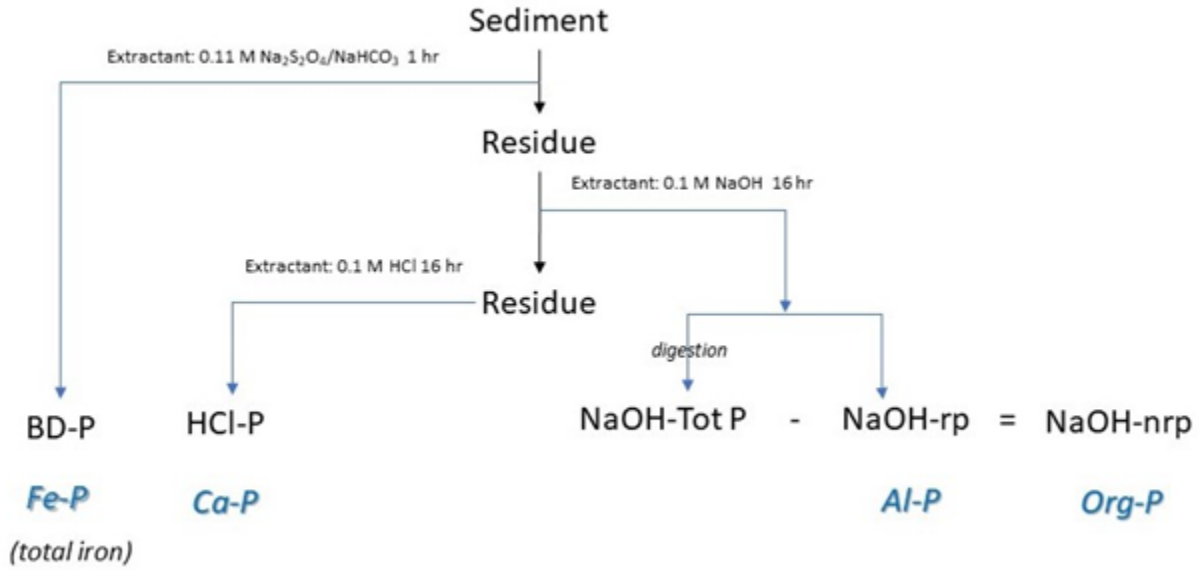

Figure 3. Simplified Phosphorus Fractionation Scheme for Lake Bottom Sediments

In the natural environment, the dissolution of Fe-P in bottom sediments is responsible for most of the internal phosphorus release and loading to the water column when dissolved oxygen is low. However, the Org-P fraction decomposes as a function of temperature and can also contribute to internal loading where iron and dissolved oxygen levels are too low to recapture and bind it in the sediments as Fe-P. In contrast, Al-P and Ca-P fractions are stable under the environmental conditions present in most pond sediments, even when dissolved oxygen is not readily available.

In addition to the phosphorus fractionation analysis, each sample was also analyzed for moisture content, loss on ignition (percent carbon), and density. Total iron was analyzed from the Fe-P extraction.

For quality assurance purposes, duplicate samples were analyzed at a 10% rate.

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3. Results

Results of the water quality baseline monitoring and sediment phosphorus fractionation analysis are presented in the following sections.

3.1. Water Quality Baseline Monitoring

Dissolved Oxygen

As in terrestrial ecosystems, oxygen is required to support respiration in most life associated with aquatic ecosystems, including plants, algae, fish, invertebrates, and many other life forms. Oxygen dissolves in water at a rate inversely related to temperature; solubility increases with decreasing water temperature.

Additionally, the concentration of dissolved oxygen impacts chemical processes in water. Metals, such as iron and manganese, may become more soluble in their reduced forms, which dominate under anoxic conditions. Similarly, nutrients like phosphorus may be released at a higher rate from bottom sediments when dissolved oxygen is low.

In Massachusetts, the state instantaneous dissolved oxygen standard for support of warmwater fisheries in Class B waters is 5.0 mg/L (or as naturally occurs).

At Santuit Pond, dissolved oxygen values were within the standard at the surface and through the top eight feet of the water column (Figure 4 and Table 1). However, they did not meet the standard at the bottom of the water column during the June baseline monitoring event, where conditions were hypoxic (i.e., low dissolved oxygen).

This profile represents a single snapshot and should be interpreted with caution. Other factors to consider in evaluating the severity and potential impact of the observed hypoxic conditions at the bottom of Santuit Pond include:

1. Dissolved oxygen concentrations typically exhibit a diel cycle because they are influenced by photosynthesis, which produces oxygen. Levels tend to peak during the day, when plants and algae are exposed to light, and decline at night, when photosynthesis ceases. The profile collected for this study was measured mid-day and therefore is unlikely to reflect the lowest point in the diel dissolved oxygen cycle. Based on recent continuous sonde data provided by project partners for Santuit Pond, dissolved oxygen in Santuit Pond is likely to drop below 5 mg/L on some nights, even in the top three feet of the water column.
2. Water temperatures would be expected continue to warm further and persist through July and August. Warmer temperatures would be expected to increase biochemical oxygen demand while also lowering the saturation point of oxygen in water, thereby resulting in a net decrease of dissolved oxygen. The profile collected for this study was measured in early June, when temperatures where close to 22°C at the surface. Based on recent continuous sonde data provided by project partners for Santuit Pond, water temperatures are likely to near or exceed 30°C at the surface during portions of the warmest days.

