Data Review for Sarah's Pond, Orleans, MA, 2018-2024, with Emphasis on Oxygenation to Enhance Pond Conditions

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Non-Technical Executive Summary

The Orleans Pond Coalition (OPC) completed its Oxygen Demonstration Project in 2023. The results of this program were sufficiently favorable for abutting homeowners to express interest in continuing operations. Homeowners, principally Pleasant Bay Narrows Trust (PBNT) with Jeanne and Richard Berdik and the Orleans Conservation Trust (OCT), have leased the equipment with OPC agreeing to continue leading the monitoring of results. This report summarizes results for the entire program from 2018-2024.

Efforts to adjust the system for greater reliability produced favorable results in 2023 and even better results in 2024. Low oxygen was observed for approximately two weeks in late August and early September of 2023 when oxygen delivery was limited by a clogged pipe header. Overall, the OST system was successful in 2023 in elevating deep water oxygen, increasing clarity, and preventing cyanobacteria blooms in Sarah's Pond through summer, although there was one period of low oxygen late in summer and a bloom occurred in early autumn. There were no operational failures in 2024; oxygen remained high in the target area throughout the summer and clarity reached a maximum for the multi-year monitoring period, although there was a mild cyanobacteria bloom in late August and September. There were some low oxygen readings in shallower areas outside the target zone, areas the OST^{TM} system was not designed to address, and such conditions appear to be the result of prolonged hot, dry weather. The OST^{TM} system could be adapted or augmented to address those areas, but operation of the current system is recommended for at least three more years as ongoing improvement has been observed.

As background, Sarah's Pond, a 5.8-acre kettlehole pond located in Orleans, MA, has experienced low clarity due to algae blooms, especially potentially toxic summer cyanobacteria blooms. The Orleans Pond Coalition chose Sarah's Pond to test oxygenation as a preventive means for controlling problem algae. Two years of experimentation with a nanobubble system did not achieve goals and indicated that the installed equipment was not adequate to counter the observed oxygen demand, thereby allowing phosphorus to be released from the sediment under low oxygen conditions and supporting continued cyanobacteria blooms. A sidestream saturation system (SSS), also known as an oxygen saturation technology (OST^{TM}) system, was installed in spring of 2021 and operated through 2024 with improved conditions, but the target conditions were not consistently achieved. During the first two years of operation, when the system was operational, it did maintain adequate oxygen in the target zone within the pond, but multiple problems led to system shutdown or suboptimal performance.

The primary process of concern in Sarah's Pond is the loss of oxygen near the sediment-water interface. Decaying organic matter consumes oxygen faster than it can be replenished from the water above, especially during summer when water at the bottom of the pond is distinctly colder than water near the top, which impedes vertical mixing and oxygen replenishment near the bottom. That loss of oxygen facilitates a set of chemical reactions that cause phosphorus to be released from the sediment. Phosphorus is a key nutrient for algae, and its presence, at a low ratio of nitrogen to phosphorus, promotes the growth of cyanobacteria. Cyanobacteria can grow throughout the water column but often start at the sediment-water interface where the phosphorus is most available when oxygen is low. Cyanobacteria subsequently develop gas pockets within cells and rise to form surface blooms. Disrupting this progression is an objective of the Sarah's Pond project and the severity of cyanobacteria blooms has been reduced over the four years of OST^{TM} system operation. Further improvement seems possible with continued operation.

The OST^{TM} system as designed and installed in Sarah's Pond is intended to keep oxygen high near the sediment-water interface in water deeper than about 15 feet over about a two-acre area. As long as the system is running properly, enough oxygen is supplied to promote high oxygen at depths as shallow as 13 feet and beyond the two-acre target area. However, very hot weather in some summers has resulted in low oxygen at depths as shallow as 10 feet, an area the system was not designed to treat. Phosphorus released outside the target zone may be responsible for cyanobacteria blooms that have developed while the OST system was properly operating. Unfortunately, it is not possible to tell from the collected data how much of the continued cyanobacteria problem is related to suboptimal system performance and how much is due to uncontrollable weather factors. Yet the pattern of improvement over the last four years suggests that the benefits of oxygenation accrue gradually, and more time may be needed for the pond to reach a stable and favorable condition.

The importance of designing a system to handle oxygen demand in all possible problem areas of a pond is highlighted. It is also important to maintain a substantial oxygen "buffer", a higher concentration than might seem necessary, so that any system failure will not result in rapid oxygen depletion. Shutdowns for any number of reasons, including power outages as well as equipment failure, are to be expected, and having extra oxygen near the sediment-water interface allows time to bring the system back online before oxygen is depleted. Finally, it is important to have real-time monitoring of oxygen via sensors, the data from which can be accessed remotely, to allow tracking of oxygen levels and rapid response to any decline.

Overall, the oxygen saturation technology system has demonstrated its ability to enhance conditions in Sarah's Pond. Problems that prevent achievement of all project goals are largely operational challenges common to many such systems and requiring development of warning systems and implementation of rapid response to maintain successful operation. Adjustments each year improved the performance of the OST^{TM} system in Sarah's Pond and resulted in further development of OST^{TM}, which is enjoying increased use in other waterbodies with new features.

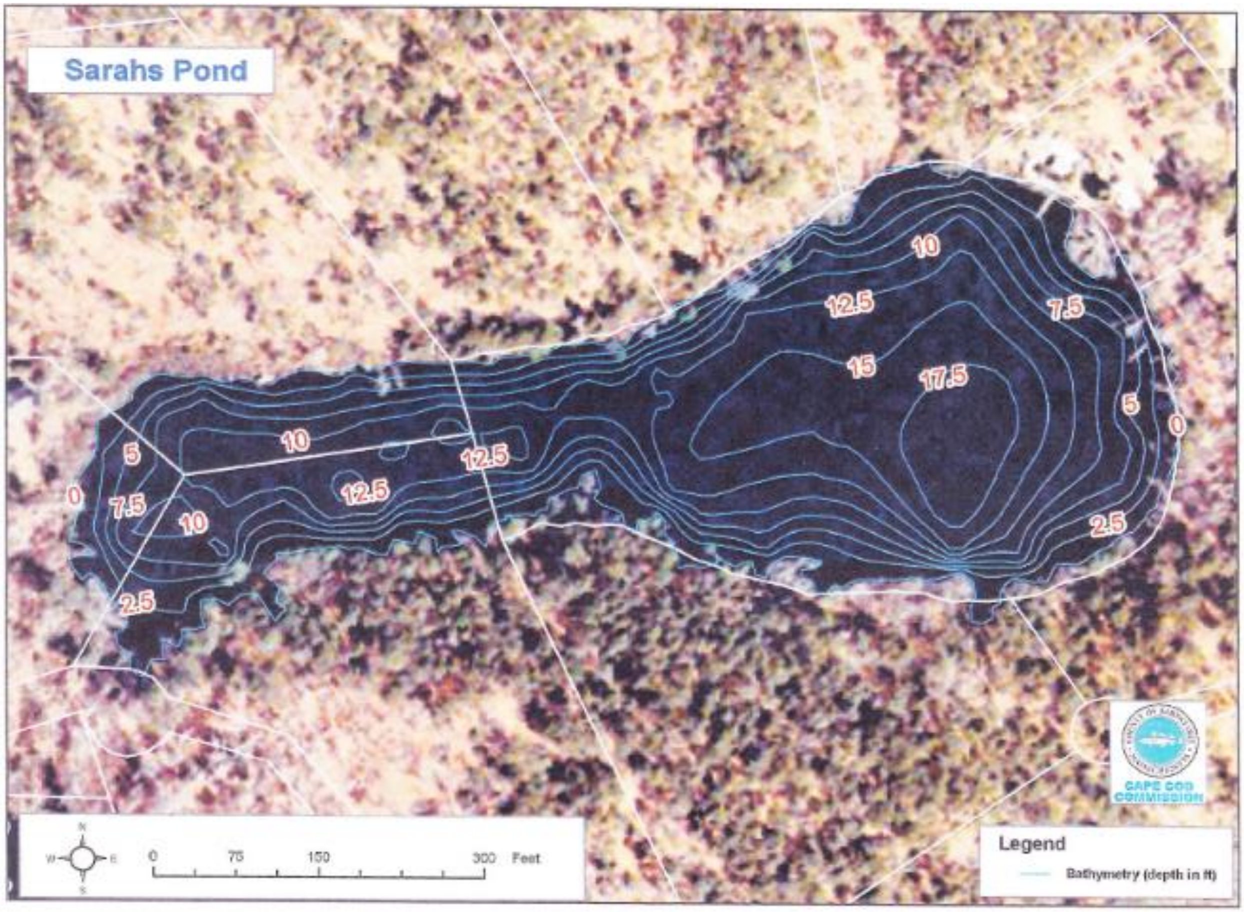
Background

Sarah's Pond is a 5.8-acre kettlehole pond located in Orleans, MA (Figure 1). The bathymetry of Sarah's Pond shows the deepest point to be 17.5 feet (5.3 m) toward the eastern end of the pond (Figure 2). The pond is elongated at the western end, achieving a maximum depth of 12.5 feet (3.7 m) in three separate, small, deep "holes". Overall, the pond has a "double bowl" that permits the testing of oxygenation technology in the eastern bowl while reserving the western bowl as a control, although the two pond sections are not truly separate, and some interaction is to be expected. Although Sarah's Pond has been described in the past as among the more pristine freshwater bodies in Orleans, this reputation may have more to do with its largely undeveloped watershed, which has an agricultural past but is now largely forested. Sarah's Pond has experienced low clarity due to algae blooms in recent years, including cyanobacteria. A few blooms were observed between 2005 and 2010, but monitoring was not extensive enough to quantify bloom frequency or severity.

Water quality data have been collected in Sarah's Pond since 2001 and show impaired conditions in recent years, including average deep summer oxygen concentrations less than the MassDEP regulatory minimum and virtually anoxic near the sediment-water interface in deeper water in most summers. Sampling at the deepest location occurs at about 16.5 ft (5 m), but measurement of oxygen near the sediment-water interface in other parts of the pond reveals low oxygen conditions in water as shallow as 10 ft (3 m) deep at times. Mean Secchi transparency depth has been 9.1 ft (2.8 m), but clarity has been lower most of the summer. The thermal profile suggests some

Figure 1. Sarah's Pond and general vicinity in Orleans, MA

Figure 2. Sarah's Pond bathymetry



stratification, with a thermocline between 10 and 13 ft (3-4 m) deep. Review of nutrient data shows strong evidence of summer nutrient release from the sediment. The average change in phosphorus (P) concentration over the summer suggests a P mass net increase of just under 1 kg, nearly all of which is probably due to internal loading and sufficient to raise P concentration enough to support algae blooms. More recent sediment testing revealed very high phosphorus associated with redox-sensitive compounds, mostly iron based; this means that large quantities of phosphorus can be released from sediment exposed to anoxia.

The Orleans Pond Commission (OPC) wanted to try an oxygenation approach to improving pond water quality and Sarah's Pond afforded such an opportunity. Cooperation by landowners and the caretakers set up a highly desirable test situation. While improvement of Sarah's Pond is certainly desired, the primary goal of the OPC is to demonstrate an affordable technology for pond improvement that can compete with alternatives such as phosphorus inactivation by aluminum addition on Cape Cod.

The target test area outlined in Figure 3 is roughly 2 acres, bounded by the 10-foot water depth contour. Using past data and more frequently collected data from the pond through June 2018, oxygen demand in the target volume to be addressed by an oxygenation system was estimated at

Figure 3. Target oxygenation area in Sarah's Pond

1.0 to 1.5 g/m2/day, equating to a hypolimnetic oxygen demand (HOD) or 8-12 kg/day, including an appropriate margin of safety to cover induced oxygen demand. This is a very typical release rate for phosphorus in sediments exposed to anoxia.

The OPC has provided additional monitoring for Sarah's Pond beyond the PALS program and the same program was conducted in 2018 prior to oxygenation and in 2019 through 2023 during testing of the oxygenation systems. Temperature and oxygen were assessed with a field instrument at 0.5m increments at station 1 in the target area for oxygenation (5.3 m deep) and at station 2 at the other end of the pond (3.7 m deep). Monthly samples were collected for total phosphorus (P), total nitrogen (N), and total chlorophyll-a (Chl) in the targeted oxygenation area at the surface and near the bottom. The Center for Coastal Studies provided sample analysis in its laboratory. Phytoplankton samples were collected weekly to monthly from the surface depending on observed conditions and analyzed by WRS Inc.

Testing of a nanobubble oxygenation system was conducted in 2019 and 2020 but results did not meet expectations. Performance standards were not met, and the system was removed at the end of 2020. A type of side-stream saturation system (SSS) identified as oxygen saturation technology (OST™) was installed in spring 2021 and operated from mid-April into October of that year. Adjustments to the system were made in the last half of March 2022 and the system operated between early April and mid-October 2022. Further adjustments were made at the end of the 2022 operational period and at the start of the 2023 operation. Operation from April through October of 2024 was accomplished with maintenance but minimal further adjustment.

Oxygenation system specifications

The key specifications for the oxygenation system included:

- The system should be able to provide 8-12 kg/day of oxygen to the target area at a depth of 10 ft and greater.
- The system must not re-suspend bottom sediment or increase turbidity more than 5 NTU in the target area (East Basin) compared to what is observed in the control area (West Basin).
- Shore components should provide the smallest footprint possible and include housing for equipment that can be soundproofed as necessary.
- The system and all components should be in place and operational no later than the start of May and be operated for two consecutive years during spring and summer.