Given these factors, the observed condition during the baseline monitoring event is likely to underestimate the full extent of hypoxic to anoxic conditions in the water column of Santuit Pond during the growing season.

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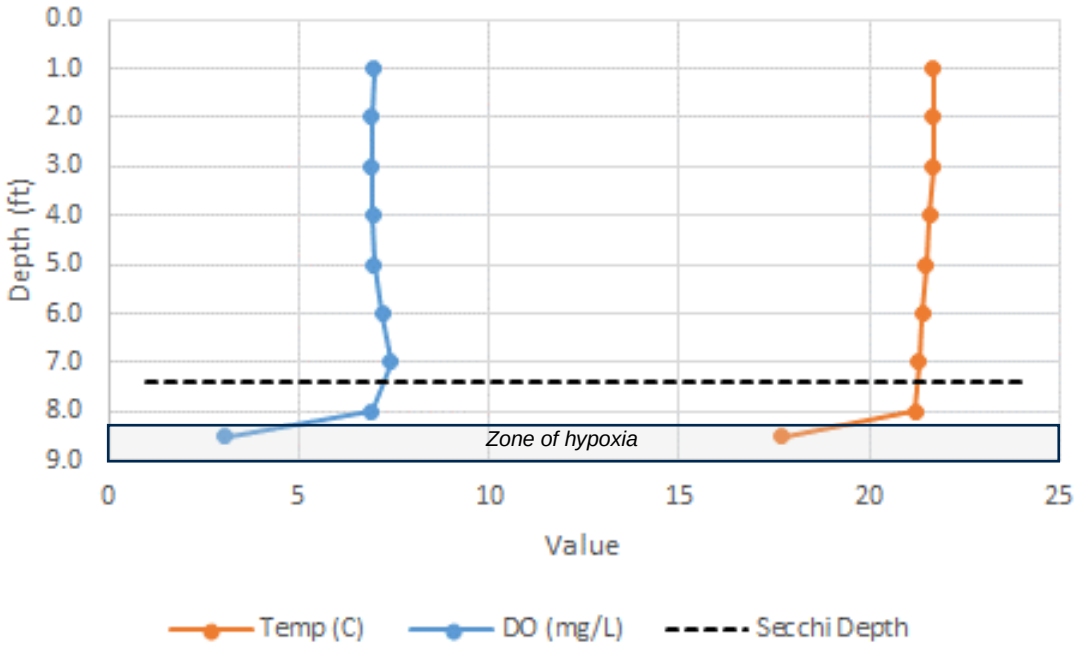

Figure 4. Temperature and Dissolved Oxygen Profile in Santuit Pond, June 10, 2022

Specific Conductance

Conductivity is a measure of dissolved ions (salts) in the water. Pavement deicing is one of the most obvious sources of human-derived conductivity, although landscape practices (such as liming and fertilization), septic systems, and treated wastewater discharges, among other contributions may also serve as sources. Salt spray is a natural factor that can also increase specific conductance levels in ponds along near the coast.

Measurements of specific conductance in Santuit Pond were approximately 150 µS/cm, which is consistent with continuous sonde data collected by others at Santuit Pond in prior years. This level of specific conductance suggests that dissolved ionic pollutants (i.e., salts) have likely had some impact on water quality in the pond. However, the measured levels are not extreme for a recreational water body and not unexpected given the year-round residences along much of the shoreline and the number of roads in the vicinity.

pH

The pH of water indicates whether it is acidic (< 7 SU), circumneutral (~7 SU), or basic (> 7 SU). As with dissolved oxygen, pH is influenced by temperature and may vary substantially over time (even on a single day), especially where plant or algal growth is substantial. Photosynthetic activity tends to increase pH because plants remove carbonic acid from the water column and convert it to oxygen. However, respiration, which dominates at night, adds carbonic acid to the water column, thereby driving pH downward. Therefore, a single snapshot of pH (as collected in this study) should be interpreted with caution.

In Massachusetts, the state standard in Class B waters is 6.5 SU to 8.3 SU and not more than 0.5 SU outside of the natural background range.

At Santuit Pond, pH values observed as part of this study were circumneutral, which places them well within the state standard for Class B waters.

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Secchi Disk Transparency

Water transparency is often expressed as the depth at which a Secchi disk just becomes visible. Low transparency measurements indicate poor transmission of light through the water column, although this may be due to a variety of causes including, but not limited to, natural staining, suspended sediments, algal growth, and manmade pollutants. Some waterbodies are naturally less transparent than others and low transparency does not necessarily indicate poor water quality. Higher transparencies are generally considered to be more aesthetically pleasing but also allow aquatic plants to grow at greater depths.

Secchi disk transparency at Santuit Pond was 2.25 meters (approximately 7.4 feet). The observed value suggests some level of interference with light transmission in the water column. However, it is not particularly low, especially for a shallow pond where plant growth may extend across the entire bottom and affect Secchi disk readings.