The real test of success would be increased oxygen levels, reduced P concentrations, reduced algae abundance, minimization of cyanobacteria, and increased water clarity through the summer, and operational adjustments including start and end dates for operation and area covered were expected to be needed. However, for the purpose of evaluating equipment performance, the above criteria were offered as standards for vendors to meet.

SOLitude Lake Management, initially using nanobubble equipment from Homeport and a design from Gaia, was selected to conduct this installation. After the Homeport system failed to achieve the performance standards, as described in the 2020 annual report, SOLItude worked with Gantzer Water to install an OST™ in spring of 2021. OPC provided monitoring support and CCS provided laboratory support. WRS provided algal analysis, data interpretation and related support. This arrangement has continued through 2024.

Installation, operation, and oxygen results

The existing small shed that had housed the Homeport nanobubble oxygenation system was used for the OST™. A pressure swing absorption (PSA) unit, or oxygen concentrator, added oxygen to water pumped from the pond and equipment installed by Gantzer Water with the aid of SOLitude returned oxygen-saturated water to the pond at its deepest point. The system differs from the nanobubble system in that oxygen is being added to water in dissolved form rather than trying to create ultra-small bubbles that stay in solution and theoretically transfer oxygen to the water. The OST™ also increases the dissolved oxygen level to a much higher degree, returning oxygen enriched water back to the bottom of the pond with oxygen levels up to 50 mg/L.

The thermal gradient present in the pond restricts upward movement of the oxygenated water, and the "excess" oxygen disperses laterally throughout the bottom waters with subsaturated oxygen levels. In essence, a deep-water layer of higher oxygen is created, blanketing the sediment and limiting the impact of sediment oxygen demand on the overlying water in the deepest area. This system is intended mainly to prevent low oxygen conditions from developing by satisfying the sediment oxygen demand as it is expressed at the sediment-water interface. The system may be able to recover oxygen to some degree if low oxygen conditions develop (e.g., if the system is shut down for some time), but that will be a less efficient operation as there is no provision to mix the discharged oxygenated water higher in the water column than the discharge point. Some diffusion can be expected, but the OST™ inputs are focused on the depth of discharge. This also means that shallower areas that go anoxic may not be treated by this system, a probable threat in the western basin and even peripherally at 10-13 feet in the eastern basin.

Initial testing of the OST™ revealed high oxygen in the discharge and quickly rising oxygen in the deepest water of the pond. The OST pumps at a rate of 60 gpm and can deliver up to 18 kg of oxygen per day. In spring, with lower water temperatures and adequate oxygen throughout the pond, operation at the maximum rate was not necessary and the system was put on a timer to run 6 hours per day. Further adjustments to get timer control over all parts of the OST (PSA and water pump) were made soon thereafter, and eventually a control system was installed that would turn the system on when oxygen dropped below a chosen lower limit and shut the system off when oxygen rose above a chosen higher limit at a designated point in the water column.

Electrical control issues resulted in the OST not running for about a week in late April 2021 and oxygen near the bottom declined rapidly. The OST was run 24 hr per day for a week and 12 hr per day for another week to recover and maintain oxygen in deeper water. Oxygen in deep water rose quickly and reached a peak of 25 mg/L on May 10, 2021 (Figure 4). Problems with the connections of the PSA input to the intake water and the outflow line to the pond resulted in a sharp decline in oxygen in the target zone of the pond in the second half of May (Figure 4). Additional issues with the PSA and various connections continued through July with two periods of proper operation that raised deep water oxygen to between 6 and 10 mg/L, but also with periods of virtually no oxygen at depths >13 feet (Figure 4).

Servicing, cleaning, and adjustments in August resulted in intermittent operation and a period with oxygen between 4 and 6 mg/L in deep water, considered adequate, but the OST™ operated sub-optimally throughout August and oxygen was lower than desired at depths >8 feet much of the time. It was determined that the discharge pipe, a PVC pipe with many slots cut into it to allow low velocity discharge, was partially clogged with iron precipitate. Periods of low oxygen allowed iron to be released from the surficial sediment into the overlying water, and when oxygen was increased by OST™ operation, the iron precipitated out in the discharge and formed a sludge that partially clogged the discharge header (Figure 5). The discharge pipe was also sinking into the sediment, potentially causing resuspension of sediment during discharge but also restricting distribution of the oxygenated water. Other portions of the piping in the lake were also not holding up, resulting in leaks. The leaks in the flexible PVC discharge pipe were identified as stirring up sediments. A temporary patch was placed on the damaged discharge pipe during the August site visit; however, the discharge pipe continued to experience failure.

After a thorough analysis of the OST™ and its operation in late August, HDPE piping and a new discharge platform were installed on September 9, 2021, to enhance operational reliability. Oxygen in deep water increased rapidly with 24 hour per day operation and reached an average daily peak of 17 mg/L at depths >15 ft, on September 23, 2021 (Figure 4). The timer was then set to limit operation to 8 hours per day and oxygen was maintained between 1.5 and 10 mg/L in deep water until October 19, 2021, when the OST was shut off until next spring and components were winterized.

Figure 4. Dissolved oxygen at four depths in Sarah's Pond in 2021

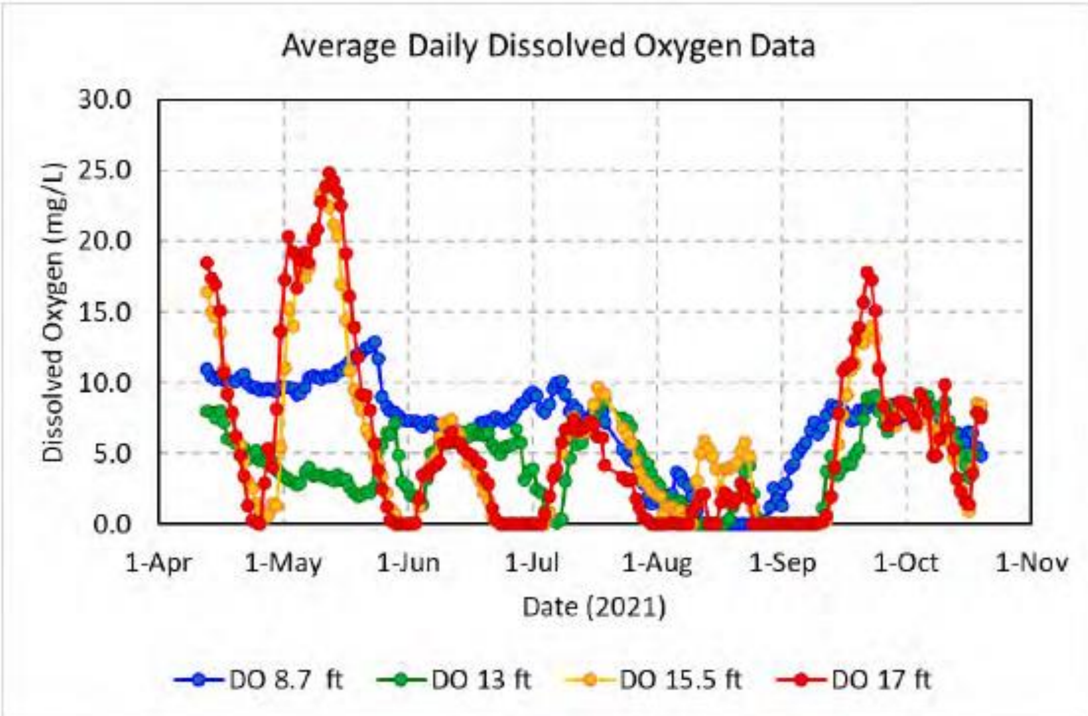


Figure 5. Cracked discharge pipe (top) and iron sludge (bottom)

Adjustments going into 2022 included replacement of the PSA unit, extension of the intake and discharge headers with use of larger slots, throttling down the pump rate from 60 to 55 gpm and the pressure from 36 to 22 psi, cleaning and adjustment of sensors, and various rewiring and reprogramming of system controls. All of this was intended to avoid some of the problems encountered in 2021. The system was set to run until oxygen reached 20 mg/L at the deep sensor and to resume operation when oxygen dropped below 15 mg/L, moving operation into a responsive mode rather than some preset time of operation each day. The high thresholds were intended to provide a buffer for oxygen in the event of any shutdown, allowing more time for detection and repair before anoxia could develop.

There were only two periods of low oxygen in summer 2022, in early July and early August (Figure 6). The first resulted from an apparent power surge that shut off the PSA unit during the July 4th weekend. The system appeared to be operating but no oxygen was being added and oxygen declined at the deepest sensor (Figure 6, but easier to visualize at an appropriate timescale in Figure 7). Oxygen at the 17 ft and 15.5 ft sensors exhibited a similar decline over time, while oxygen at the 13 ft and 8.7 ft sensors (not significantly affected by the OST) remained higher and more stable. The system had shut off near the end of June as the maximum oxygen target had been exceeded but oxygen was not being added when pumping resumed in response to decline below the lower threshold. Oxygen data from the sensors provided indication that something was not right after a few days of operation, but there was no alarm or other warning system in place to indicate that any element of the system was not working properly.

The second low oxygen event occurred in early August and was a function of multiple factors. There were a couple of power outages that caused the PSA to not resume operation when needed, possibly related to heat build-up in the pumphouse, but those were discovered fairly quickly after the experience in July 2022. A crack in the intake line and biofouling of the intake and discharge slots (Figure 8) caused a larger problem, limiting the amount of oxygenated water sent to the target zone. Superimposed on these issues was very hot weather that increased water temperatures and sediment oxygen demand. Work on other Cape ponds has shown that oxygen demand can double with just a 4 C^{o} increase in temperature at the sediment-water interface.

Below 15 ft of water depth there was a decline in oxygen when the OST^{TM} shut down on August 9, followed by full recovery when the system went back online and the trigger sensor was changed to the 15.5 ft depth level (Figure 6, with an expanded scale for just August in Figure 9). There was another oxygen decline after system shutdown on August 17, but only partial recovery as the OST^{TM} struggled to keep up with maximum oxygen demand while operating at lower than maximum capacity (as a function of a cracked pipe and biofouling).

Oxygen was low at the 13 ft sensor in August (Figure 9), well before the system shutdown around August 9th. This is a depth that the OST was not designed to fully address and includes area outside the target zone. Low oxygen was actually detected in water as shallow as 10 ft from the monitoring program, a depth at which low oxygen has occurred in the past but not at the frequency or duration observed in summer 2022. As a result, anoxic conditions and likely P release occurred in areas shallower than the OST^{TM} could efficiently address, including in the western lobe of the pond, not part of the target area. As a result, total oxygen demand for the pond was likely higher than the

Figure 6. Dissolved oxygen at four depths in Sarah's Pond in 2022

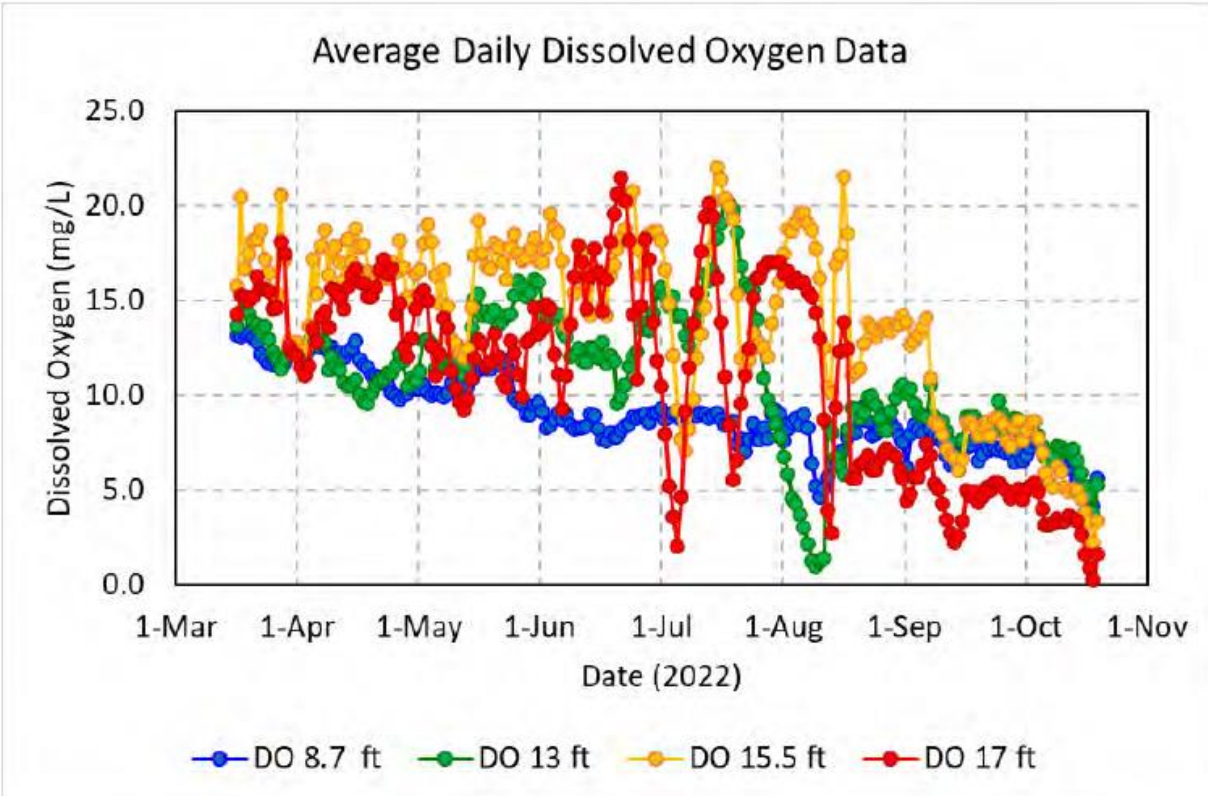


Figure 7. Dissolved oxygen at four depths in Sarah's Pond in late June-early July 2022