Table 1. Field-Measured Baseline Water Quality Results

Depth (ft)	Temperature (C)	Dissolved Oxygen (%)	Dissolved Oxygen (mg/L)	Specific Conductance (µS/cm)	pH (SU)
1.0	21.7	79.4	6.97	152.0	6.98
2.0	21.7	78.6	6.91	152.0	6.98
3.0	21.7	78.6	6.91	152.0	6.98
4.0	21.6	78.8	6.94	151.8	6.98
5.0	21.5	79.3	6.98	151.8	7.00
6.0	21.4	81.4	7.20	151.4	7.03
7.0	21.3	83.8	7.42	151.3	7.04
8.0	21.2	77.8	6.91	151.9	6.99
8.5	17.7	32.6	3.06	158.1	6.85

Total Phosphorus

Phosphorus is an essential nutrient for aquatic life but high levels of phosphorus can result in rapid growth of algae and lead to eutrophication, particularly in freshwater waterbodies. Excessive phosphorus may also encourage cyanobacteria blooms to develop, which can result in odor issues or production of cyanotoxins, such as microcystin. Total phosphorus values include dissolved phosphorus in addition to the phosphorus found in or bound to sediment and organic compounds. Dissolved phosphorus is readily available for uptake by aquatic organisms and an elevated dissolved phosphorus values may be indications of leaching of fertilizer, or human or animal waste.

Although there is no statewide phosphorus standard for Class B waters, lower concentrations are preferable and concentrations in excess of 0.025 mg/L are typically considered excessive. However, occasional nuisance algae blooms may also occur in waters with phosphorus as low as 0.020 mg/L, so that serves as a better target for management purposes in most eastern Massachusetts ponds.

The total phosphorus concentration observed in Santuit Pond was well in excess of 0.025 mg/L, with the highest concentration observed in bottom waters, where it was more than three times this (Table 2). Although this is just one snapshot, the higher phosphorus concentration observed in bottom waters may be a reflection of sediment release (internal loading). Regardless of this, the total phosphorus concentration in surface waters of Santuit Pond was itself quite high, suggesting plentiful phosphorus was available to fuel algal growth throughout the water column.

Chlorophyll a

Algal density can be inferred by measuring chlorophyll a, the primary photosynthetic pigment found in most algal cells. Although there is no statewide chlorophyll a standard for Class B waters, high chlorophyll a levels are generally considered undesirable because they are associated with elevated algal production and eutrophic conditions.

Chlorophyll a was detected in both surface and bottom waters of Santuit Pond (Table 2). The detected concentrations were not indicative of a severe bloom but suggest some algal growth within the pond at the time of sampling.

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Table 2. Water Quality Analytical Laboratory Results

Sample ID	Sample Location	Total Phosphorus (mg/L)	Chlorophyll a (mg/m^3)
SW-1S	1 foot below surface	0.055	3.22
SW-1B	1 foot above bottom	0.079	3.92

Quality Assurance / Quality Control

No significant deviations from the project-specific Quality Assurance Project Plan were noted during the water quality baseline monitoring event.

The blind field duplicate samples for both total phosphorus and chlorophyll a were slightly outside of the precision objective based on relative percent difference (RPD), which was 24% for phosphorus (compared to target of 20%) and 39% for chlorophyll a (compared to target of 35%). However, laboratory QA/QC reports indicated that all analytical acceptance limits were met. Therefore, we believe the data to be of acceptable quality and useful for the intended purpose.

All other data quality objectives for field and laboratory measured parameters were met.

3.2. Sediment Coring and Phosphorus Fractionation

Based on the laboratory results received from BEC, Org-P was the primary extractable phosphorus fraction, comprising more than 50% of the total sediment phosphorus in surficial sediments (defined here as the top four centimeters) of each core on a dry-weight basis, except SCP3 (Table 3). Fe-P was also plentiful and constituted the primary phosphorus fraction at SCP3. The Ca-P and Al-P fractions together accounted for only a minor portion of the total phosphorus in the sediments of Santuit Pond.

Full sediment phosphorus fractionation laboratory results tables and charts are provided in Appendix A.

Although Org-P was nominally the primary phosphorus fraction, studies of internal loading in other shallow lakes suggest that the Org-P concentration needs to be approximately 1 mg phosphorus per gram of dry sediment before substantially contributing to internal loading. Org-P was well below this concentration in all cores collected from Santuit Pond. Therefore, Fe-P is likely to be the most significant fraction with regard to phosphorus cycling in Santuit Pond.

Table 3. Summary of Sediment Characteristics and Composition

Sediment Core ID	Water Depth (ft)	Composition: Avg of Top 4 cm			Composition: Avg of Top 4 cm (mg g^{-1} dry sediment)				
		% Moisture	% Organic Solids	% Inorganic Solids	Reducible Extractable Iron (Fe)	Iron and Loosely Sorbed P (Fe-P)	Organically Bound P (Org-P)	Calcium Bound P (Ca-P)	Aluminum Bound P (Al-P)
SCP1	5.6	96%	41%	59%	13.1	0.31	0.52	0.027	0.023
SCP2	5.3	96%	40%	60%	12.7	0.29	0.58	0.030	0.025
SCP3	6.7	95%	37%	63%	11.6	1.01	0.53	0.041	0.041
SCP4	4.9	96%	36%	64%	12.8	0.29	0.69	0.039	0.069
SCP5	5.6	96%	39%	61%	22.3	0.29	0.68	0.038	0.038
Average	**5.6**	**96%**	**39%**	**61%**	**14.5**	**0.44**	**0.60**	**0.035**	**0.039**

Estimates of maximum potential internal loading (as mg phosphorus per meter squared of pond bottom sediment per day) are provided in Table 4. The estimates are based on relationships derived from published research (Pilgrim et al. 2007). The highest Fe-P concentration (and highest potential release rate of 7.42 mg m^{-2} d^{-1}) occurred in core SCP-3, which also was the deepest core collected. Except for SCP4, which was located in the far northern portion of the pond, sediments in each core exhibited a maximum internal phosphorus release rate exceeding 1.0 mg m^{-2} d^{-1}. Some locations, such as SCP3, could potentially exhibit much phosphorus release rates. For illustration purposes, the average rate of 2.36 mg m^{-2} d^{-1} would be the equivalent of more than 0.64 kg of phosphorus per day if only the deepest (i.e., deeper than the 8-ft contour) areas of the pond are included. If areas as shallow as 4 ft are included,

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this would equate to a release rate of more than 1.39 kg of phosphorus per day. While these release rates are lower than those estimated by AECOM (2010), this is due more to a difference in methodology rather than a reduction in available phosphorus. In fact, the Fe-P dry-weight concentrations found by this study are highly comparable (average of 0.44 mg g^{-1} for this study compared to 0.37 mg g^{-1} found by AECOM).

Table 4. Estimated Internal Phosphorus Loading Rates from Fe-P and Org-P

Sediment Core ID	Maximum Internal P Release Rate (mg m^{-2} d^{-1}) Iron and Loosely Sorbed P (Fe-P)
SCP1	1.40
SCP2	1.10
SCP3	7.42
SCP4	0.83
SCP5	1.04
Average	**2.36**

Org-P appears to decay in Santuit Pond sediments over time as suggested in Figure 5. The phosphorus decay product from Org-P may be converted to Fe-P because, on average there is more than 12 times more iron than total phosphorus in bottom sediments (Table 3). This suggests that if the sediments were aerobic near the sediment-water interface at all times, there would be enough iron to keep phosphorus bound in the sediment. Santuit Pond is not deep enough for strong thermal stratification to establish during the warm season. However, based on the water quality vertical profile collected for this study as well as the continuous data collected by others using an in-pond water quality sonde, depletion of dissolved oxygen is evident. Given the insufficient dissolved oxygen in bottom waters of the pond for at least part of the year (itself partly due to a positive feedback loop between algal productivity and oxygen depletion), iron instead serves as a ready source of phosphorus to the water column. This can occur when bottom waters partially stratify or stagnate during periods of relatively calm, warm weather, which promotes the release of iron-bound phosphorus from the sediments. The pond is also shallow enough that this phosphorus from bottom waters can be readily transported to surface waters with a change in weather, which induces vertical mixing.

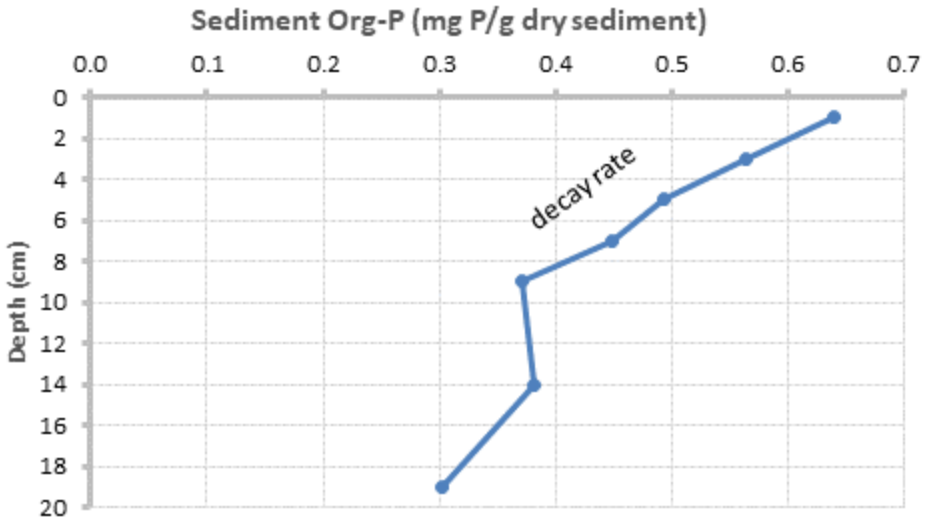

Figure 5. Depth Distribution of Org-P in Santuit Pond Sediments
Concentrations shown are a composite of the five cores collected.

Quality Assurance / Quality Control

No significant deviations from the project-specific Quality Assurance Project Plan were noted during the water quality baseline monitoring event.

All blind field duplicate samples met the precision objective based on RPD, except for the sample and duplicate pair from SCP2, which was slightly above the target. The RPD for phosphorus in SCP2 was 25% (compared to a target of 20%). However, examination of the fraction-specific QA/QC data indicates that this slight elevation in RPD was due primarily to the Al-P and Org-P fractions and may have been related to natural heterogeneity of the sample matrix. Therefore, we believe the data to be of acceptable quality and useful for the intended purpose.

All other data quality objectives for field and laboratory measured parameters were met.