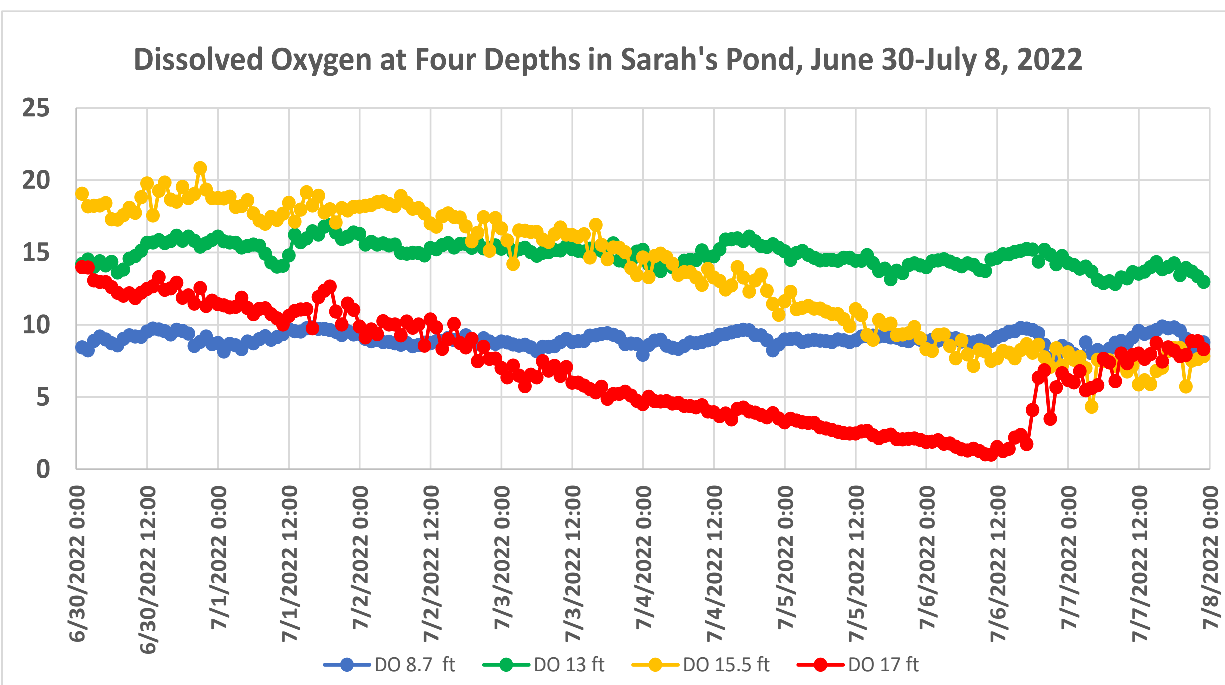
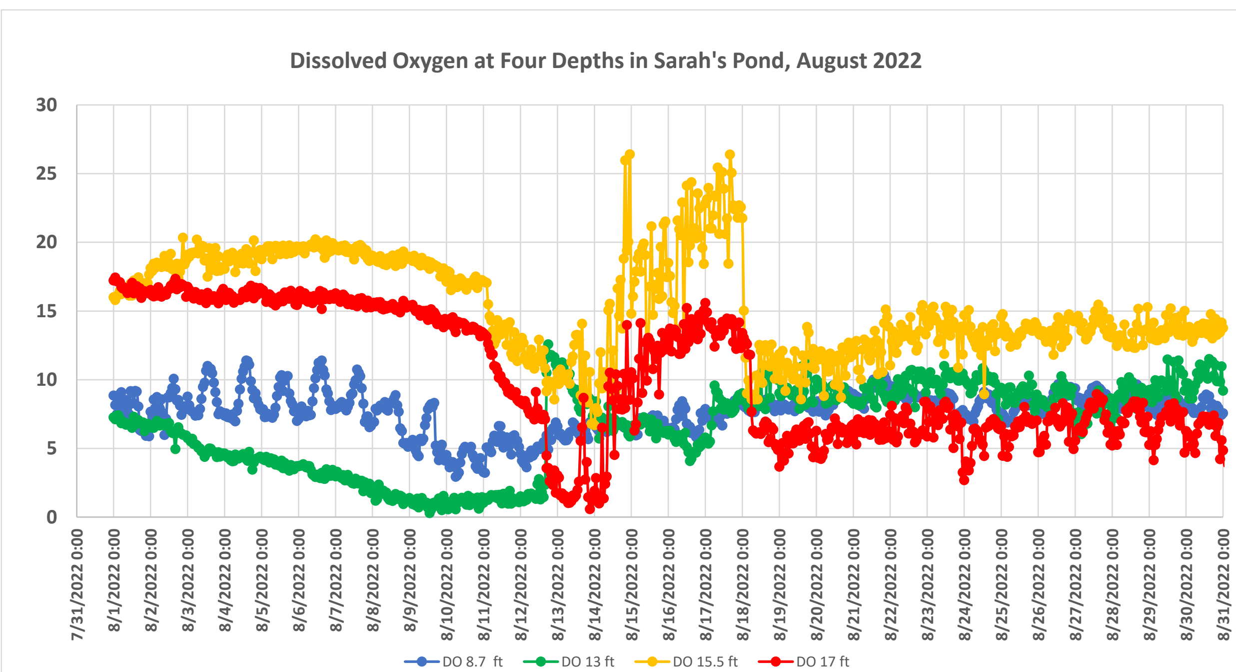


Figure 8. Biofouling of suction and discharge header pipes

Figure 9. Dissolved oxygen at four depths in Sarah's Pond in August 2022



OST™ was designed to counteract and what oxygen was added did not reach all areas in need of oxygen as a consequence of the thermal regime.

From the July shutdown event, oxygen decline ranged from 1.2 to 1.8 g/m2/day. Applying that range of values to the 9,716 m^2 of Sarah's Pond deeper than 10 ft, oxygen demand in Sarah's Pond would have been 12 to 18 kg/day, above the requested system specs and near the limit of the OST™ installed. With limited flow due to a cracked pipe and biofouling and a layout focused on water deeper than about 15 feet, meeting that demand was unlikely.

With the OST™ again in operation and the trigger sensor set at 15 ft instead of 17 ft, there was recovery of oxygen at the 13 ft depth sensor, but not before substantial P is likely to have been released. The OST™ managed to prevent extremely low oxygen throughout the pond for the rest of August and through September into October, but there may have been some anoxia right at the sediment-water interface that made P available to cyanobacteria growing at that interface. Yet the anoxic period that lasted about a week (August 8-14) at depths as shallow as 10 ft appears to have been sufficient to make enough P available to support the ensuing cyanobacteria blooms.

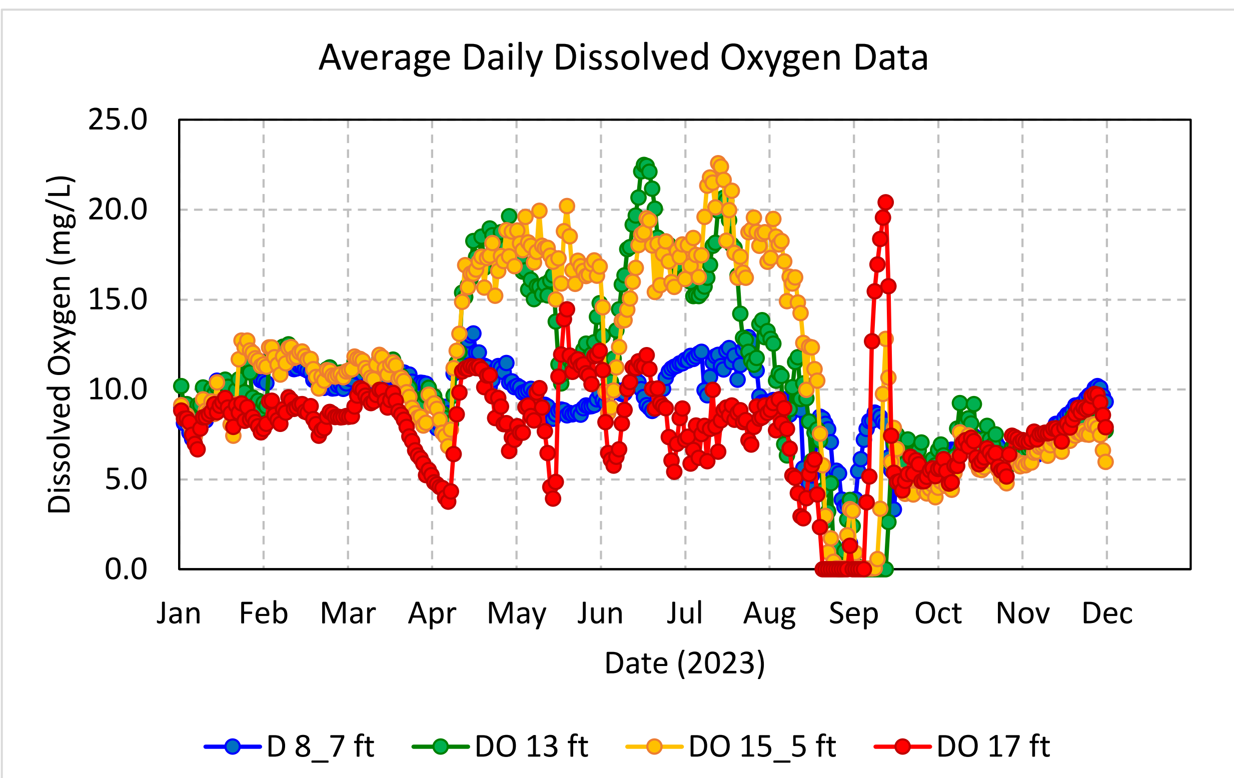
The OST™ was shut down in mid-October and on October 20 and 21, 2022 all PVC pipe on shore was replaced with HDPE pipe to minimize the risk of cracks. Intake and discharge pipes were bundled, and a buoyancy pipe was added to allow pipes to be easily brought to the surface for inspection and maintenance (Figure 10). Overall system maintenance was performed, including sending the PSA for refurbishment. The slots in the intake and discharge headers were enlarged in 2023 and the headers were wrapped in copper mesh to reduce biofouling.

Figure 10. Updated piping on shore (top) and in the lake (bottom)

The ability of the OST to deliver enough oxygen to maintain desirable conditions was apparent when the system operated properly, but shutdowns, leaks, and sub-optimal operation were frequent in 2021, and oxygen depletion still occurred. System improvements and a switch to operation triggered by oxygen levels with a substantial buffer to facilitate response time resulted in better performance and fewer issues in 2022. However, there were still several brief periods of shutdown and about two months of suboptimal operation in August and September that compromised performance. The very hot weather also increased demand on the system and affected areas not part of the target zone. As the system is not designed to handle oxygen demand from the entire pond bottom and low oxygen was observed higher in the water column than usual, P release sufficient to support algae blooms appears to have occurred in August 2022 and conditions deteriorated thereafter. Yet even with a cracked pipe and biofouling that limited performance, the OST prevented low oxygen events from mid-August into October. Unfortunately, it appears that the earlier low oxygen events were sufficient to support observed algal blooms after early August.

The system was turned on as of April 11, 2023, and performed well for about 5 months. The system ran when oxygen in the deepest area was <15 mg/L and shut down if oxygen reached 20 mg/L. Oxygen was sufficient to avoid significant internal P loading by redox reactions through most of the summer (Figure 11). However, noise from the oxygen concentrator was assumed to represent pending failure and declining oxygen in deep water seemed to support that conclusion, so the oxygen concentrator was replaced on about August 22nd. Unfortunately, the replacement unit did not solve the problem, which was eventually determined to be a clogged intake pipe. The pipe

Figure 11. Dissolved oxygen at four depths in Sarah's Pond in 2023

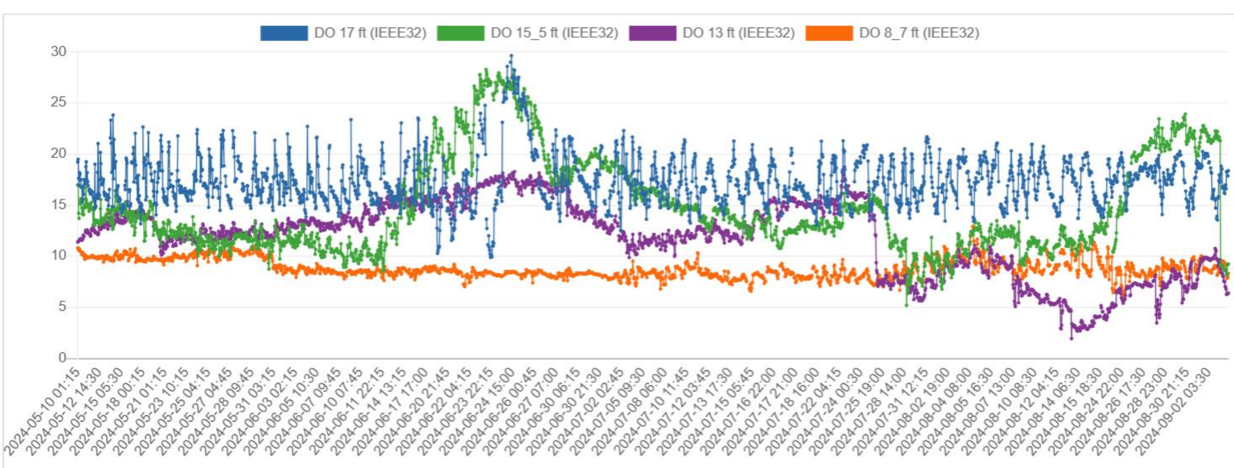


headers were raised and cleaned on about September 6, 2023, and oxygen recovered quickly in deep water once flow of oxygenated water was resumed at the design level. For the intervening 2+weeks oxygen declined precipitously at all levels, resulting in anoxia at depths as shallow as 13 feet for much of that period and contravening the standard of 5 mg/L even at the 8.7 foot depth for almost a week. It took longer for the shallower zones to lose oxygen and also to recover than for the deeper water, as the OST is not set up to directly serve shallower areas. Seasonal cooling combined with a storm on September 17th to mix the pond and evened oxygen at all depths.