4. Recommendations

One way to address the observed issue of sediment phosphorus release at Santuit Pond would be to supply a sufficient amount of oxygen to bottom waters at all times. This could prevent the release of phosphorus from Fe-P, which would reduce the amount of phosphorus available to drive excessive algal growth. Although this was the intention of deploying the SolarBee circulators and they may have improved dissolved oxygen in the pond, the seasonal and diel depletion of dissolved oxygen in bottom waters appears to continue. This is reflected in the water column's excessive phosphorus concentrations, which appear not to have meaningfully decreased since 2010. If the aeration promoted by the SolarBee circulators were fully capturing the internal phosphorus load, in-pond concentrations should now be close to 0.015 mg/L, based on the lake water quality response modeling completed by AECOM (2010). However, they are roughly three to five times higher than the predicted value.

Another way to address this issue would be to increase the amount of an alternative, phosphorus-binding substrate in the sediments. This approach would inactivate the phosphorus currently present in the pond regardless of the dissolved oxygen concentration, although external sources of phosphorus would still need to be controlled to prevent problems from redeveloping. Of the options available, aluminum is widely used to treat potable water sources, has the longest track record of safe and effective use as a phosphorus inactivation agent, and has been used for this purpose in a number of ponds on Cape Cod (Wagner et al. 2017). Additionally, aluminum is one of the most widely distributed and common metals on Earth and is already present in Santuit Pond sediments. The most frequently used method of increasing the availability aluminum as a phosphorus-binding agent is through the careful application of aluminum sulfate (alum), often in conjunction with sodium aluminate to serve as a buffering agent in softwater ponds.

Table 5 identifies the estimated amount of aluminum that would need to be added to Santuit Pond sediments to convert readily released Fe-P to strongly bound Al-P.

Higher phosphorus concentrations are often found in the deep areas of ponds due to a process called focusing. Fine sediments and associated nutrients tend to focus toward the deepest points in a pond over time. This is due to the combination of physical disturbance (currents, wave action, etc.), biological disturbance (fish and macroinvertebrates), and gravity acting on fine sediment particles. Hence, it can be assumed that the deeper central areas of Santuit Pond will have the highest Fe-P, which is observable in the results from the deepest coring location, SCP3. Additionally, deeper areas are the most likely to become hypoxic or anoxic during the growing season, as they are farthest from atmospheric sources of oxygen and can stagnate due to thermal and physical interferences in pond circulation patterns. Those factors combined indicated that internal phosphorus loading rates will be higher from sediments in deep waters during the warmer months. Therefore, dosing is split into two different rates: a lower rate for portions of the pond between the 4- and 8-foot contours and a higher rate for areas below the 8-foot contour (Table 5 and Figure 6). Areas shallower than the 4-foot contour are not currently recommended as target areas for nutrient inactivation.

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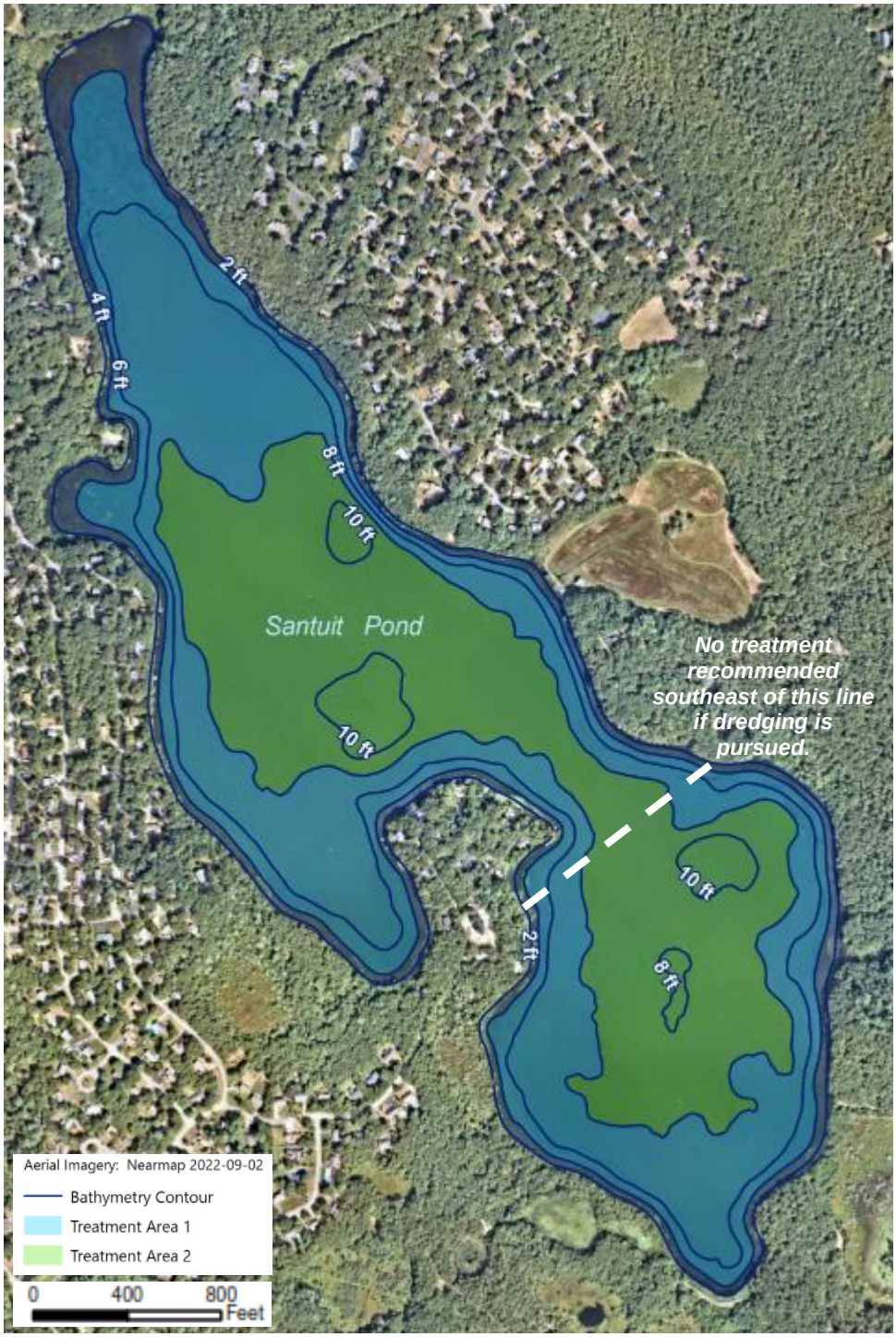