The other operational concern in 2023 was heat buildup in the enclosed shed housing the pumps and oxygen concentrator. Newer OST^{TM} design puts as much equipment in the water as possible, aiding cooling and improving oxygen transfer due to greater ambient pressure, but the OST^{TM} at Sarah's Pond is a first generation design which has all components other than intake and discharge pipes on land. Overheating is a primary cause of system failure for almost all forms of oxygenation. Installation of a fan to minimize heat buildup was prescribed but the fan was not installed until late summer. Even then, the oxygen concentrator was still very hot when trying to recover pond oxygen levels in early September after a period of shutdown. While overheating does not appear to have been the direct cause of any loss of oxygen in 2023, clogging of pipes, relating to precipitation of iron oxides and possible bacterial growth, was an operational impediment in 2023 and might have been related to the overheating through reduced performance. Mid-season cleaning of pipe headers should become part of normal system maintenance, and the piping system has been set up to allow headers to be raised, inspected, and cleaned as needed.

Operation in 2024 was the smoothest of all years to date. The OST system was turned on in mid-April after inspection and servicing and ran as planned through September. The monitoring system was shut down prematurely, so continuous oxygen data were not available after early September, but the monthly manual monitoring program and a check at shutdown in early October provided data that indicated no oxygen values <5 mg/L in the target area at depths of 15 ft or more (Figure 12). However, oxygen at the sensor at13 ft did dip below 5 mg/L in the last half of August and manual monitoring did reveal low oxygen at depths >3 m in the western basin in July and August, so not all pond bottom was oxygenated all summer long.

Figure 12. Dissolved oxygen at four depths in Sarah's Pond in 2024



Maintenance of the system was minimal during the operational period in 2024. End of season maintenance by SOLitude did not reveal any significant biofilm development and the sensor data (Figure 12) indicate no significant oxygen issues within the target zone for the OST system into September. Issues with low oxygen in the western basin are a function of lack of oxygen distribution to the area, something the OST^{TM} system was never designed to provide. The western basin forms an imperfect control, demonstrating the effect of lack of oxygenation in its deepest area but not being completely separate from eastern basin, allowing lateral mixing at shallower depths. Summer of 2024 was again a hot summer, much like 2022, yet the results of oxygenation were better in 2024.

The oxygen concentration in deeper water represents the most obvious manifestation of OST^{TM} results (Figures 4, 6-7 and 9, 11-12). The OST^{TM} system did not consistently achieve >2 mg/L throughout the pond in each of four summers, but did improve conditions measurably and did get better at maintaining oxygen in the target eastern basin with each year. This improvement may be a function of better operation each year or incremental effects of sequential summers of oxygenation, probably both. The key to success appears to be reliable, on-demand operation of the OST^{TM} over multiple years; successful oxygenation is a gradual process.

OST^{TM} shutdown after a period of successful operation allows assessment of oxygen demand during a time when oxygen levels would otherwise be too low to make valid measures. Hypolimnetic oxygen demand (HOD) measurements in 2018 through 2020 prior to OST^{TM} system operation suggested HOD values in the range of 0.7 to 1.1 g/m^2/day. Knowing that there is often some additional demand induced when oxygen is added (full oxygen demand can be better expressed with higher amounts of available oxygen), the oxygen demand applied in the specs was 1.0-1.5 g/m^2/day, leading to the oxygen delivery specification of 8 to 12 kg/day for an area of about 8,000 m^2.

With oxygen raised by the OST^{TM} in 2021-2022 then declining when the system was not operating, HOD values ranging from 1.2 to 2.2 g/m^2/day were obtained. This means that as much as 18 kg might be needed to keep the target zone fully oxygenated, although that would not be a regular occurrence. The installed OST^{TM} has a capacity of about 18 kg/day, so no oxygen shortage is predicted based on possible maximum HOD in the target zone. However, HOD extended to areas as shallow as 10 ft deep in several years, expanding the area to almost 10,000 m^2 and going beyond the target area. Sarah's Pond is small enough that events in any one part of the pond can affect the entire pond. Further, the lateral movement of oxygen into lower concentration areas means that the OST^{TM}, despite having a defined target zone, is functionally serving the entire pond. Its capacity for handling the maximum oxygen demand of the entire pond is marginal and its design will not lead to efficient countering of oxygen demand in water shallower than about 13 feet.

The issue for maintaining oxygen in Sarah's Pond in 2019 and 2020 was the inability of the nanobubble system to provide enough oxygen; the highest measured input was 6 kg/day. In 2021 very high oxygen concentrations were observed with the OST^{TM} running for 24 hr per day and acceptable oxygen with it running for as little as 8 hr per day as long as there were no problems with leaks or clogging. The issue in 2021 was operational; the system did not run at all times when it was assumed to be running and downtime of more than a few days results in low oxygen conditions that are more difficult to reverse than prevent by normal operation. There were a few shutdowns in 2022, but the shift to operation upon demand at oxygen <15 mg/L at the chosen trigger sensor (17 ft early in summer 2022, 15.5 ft later) provided an oxygen buffer that prevented anoxia in the deep water except for one brief period in early August. Excessive heat in the pumphouse also compromised system performance but oxygen was maintained even with lower output. Of greater concern in 2022 was a cracked intake pipe and biofouling of the headers, leading to suboptimal oxygen output. And of paramount concern in 2022 was the very hot weather that fostered higher oxygen demand and low oxygen as shallow as 10 ft below the water surface, an area the OST™ was not designed to fully address.

Almost all operational problems were solved in 2023. The prescribed fan to cool equipment in the shed was not installed until later in summer, but heat was not an obvious factor in system performance in 2023. Clogging of the intake header caused the only low oxygen readings of 2023, and this could have been avoided with a mid-season cleaning of the headers, facilitated by installation of a buoyancy line in 2023 to bring the pipe assembly to the surface as desired. While shutdowns are to be expected with any oxygenation system, all tools and procedures were in place to minimize adverse effects in 2023. Operation is 2024 was as planned into September. There was a cessation of the recording of sensor monitoring, but all available information suggests that the OST™ system operated properly until shutdown in early October. It took several years of adjustments, but the OST™ system ran as intended in 2024 with no appreciable maintenance.

A complete financial review of this program is beyond the scope of this report, but the need for oxygen input has decreased over time through OST™ operation and has distinct implications for future operation. Other oxygenation projects have demonstrated reduced need over time, as pent-up oxygen demand is satisfied. The electrical cost to operate such systems has declined by as much as 75% from the initial start-up year, although that could take a couple of decades to reach. For Sarah's Pond, with unintended shutdowns, the direct comparison of costs among years is somewhat confounded, but the energy cost to achieve the 2024 conditions was only 78% of what was required in 2021, and the system had no breakdowns in 2024. The amount of oxygen necessary to maintain the desired oxygen regime was less in 2024 than in 2021, suggesting a gradual amelioration of oxygen demand. Again, the oxygen demand will likely never be completely satisfied, with ongoing inputs of organic matter, but the cost to maintain adequate oxygen is expected to decline over time.

Program results for nutrients, water clarity, and algae

The same monitoring program conducted in 2019 was continued through 2024, although the number of dates on which manual monitoring and water quality sampling occurred has not been constant over the years and was only monthly in 2024. Sampling for forms of phosphorus (P) and nitrogen (N) occurred near the surface and bottom of the deepest part of the eastern basin, marked with a buoy. Water clarity was measured there and at a second site in the western basin. Temperature and oxygen profiles were collected at each of those two sites at the time of water sampling. A phytoplankton sample was also collected near the surface in the eastern basin and sometimes in peripheral areas where algae accumulations were visible. Comparison of data among years has some limitations based on sampling locations and frequency, but enough sampling was performed to allow general comparisons over time.

While a specific P target for Sarah's Pond was not set, it is generally accepted that algae blooms are rare with total P <10 ug/L and common with total P >25 ug/L. Total P concentrations for samples collected in 2018-2024 (Figure 13) always exceeded the 10 ug/L level and often the 25 ug/L level. Total P concentrations in surface water were routinely <25 ug/L once the OST^{TM} system was turned on. Total P values in bottom water tended to be higher, a product of both release from sediment under low oxygen conditions and settling of particles containing P (such as dead algae) from above. But half the deep water total P values in 2024 were <25 ug/L for the first time since oxygenation was initiated. The reduction in total P concentration with OST^{TM} operation is evident, and improvement over the four years of operation is apparent. This may be a function of improved operation but may also be related to cumulative effects over sequential years of operation.

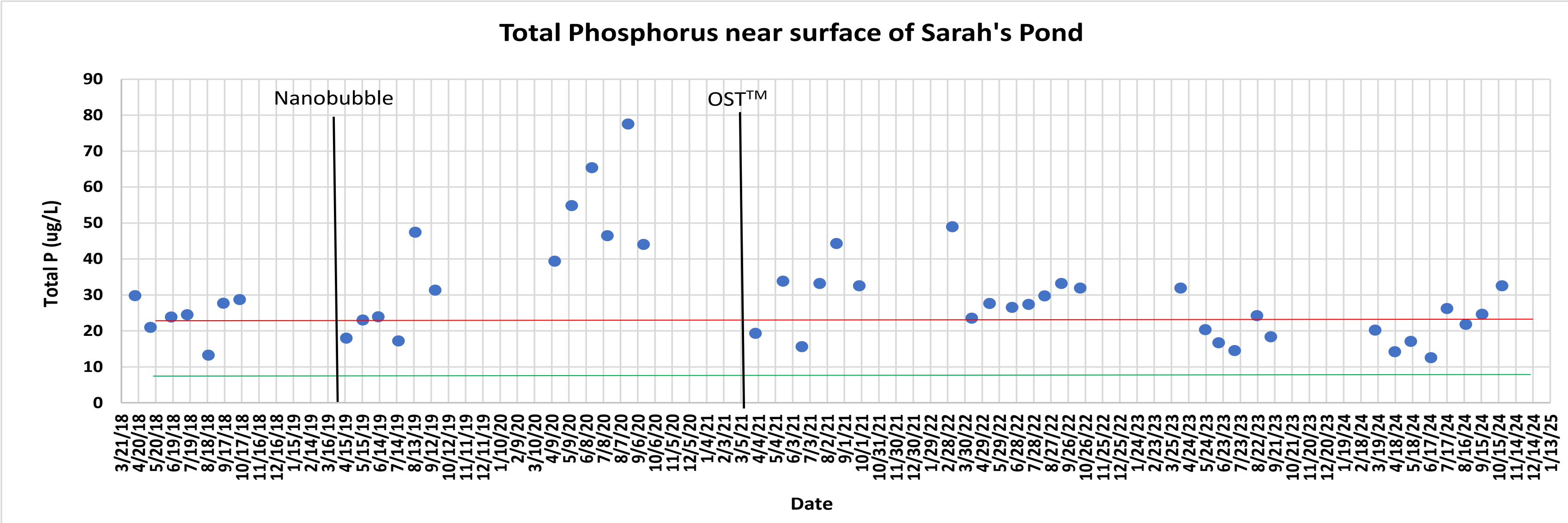
Beyond periods of system operation and shutdown, the most influential factors appear to be weather and water level. Higher temperatures and higher water level foster increased P concentrations through related processes and induce variability into the results. The OST^{TM} cannot address every possible factor affecting the pond but did keep oxygen higher when it was operating, and this reduces the potential for internal P loading and related algal blooms. Summers of 2021 and 2023 were relatively cool and wet, while summers of 2022 and 2024 were hotter and drier. Yet the trend among years is for declining P concentrations. It is more evident for surface water than deep water, and there can be increases in late summer, especially in the hotter summers, but total P has declined in Sarah's Pond as a function of OST^{TM} operation.

Ortho-phosphorus represents readily available P in the water column, and is generally scarce, as uptake is rapid in most aquatic systems. Values for Sarah's Pond (Figure 14) indicate that most values are <10 ug/L, often below the detection limit. Measurement of ortho-phosphorus will not be very helpful in understanding the effects of oxygenation and could be discontinued in future monitoring for that purpose.

The only sediment sample tested for Fe-P content was collected in 2021 and had a value of 1610 mg P/kg sediment as dry weight, which is very high. Even with a low solids content of 8.9%, the upper 10 cm of sediment (the portion that normally interacts with the water above), contains almost 16 g of P per square meter of sediment. With 8,000 m^2 in the target zone of the pond, this suggests a Fe-P reserve of 126 kg. If only 10% of that reserve was liberated during the summer (a fairly typical portion for Cape ponds), that would put 12.6 kg of P into the water column, enough to raise the pondwide P concentration by 182 ug/L. Release of enough P to support algae blooms could occur after just a week of low oxygen conditions, making it critical to keep that P bound in the sediment.

By keeping the surficial sediment highly oxidized, the OST^{TM} can accomplish that task, but deterioration of conditions can be rapid in the event of a shutdown. Targeting a much higher oxygen concentration (i.e., 15 mg/L) just above the sediment-water interface is intended to provide a grace period in the event of a shutdown, allowing the system to become operational again before oxygen is depleted. As observed multiple times during this four-year OST^{TM} project, however, it takes less than a week for anoxia to occur after a system shutdown.

Figure 13. Total Phosphorus at the surface and bottom of Sarah's Pond



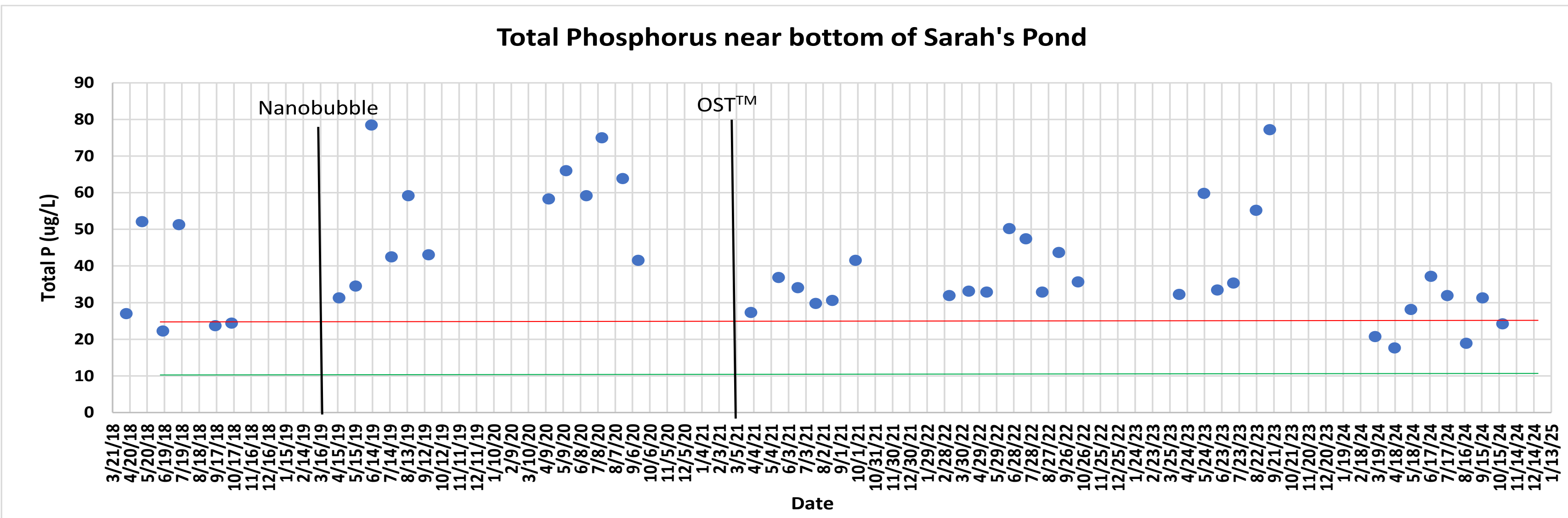
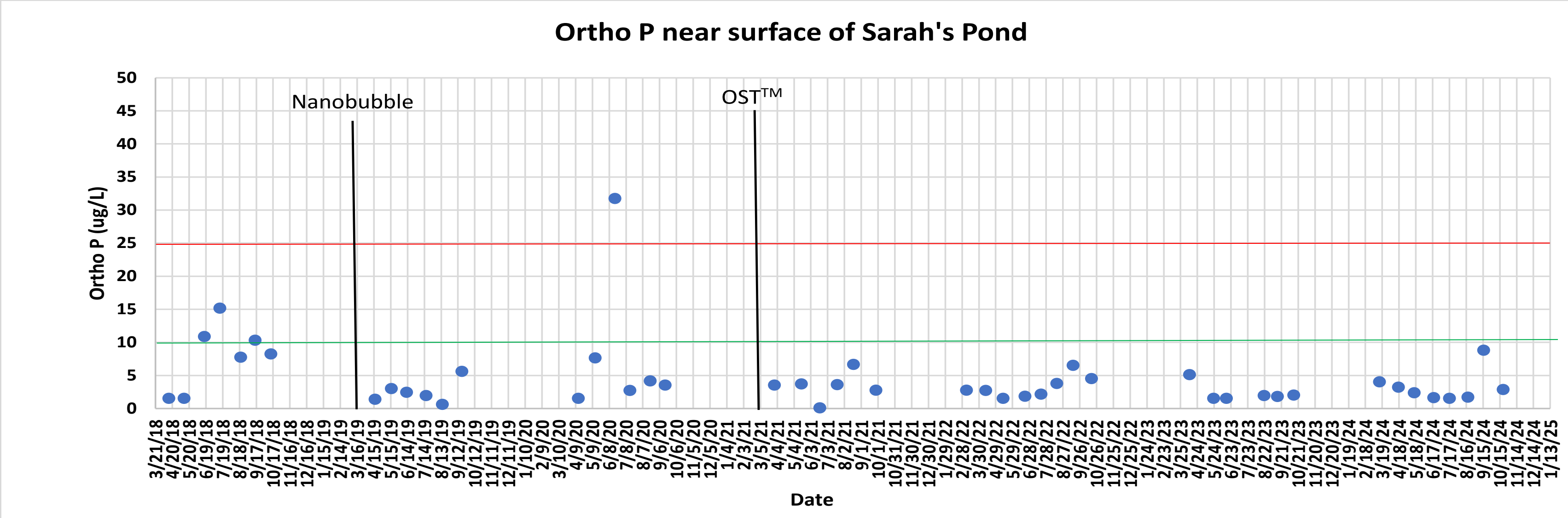
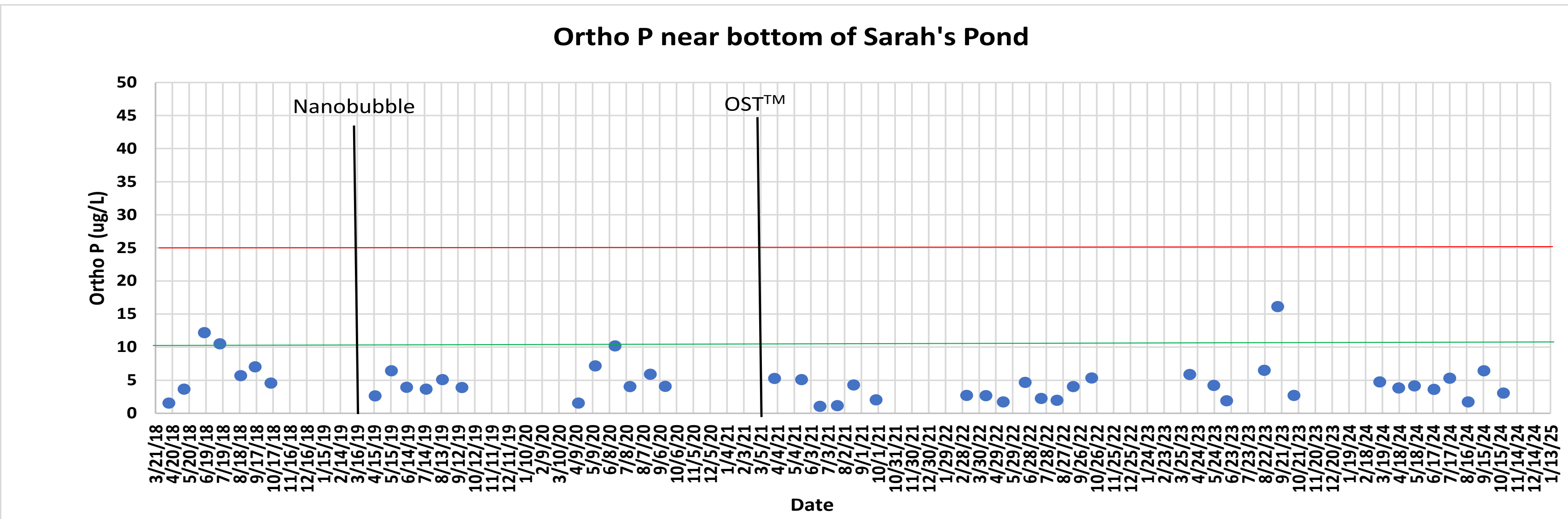


Figure 14. Ortho-phosphorus at the surface and bottom of Sarah's Pond





Total nitrogen concentrations (Figure 15) in 2021 and 2022 were similar to concentrations in 2018-2020 in the first half of the monitoring period but increased in late summer, leading to higher overall nitrogen concentrations in 2021 and 2022. The reason for the higher nitrogen concentrations is not certain but could relate to decomposition of organic matter with higher oxygen levels. P could increase from such decomposition too, but the presence of large amounts of iron dictates that any loose P (including all ortho-phosphorus) will bind to iron and precipitate to the sediment. The rise of cyanobacteria from deep water to the surface, with nitrogen and phosphorus in those cells, is also major mechanism of nutrient transport to the surface.

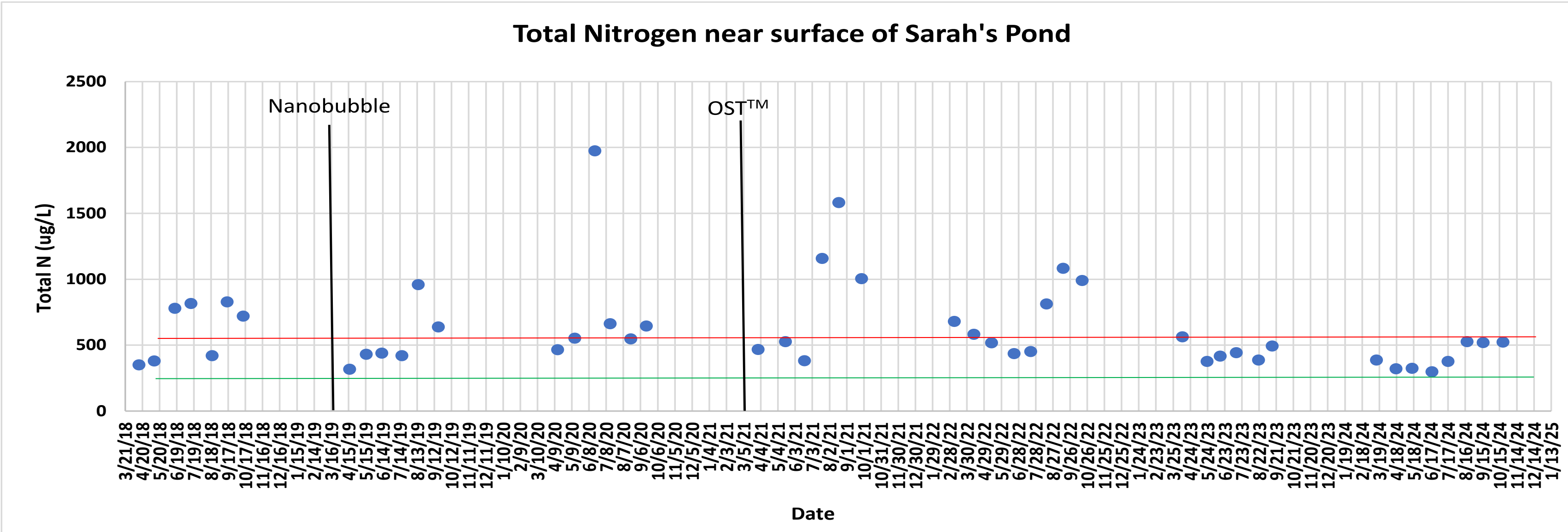
Surface nitrogen concentrations were much lower in 2023 and 2024 than in previous years, while the deep area values were similar to those of 2021 and 2022, rising over the course of the summer. It appears that nitrogen remained in deeper water and was not transferred to the upper waters in 2023, coincident with prevention of major cyanobacteria blooms. Those cyanobacteria, which tend to start growth near the sediment-water interface and rise to the surface, take a lot of nitrogen with them. The same process pertains to phosphorus. Prevention of this mechanism of bloom formation appears to affect nitrogen and phosphorus dynamics to a substantial degree.

Forms of nitrogen are important in aquatic ecosystems, and both nitrate and ammonium nitrogen were measured in this monitoring program (Figures 16 and 17). Nitrate, much like ortho-phosphorus, tends to be scarce as it is rapidly taken up by algae. Concentrations of nitrate-nitrogen are routinely low in Sarah's Pond. Low nitrate is a stimulant for many cyanobacteria, however, so in the absence of nitrate it becomes even more important to control P to limit algae blooms. Nitrate could be eliminated from future monitoring to save funds for other assessments.