Figure 6. Recommended Treatment Areas

Table 5. Recommended Alum and Sodium Aluminate Dosing

Element	Value		Unit
Aluminum Dosing	**4- to 8-foot contour**	**Below 8-foot contour**	
Targeted Binding Ratio Al:Al-P formed	150	100	
Estimated Active Layer	4	4	cm
Total Aluminum Dose	42	80	g Al m^{-2}
Alum and Sodium Aluminate Treatment Volumes			
Treatment Area	78	67	acre
Total Mass Aluminum Applied	13,173	21,575	kg
Liquid Alum Composition	0.22	0.22	kg Al/gallon
Liquid Sodium Aluminate Composition	0.57	0.57	kg Al/gallon
Total Treatment Volume as Alum	59,877	98,068	gallon
Targeted Ratio of Alum to Sodium Aluminate	2:1	2:1	
Final Alum Dose*	26,085	42,723	gallon
Final Sodium Aluminate Dose*	13,042	21,361	gallon
Check	13,173	21,575	total mass Al applied in kg
Alum Dose per Acre	334.42	637.66	gallon
Sodium Aluminate Dose per Acre	167.21	318.82	gallon

*If dredging not pursued. Dosing rates per acre would remain the same for a partial-pond treatment but would be applied over a smaller area of the pond bottom, thereby also reducing the treatment volume needed.

If using a buffered alum approach, we recommend that aluminum be applied at a 2:1 ratio of alum (aluminum sulfate) and sodium aluminate (sodium, aluminum, and hydroxide) injected simultaneously into the water column. This will buffer the treatment with a goal of maintaining pH within the desired band of 6 to 8 SU. Depending on the pH at initiation of treatment, this ratio may need to be altered slightly. However, the 2:1 ratio has performed admirably in other softwater ponds on the Cape, eastern Massachusetts, and Rhode Island, while avoiding fish kills or other measurable negative impacts to non-target species.

Although polyaluminum chloride (PAC) could also be used for the nutrient inactivation treatment, it is harder to obtain in large volumes and may prove cost-prohibitive when compared to buffered alum. Another alum alternative is Aqual-P, a proprietary, zeolite-based product that has not been widely used in the US but shows some potential for use in phosphorus inactivation and other water quality improvement applications. Other non-aluminum based nutrient inactivation agents, such as the proprietary product Phoslock, could also be considered. However, Phoslock consists of rare earth materials (lanthanum) and bentonite clay, which makes it more cumbersome and costly to apply.

Given the shallowness of Santuit Pond and low alkalinity of its waters, we also recommend that the treatment be split into two doses (Table 6). This will serve as an additional safeguard against pH swings during treatment and allow the aluminum flocculent more time to become incorporated into the sediments before applying the full dose. It would also be anticipated to generate the additional benefit of improved stripping of phosphorus from the water column over two years, which will provide more immediate improvements to water transparency as well as the expected reduction in internal phosphorus loading.

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Table 6. Recommended Split Dosing over Two-Year Period

Year	Alum (gal)*	Sodium Aluminate (gal)*
Year 1	41,285	20,642
Year 2	27,523	13,761
Total	**68,808**	**34,403**

*If dredging not pursued. The annual treatment volume needed would be reduced for a partial-pond treatment.

Alum is best applied when the water temperature is cool but not cold and the water column is fully mixed. This allows for good flocculent formation while also avoiding periods when ambient water quality puts more stress on aquatic life. Given the fact that the Santuit Pond system also supports a river herring run, it is likely that the Massachusetts Division of Marine Fisheries will recommend a time-of-year restriction of March 15 to June 30 to avoid impacts on spawning success. Therefore, the best time for treatment is likely to be autumn.

It is also recommended that the SolarBee circulators be temporarily removed from the treatment areas or deactivated during treatment to allow the flocculent to settle more evenly along the pond bottom and become incorporated into pond sediments. However, it is not currently anticipated that the permanent removal of the SolarBee circulators will be necessary. In fact, by enhancing the dissolved oxygen concentrations in the pond, the SolarBees may reinforce benefits to aquatic life that will come from reduced internal loading of phosphorus.

Finally, it is recommended that any nutrient inactivation project be accompanied by pre-, during, and post-treatment monitoring. This will allow changes in water quality to be documented and quantified while also ensuring that the treatment is implemented in way that avoids or minimizes impacts to protected resources.

5. References

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Appendix A
Sediment Phosphorus Fractionation Lab Tables

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Results of sediment chemical analysis

Core	Sediment Depth Interval (cm)		General Properties			Phosphorus Fraction (mg P g^{-1} dry sediment)[1]				Reducible-Extractable Iron (mg Fe/g dry sediment)[2]
			% Moisture	% Loss on Ignition	Density (g/cm^3)	Fe-P	Al-P	Org-P	Ca-P	
Santuit SCP-1	1	2	96%	42%	1.02	0.299	0.017	0.546	0.026	13.05
Santuit SCP-1	3	4	95%	41%	1.02	0.314	0.029	0.485	0.029	12.66
Santuit SCP-1	5	6	94%	42%	1.02	0.261	0.014	0.447	0.021	---
Santuit SCP-1	7	8	94%	47%	1.02	0.205	0.025	0.410	0.025	---
Santuit SCP-1	9	10	90%	28%	1.05	0.078	0.009	0.181	0.013	---
Santuit SCP-1	14	15	93%	37%	1.03	0.903	0.022	0.254	0.037	---
Santuit SCP-1	19	20	90%	27%	1.05	1.433	0.212	0.306	0.044	---
Santuit SCP-2	1	2	97%	40%	1.01	0.313	0.034	0.603	0.034	11.43
Santuit SCP-2	3	4	95%	39%	1.02	0.260	0.017	0.563	0.026	11.10
Santuit SCP-2	5	6	94%	40%	1.02	0.196	0.015	0.486	0.029	---
Santuit SCP-2	7	8	94%	40%	1.02	0.178	0.016	0.461	0.032	---
Santuit SCP-2	9	10	94%	41%	1.02	0.145	0.017	0.435	0.026	---
Santuit SCP-2	14	15	94%	50%	1.02	0.118	0.050	0.588	0.025	---
Santuit SCP-2	19	20	93%	46%	1.03	0.061	0.013	0.330	0.013	---
Santuit SCP-3	1	2	95%	37%	1.02	1.028	0.029	0.558	0.037	22.27
Santuit SCP-3	3	4	94%	36%	1.02	1.001	0.052	0.511	0.044	19.55
Santuit SCP-3	5	6	94%	36%	1.03	0.763	0.034	0.422	0.046	---
Santuit SCP-3	7	8	93%	36%	1.03	0.524	0.031	0.383	0.047	---
Santuit SCP-3	9	10	91%	33%	1.04	0.506	0.020	0.336	0.040	---
Santuit SCP-3	14	15	89%	26%	1.05	2.483	1.134	0.407	0.069	---
Santuit SCP-3	19	20	91%	31%	1.04	1.995	0.681	0.444	0.071	---
Santuit SCP-4	1	2	97%	36%	1.01	0.386	0.086	0.715	0.043	8.83
Santuit SCP-4	3	4	96%	36%	1.02	0.193	0.053	0.668	0.035	8.02
Santuit SCP-4	5	6	95%	35%	1.02	0.137	0.038	0.623	0.030	---
Santuit SCP-4	7	8	93%	37%	1.03	0.105	0.022	0.509	0.022	---
Santuit SCP-4	9	10	94%	37%	1.03	0.106	0.027	0.490	0.033	---
Santuit SCP-4	14	15	92%	41%	1.03	0.066	0.020	0.397	0.015	---
Santuit SCP-4	19	20	92%	39%	1.03	0.045	0.015	0.279	0.010	---

1. Phosphorus Fraction Definitions:

Fe-P = iron-bound and loosely sorbed phosphorus

Al-P = Aluminum-bound phosphorus

Org-P = Organically bound phosphorus

Ca-P = Calcium bound phosphorus

2. Reducible-extractable iron is an extract of the iron-bound phosphrous extraction (BD step) that is

3. BD is blind duplicate

Results of sediment chemical analysis

Core	Sediment Depth Interval (cm)		General Properties			Phosphorus Fraction (mg P g^{-1} dry sediment)[1]				Reducible-Extractable Iron (mg Fe/g dry sediment)[2]
			% Moisture	% Loss on Ignition	Density (g/cm^3)	Fe-P	Al-P	Org-P	Ca-P	
Santuit SCP-5	1	2	97%	41%	1.01	0.365	0.046	0.775	0.046	12.88
Santuit SCP-5	3	4	95%	38%	1.02	0.221	0.030	0.594	0.030	12.39
Santuit SCP-5	5	6	94%	40%	1.02	0.253	0.029	0.492	0.029	---
Santuit SCP-5	7	8	94%	42%	1.02	0.202	0.027	0.478	0.034	---
Santuit SCP-5	9	10	93%	40%	1.03	0.112	0.032	0.415	0.027	---
Santuit SCP-5	14	15	91%	37%	1.04	0.067	0.022	0.258	0.022	---
Santuit SCP-5	19	20	89%	25%	1.05	0.051	0.020	0.148	0.020	---
BD 1-SCP 5	5	6	94%	40%	1.02	0.245	0.03	0.476	0.037	---
BD 2-SCP 3	9	10	91%	29%	1.04	0.54	0.033	0.364	0.038	---
BD 3-SCP 2	15	16	94%	48%	1.02	0.132	0.031	0.389	0.023	---
BD 4-SCP 1	3	4	95%	118%	0.99	0.35	0.026	0.508	0.026	---

1. Phosphorus Fraction Definitions:

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Results of sediment chemical analysis