Ammonium nitrogen is the degradation product of decomposition and can accumulate where oxygen is low. Where oxygen is adequate and the correct bacteria are present, conversion of ammonium to nitrite and then nitrate is expected to be fairly rapid. Ammonium nitrogen in the surface waters of Sarah's Pond (Figure 17) tend to be low, suggesting conversion to nitrate and then uptake of that nitrate by algae, as nitrates are also low. Yet ammonium nitrogen concentrations were elevated in deep water, a condition usually associated with low oxygen. Oxygen has only rarely been low in the deep water of the eastern basin of Sarah's Pond, where the samples were collected, since the OST™ system was installed, so this is a surprising situation. Oxygen where the samples were collected has been documented to be very high much of the time, so the only explanation for the accumulating ammonium is either lack of the necessary bacteria or a much slower conversion process than is typical.

It is possible that the high level of oxygenation stimulates decomposition and release of ammonium at a rate faster than the conversion can occur. There is some indication that ammonium levels have decreased over the four years of OST™ operation, so it may take time for a new equilibrium to be reached. It is interesting to note that the nanobubble system in place in 2019 and 2020 did not appear to stimulate ammonium generation; this may be matter of inadequate oxygenation or mixing into the shallower waters. However, ammonium levels were elevated in 2018, prior to any oxygenation effort. It is also possible that sampling was close enough to the bottom to capture ammonium that had not yet been converted but would be shortly. There is more to understand about ammonium generation in Sarah's Pond than the current data can illuminate.

Figure 15. Total Nitrogen at the surface and bottom of Sarah's Pond



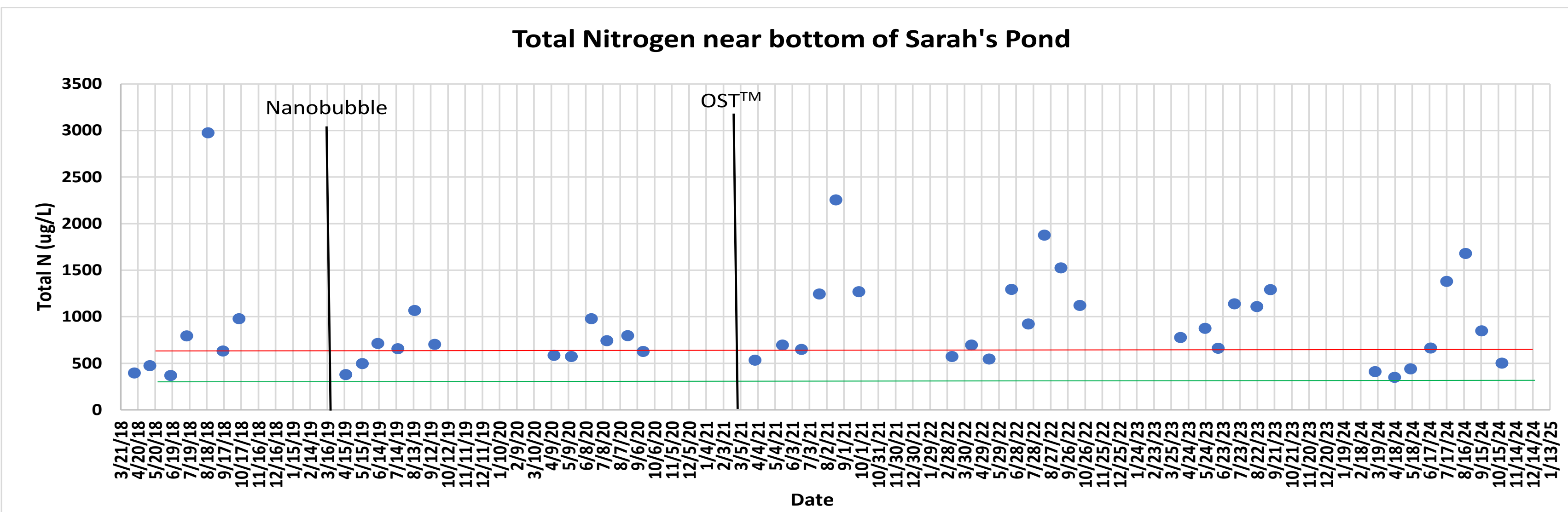
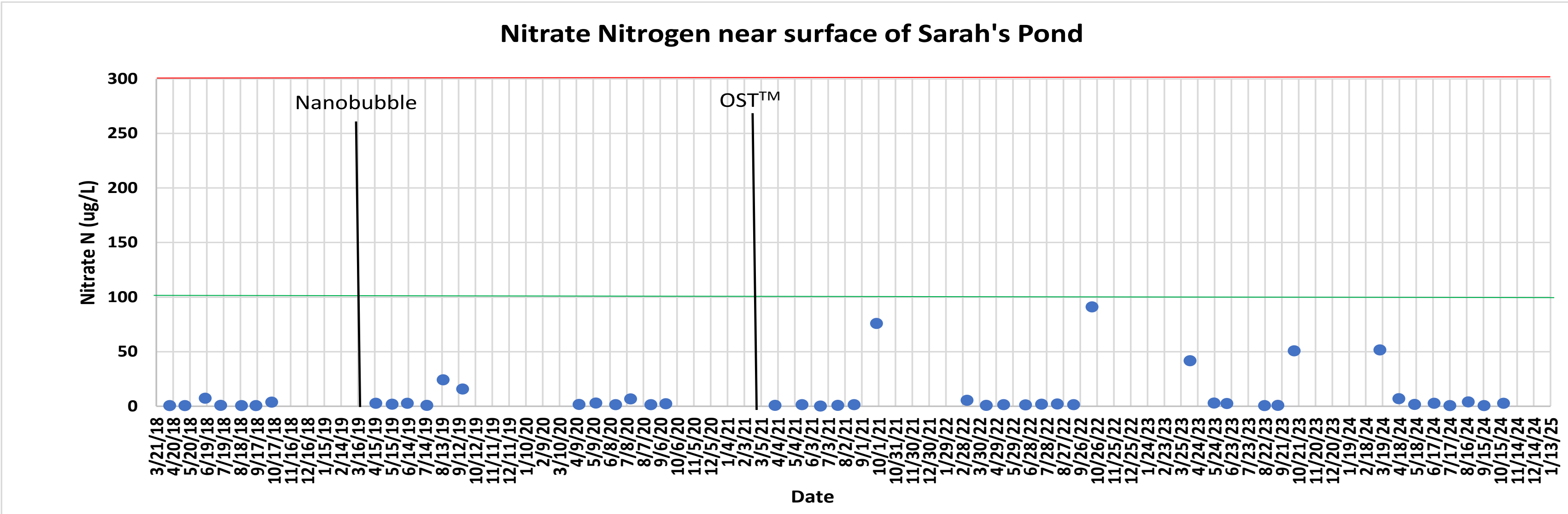


Figure 16. Nitrate Nitrogen at the surface and bottom of Sarah's Pond



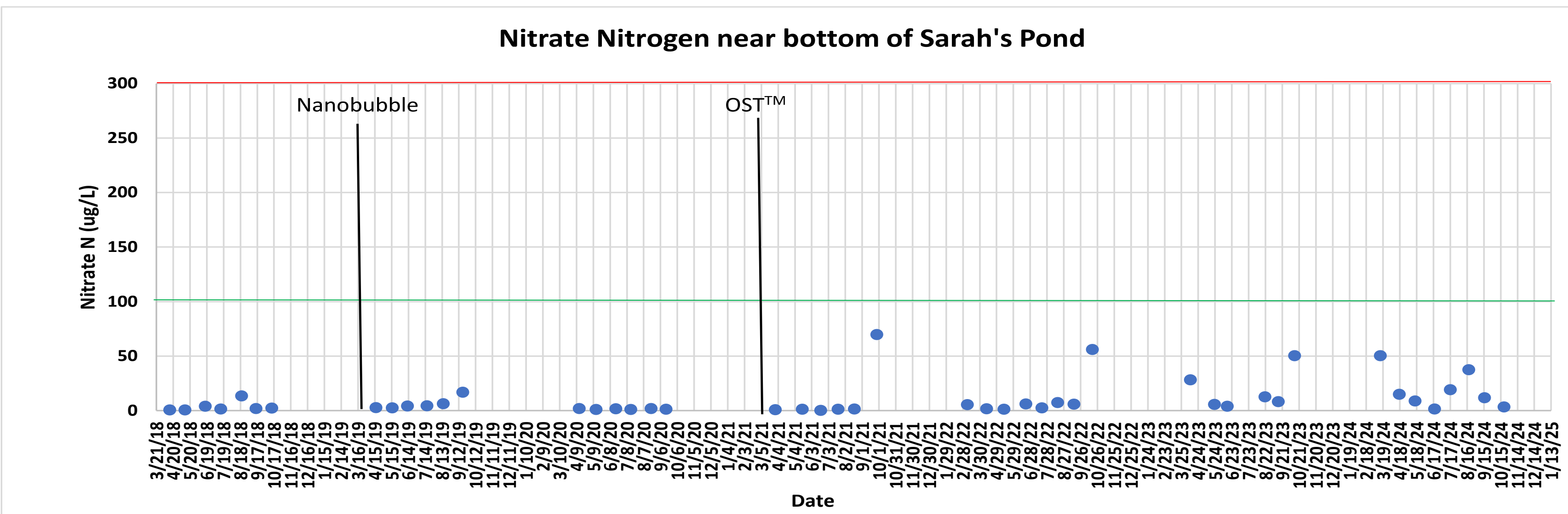
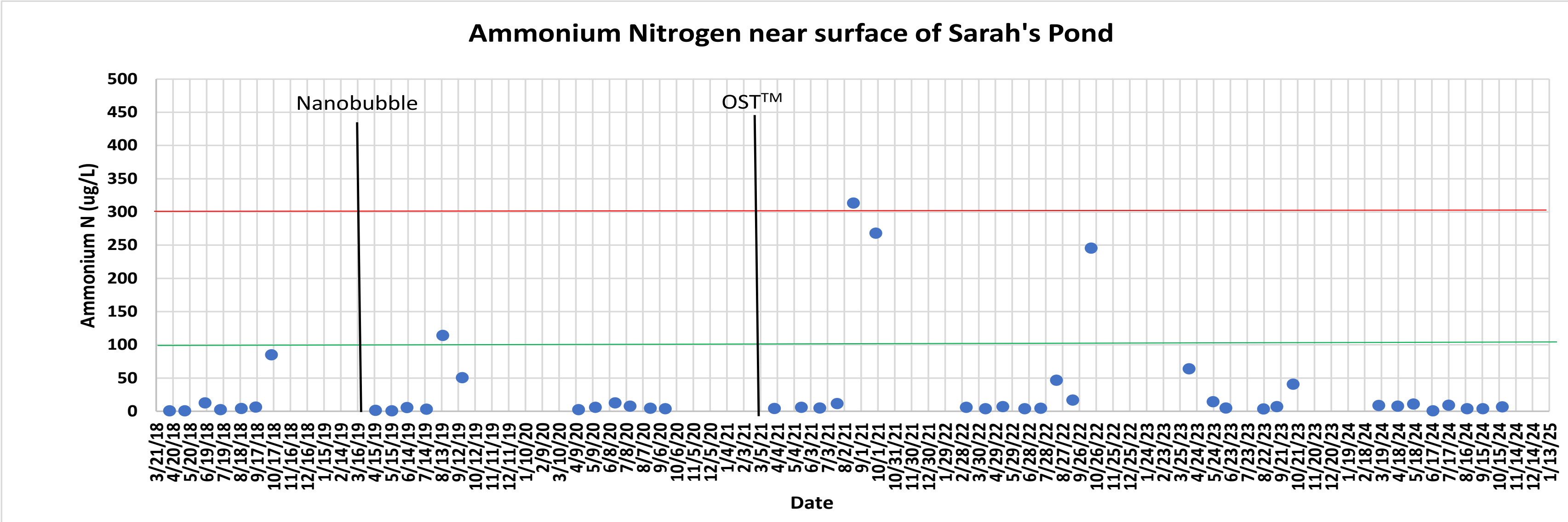
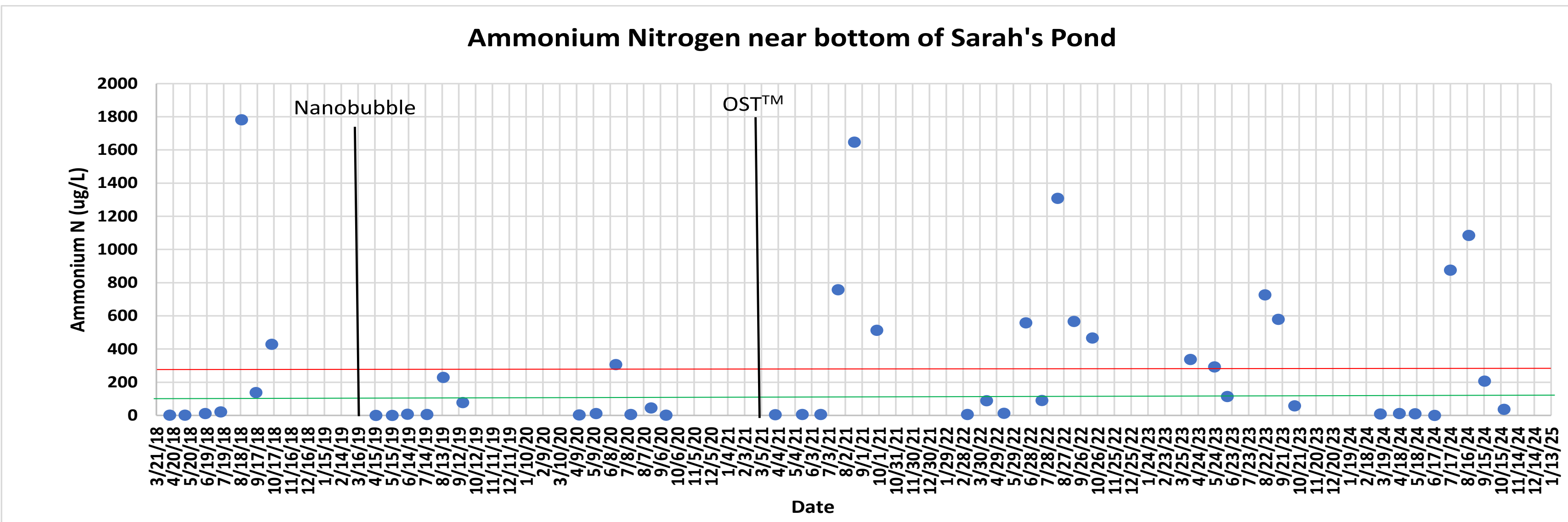


Figure 17. Ammonium Nitrogen at the surface and bottom of Sarah's Pond





Increased N to P ratio can help reduce the probability of cyanobacterial dominance, so the relative increase in N in deep water is not necessarily a problem. Ratios of N to P >20 rarely foster cyanobacteria, which have a competitive advantage at N to P ratios <10 since many forms can utilize dissolved nitrogen gas, unlike other algae. The pond may still be green with high available P but would not be expected to have an algal community dominated by cyanobacteria. P release from sediment tends to come with a low N to P ratio (usually <5:1), favoring cyanobacteria, so suppression of that release will tend to raise the overall N to P ratio in the pond and especially in deep water, favoring algae other than cyanobacteria.