Core	Sediment Depth Interval (cm)		General Properties			Phosphorus Fraction (g P m^{-2} cm^{-1} wet sediment)[1]				Reducible-Extractable Iron (mg Fe/g dry sediment)[2]
			% Moisture	% Loss on Ignition	Density (g/cm^3)	Fe-P	Al-P	Org-P	Ca-P	
Santuit SCP-1	0	2	96%	42%	1.02	0.127	0.007	0.233	0.011	5.56
Santuit SCP-1	2	4	95%	41%	1.02	0.151	0.014	0.234	0.014	6.11
Santuit SCP-1	4	6	94%	42%	1.02	0.167	0.009	0.286	0.013	---
Santuit SCP-1	6	8	94%	47%	1.02	0.130	0.016	0.261	0.016	---
Santuit SCP-1	8	10	90%	28%	1.05	0.084	0.009	0.196	0.014	---
Santuit SCP-1	13	15	93%	37%	1.03	0.675	0.017	0.190	0.028	---
Santuit SCP-1	18	20	90%	27%	1.05	1.499	0.222	0.320	0.047	---
Santuit SCP-2	0	2	97%	40%	1.01	0.109	0.012	0.210	0.012	3.98
Santuit SCP-2	2	4	95%	39%	1.02	0.129	0.009	0.280	0.013	5.51
Santuit SCP-2	4	6	94%	40%	1.02	0.112	0.008	0.279	0.017	---
Santuit SCP-2	6	8	94%	40%	1.02	0.113	0.010	0.293	0.021	---
Santuit SCP-2	8	10	94%	41%	1.02	0.095	0.011	0.285	0.017	---
Santuit SCP-2	13	15	94%	50%	1.02	0.076	0.033	0.380	0.016	---
Santuit SCP-2	18	20	93%	46%	1.03	0.046	0.010	0.250	0.010	---
Santuit SCP-3	0	2	95%	37%	1.02	0.486	0.014	0.264	0.017	10.525
Santuit SCP-3	2	4	94%	36%	1.02	0.590	0.031	0.301	0.026	11.519
Santuit SCP-3	4	6	94%	36%	1.03	0.504	0.023	0.278	0.030	---
Santuit SCP-3	6	8	93%	36%	1.03	0.399	0.024	0.292	0.036	---
Santuit SCP-3	8	10	91%	33%	1.04	0.451	0.018	0.299	0.036	---
Santuit SCP-3	13	15	89%	26%	1.05	2.833	1.293	0.465	0.078	---
Santuit SCP-3	18	20	91%	31%	1.04	1.913	0.653	0.426	0.068	---
Santuit SCP-4	0	2	97%	36%	1.01	0.122	0.027	0.227	0.014	2.80
Santuit SCP-4	2	4	96%	36%	1.02	0.080	0.022	0.276	0.015	3.31
Santuit SCP-4	4	6	95%	35%	1.02	0.073	0.020	0.332	0.016	---
Santuit SCP-4	6	8	93%	37%	1.03	0.078	0.016	0.379	0.016	---
Santuit SCP-4	8	10	94%	37%	1.03	0.070	0.018	0.326	0.022	---
Santuit SCP-4	13	15	92%	41%	1.03	0.052	0.016	0.310	0.012	---
Santuit SCP-4	18	20	92%	39%	1.03	0.039	0.013	0.242	0.009	---

1. Phosphorus Fraction Definitions:

Fe-P = iron-bound and loosely sorbed phosphorus

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Results of sediment chemical analysis

Core	Sediment Depth Interval (cm)		General Properties			Phosphorus Fraction (g P m^{-2} cm^{-1} wet sediment)[1]				Reducible-Extractable Iron (mg Fe/g dry sediment)[2]
			% Moisture	% Loss on Ignition	Density (g/cm^3)	Fe-P	Al-P	Org-P	Ca-P	
Santuit SCP-5	0	2	97%	41%	1.01	0.116	0.014	0.246	0.014	4.08
Santuit SCP-5	2	4	95%	38%	1.02	0.116	0.014	0.246	0.014	6.42
Santuit SCP-5	4	6	94%	40%	1.02	0.114	0.016	0.308	0.016	---
Santuit SCP-5	6	8	94%	42%	1.02	0.148	0.017	0.287	0.017	---
Santuit SCP-5	8	10	93%	40%	1.03	0.127	0.017	0.301	0.021	---
Santuit SCP-5	13	15	91%	37%	1.04	0.077	0.022	0.287	0.018	---
Santuit SCP-5	18	20	89%	25%	1.05	0.063	0.021	0.240	0.021	---
BD 1-SCP 5	4	6	94%	40%	1.02	0.057	0.023	0.167	0.023	---
BD 2-SCP 3	8	10	91%	29%	1.04	0.148	0.018	0.288	0.022	---
BD 3-SCP 2	14	16	94%	48%	1.02	0.481	0.030	0.325	0.034	---
BD 4-SCP 1	2	4	95%	118%	0.99	0.087	0.021	0.256	0.015	---

1. Phosphorus Fraction Definitions:

Fe-P = iron-bound and loosely sorbed phosphorus

Al-P = Aluminum-bound phosphorus

Org-P = Organically bound phosphorus

Ca-P = Calcium bound phosphorus

2. Reducible-extractable iron is an extract of the iron-bound phosphrous extraction (BD step) that is

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