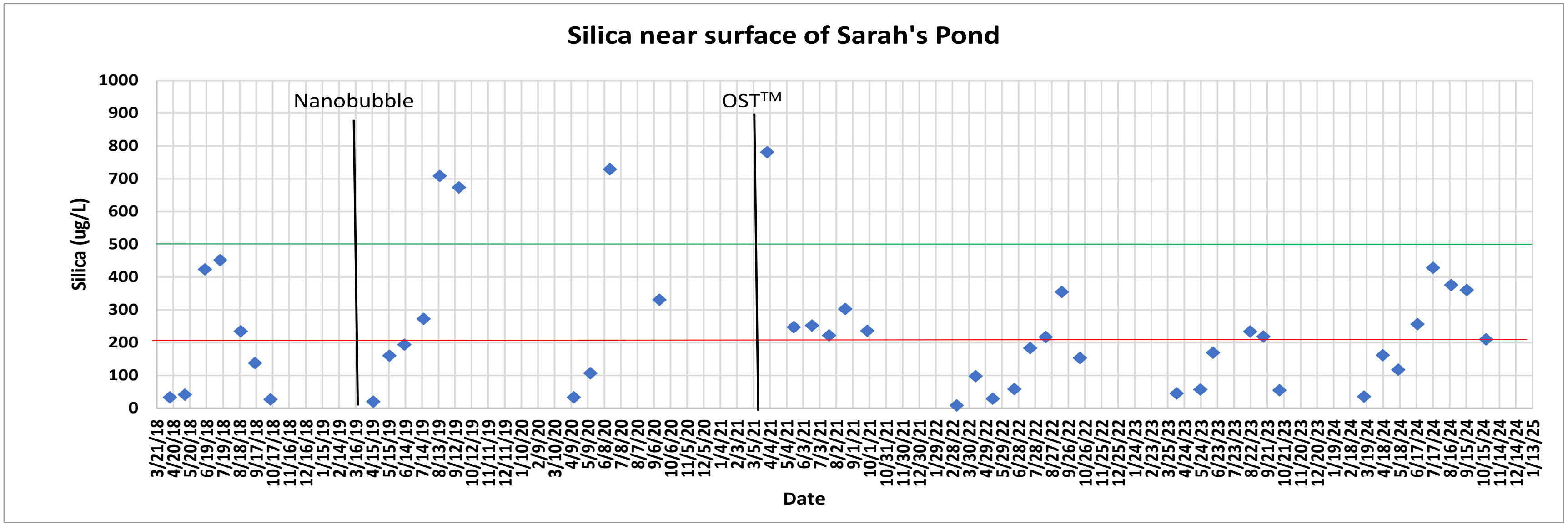
The average N:P ratio in deep water of Sarah's Pond, where cyanobacteria blooms develop, has risen from 15.6 to 28.9 with OST™ operation, a significant and favorable increase. The surface N:P ratio has also increased, but not significantly (20.5 to 22.9), and is less indicative of support for cyanobacteria than the deep water values.

Silica has also been measured as part of the monitoring program (Figure 18). Silica is important to the growth of diatoms and some golden algae, which use it in their cell walls, but is otherwise not as important as N or P as nutrients for algal growth. Values for silica vary substantially and are sometimes low, which may partly explain the relatively low density of diatoms in Sarah's Pond. The covering of silica-rich sand with organic muck may lead to this condition, limiting release of silica into the water column. It is generally not a problem that receives much management attention, but injections of silica have been used in some systems to prolong diatom growth going from spring into summer and limit nutrient availability for other algae. Sarah's Pond is better off focusing on P control.

Chlorophyll-a is an algal pigment that is often used as a surrogate for algae biomass, although the ratio of chlorophyll-a to biomass among algae groups can vary by about sixfold. However, chlorophyll-a concentrations provide an indication of algae blooms when values are higher than 10 ug/L and certainly when concentrations exceed 20 ug/L. Values for Sarah's Pond in all years exhibit a rise in late summer, usually coincident with cyanobacteria blooms (Figure 19). Concentrations of chlorophyll-a in Sarah's Pond surface water reveal a decrease since the OST system has been in operation. Concentrations in 2023 and 2024 were all <20 ug/L and averaged <10 ug/L. Peaks near 40 ug/L occurred in 2021 and 2022, with even higher values in 2020 (the last year of nanobubble testing) and similar values in 2018 and 2019. The decrease in recent years is either a product of more effective oxygenation or a cumulative effect of oxygenation over multiple years, possibly both.

Concentrations of chlorophyll-a in deeper water tended to be higher in all years and do not have as strong a seasonal component but exhibit a similar pattern of decrease since OST™ was installed. However, deep water measurements are often confounded by non-living organic particles that fluoresce at the same wavelength as chlorophyll, so deep water values are not as useful for assessing algae density or management progress. Still, oxygenation has reduced this measure of algal abundance.

Figure 18. Silica at the surface and bottom of Sarah's Pond



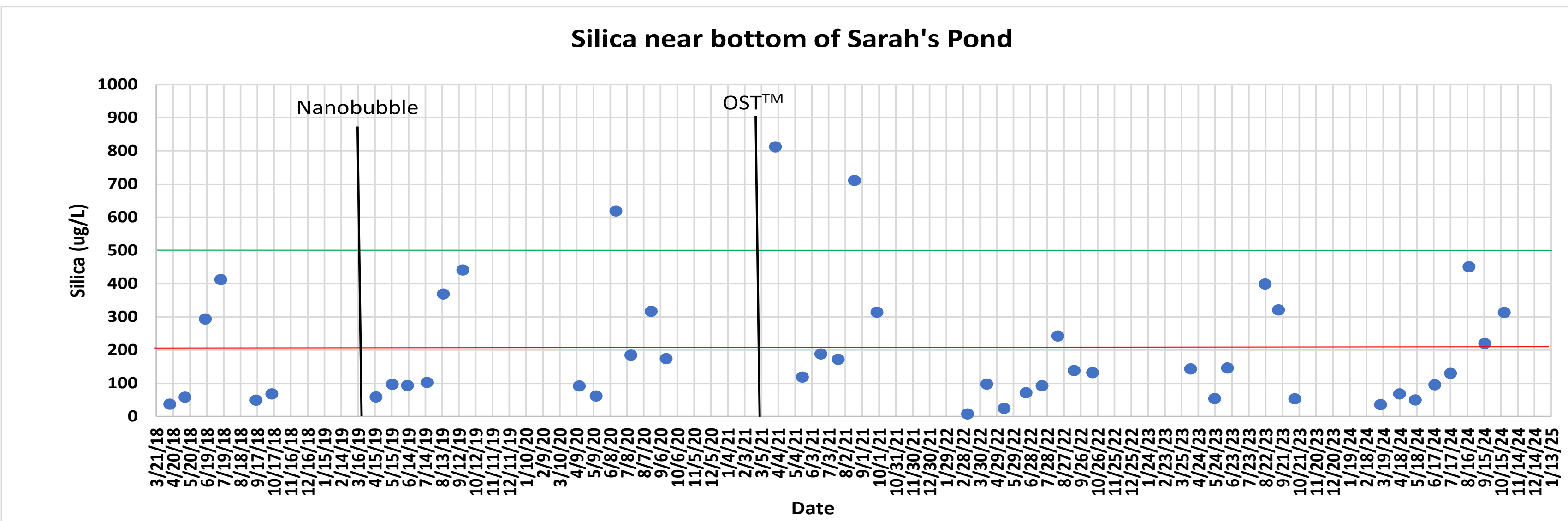
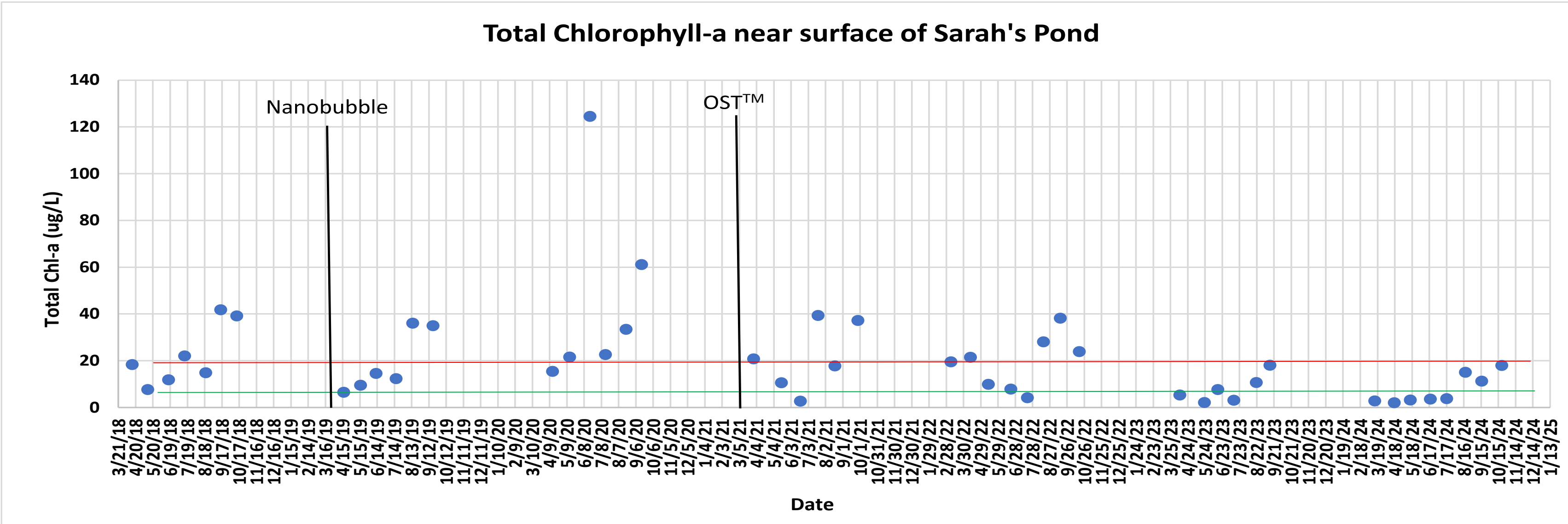
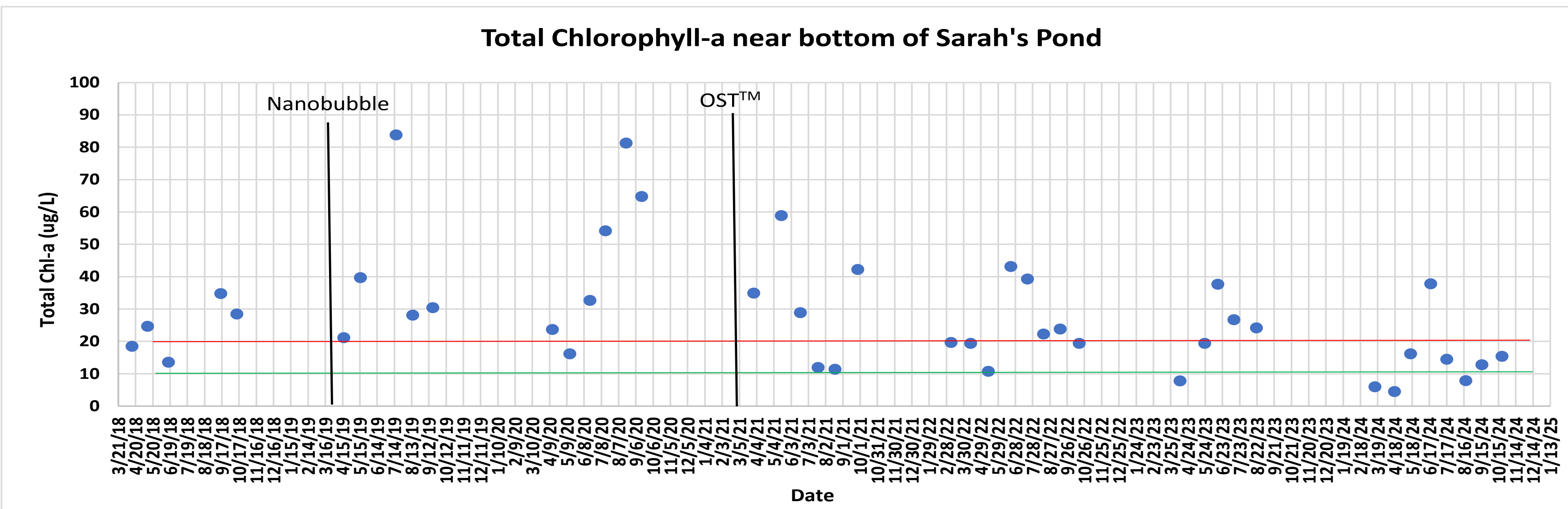


Figure 19. Total Chlorophyll-a at the surface and bottom of Sarah's Pond





Water clarity is often what people perceive as most indicative of lake quality but is affected by multiple factors besides the abundance of algae. Non-living particles can enter with runoff or be resuspended with wind, lowering clarity. Yet algal abundance is a major factor in water clarity, and Sarah's Pond has suffered low clarity due to blooms of multiple algal groups, not just cyanobacteria. Spring blooms of golden algae are common in Cape Cod lakes, including Sarah's Pond, and may be less indicative of excess P than elevated dissolved organic matter, as those algae can utilize such compounds and do not depend entirely on photosynthesis. Summer blooms can include golden algae but are more often green algae or cyanobacteria, with the latter creating greater concern due to possible toxicity. Sarah's Pond has experienced summer blooms of all of these forms, with concurrent decreases in water clarity.

The general clarity pattern for Sarah's Pond is possible depression in early spring from golden algae, followed by an increase to maximum clarity in late spring, succeeded by declining clarity through the summer, often with some increase in clarity in early autumn (Figure 20). The summer decline in clarity has been observed in all years, even with OST operation, but the maximum clarity has increased and the date of lowered clarity has gotten later each year since OST™ installation. There is considerable variation, a lot of that likely induced by weather pattern, but the improvement is clarity overall is obvious. The reasons for the eventual lowering of clarity are less obvious, but the loss of clarity coincides with the rise of total P in the pond. P control remains the logical target where blooms are to be prevented.

In past years, as described in annual reports, cyanobacteria blooms followed OST™ shutdowns that allowed anoxia to develop. However, there were not such shutdowns in 2024 and there was still a cyanobacteria bloom, milder than in other years, but still quite unsightly. Yet the oxygen data indicate that some areas of sediment were subjected to low oxygen, all outside the depth or lateral area targeted by OST™, and P did increase in a manner that suggested release from sediment exposed to anoxia. The OST™ is not designed to handle all possible contributory areas of Sarah's Pond.

Ultimately, it is the amount and composition of the phytoplankton that was the target of management at Sarah's Pond, with oxygenation as the chosen tool. Detailed phytoplankton assessment was conducted for samples collected as part of the monitoring program, but summarization by major algal groups (Figure 21) is sufficient for the purposes of assessing oxygenation program results. Although OST™ did not prevent an eventual shift to an assemblage including or even dominated by cyanobacteria, the pattern over time suggests that cyanobacteria have become less dominant and occur later in the summer season than they did without OST™.

An even simpler summary, using the average of all phytoplankton from each of the major groups in a stacked bar graph for each year (Figure 22), provides immediate perspective. Cyanobacteria were dominant prior to OST™ installation and appear to have been even more abundant during the nanobubble experiment years, but cyanobacteria have declined substantially since OST™ has been in operation. Algal abundance in the first year of OST™ (2021) was just as high as in 2020, but green algae replaced much of the cyanobacteria biomass. Average algal biomass declined in each successive year with a concurrent shift toward less and less cyanobacterial biomass. Golden algae have maintained dominance in most samples since 2022.

Figure 20. Secchi Disk Transparency in Sarah's Pond

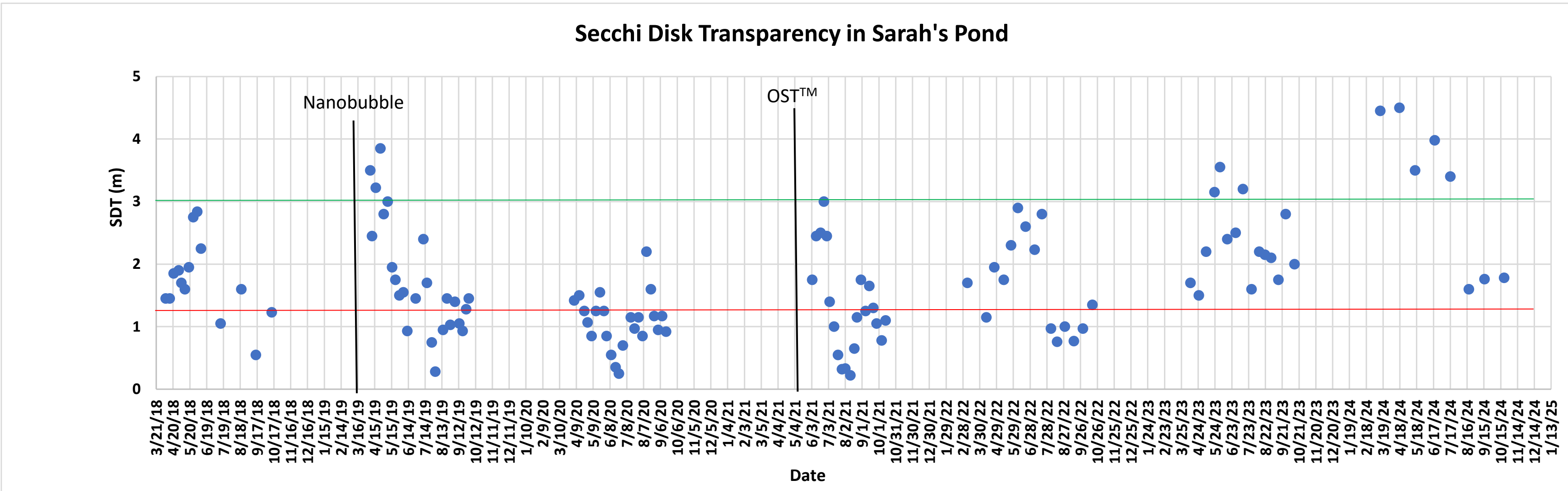
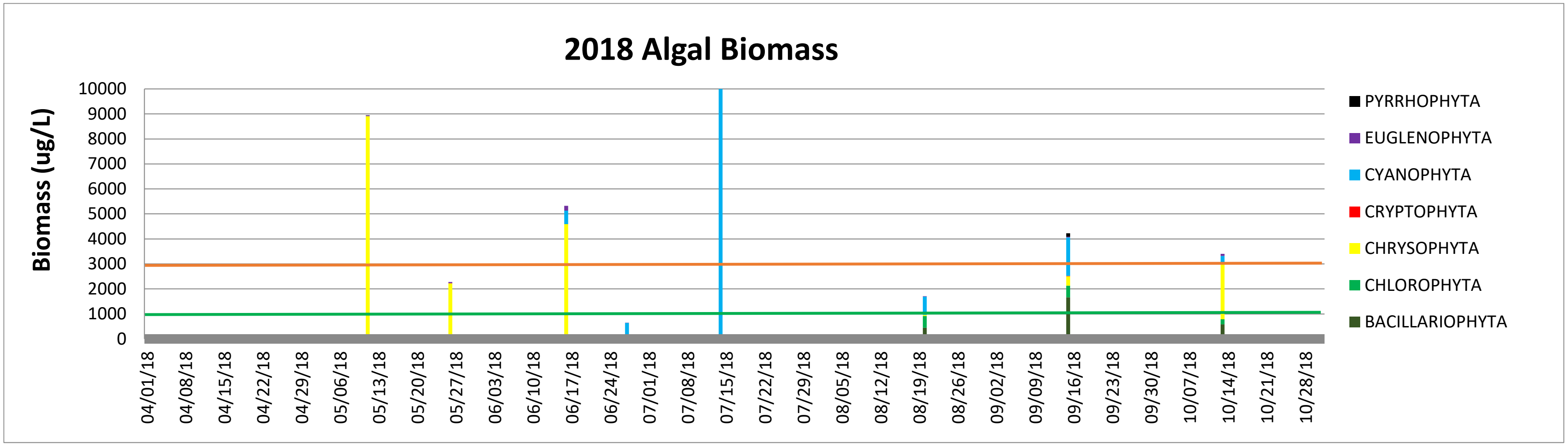


Figure 21. Phytoplankton of Sarah's Pond



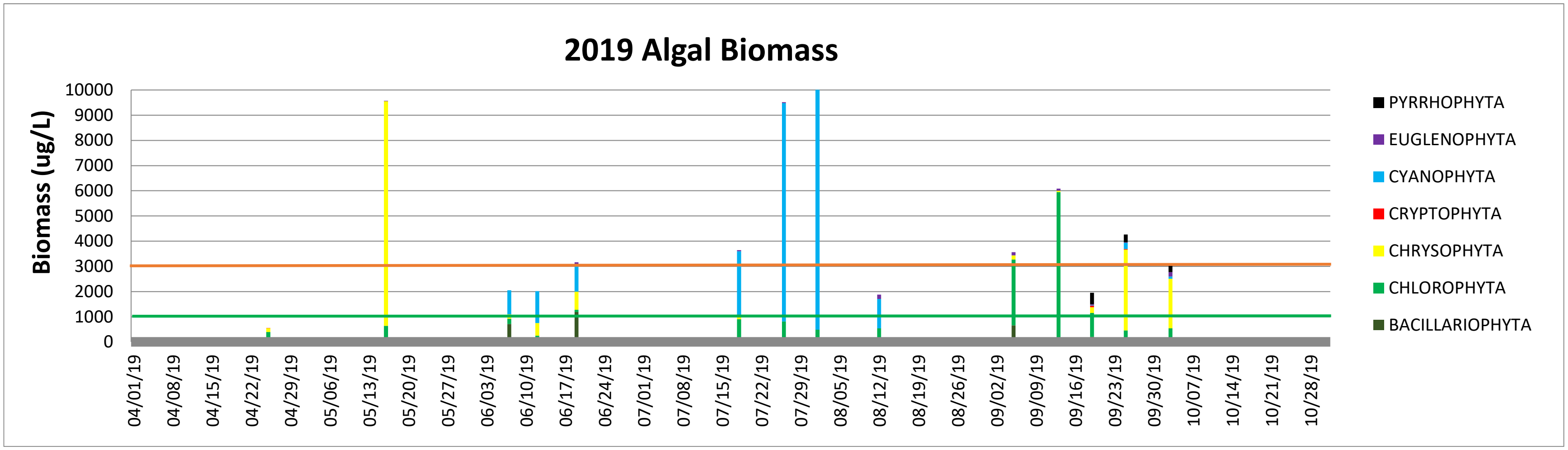
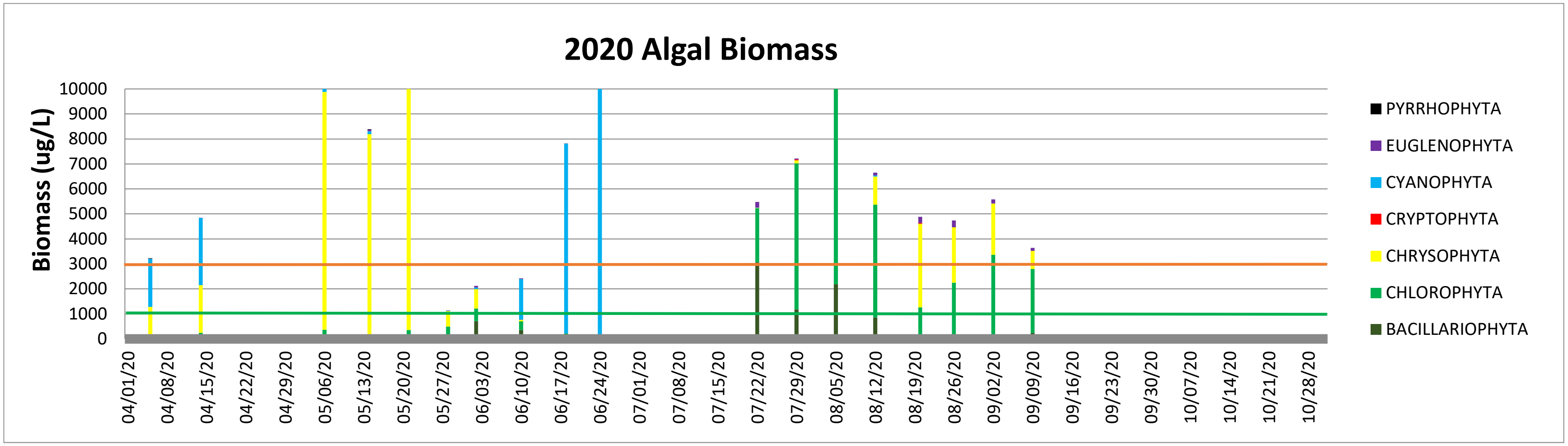


Figure 21 continued. Phytoplankton of Sarah's Pond



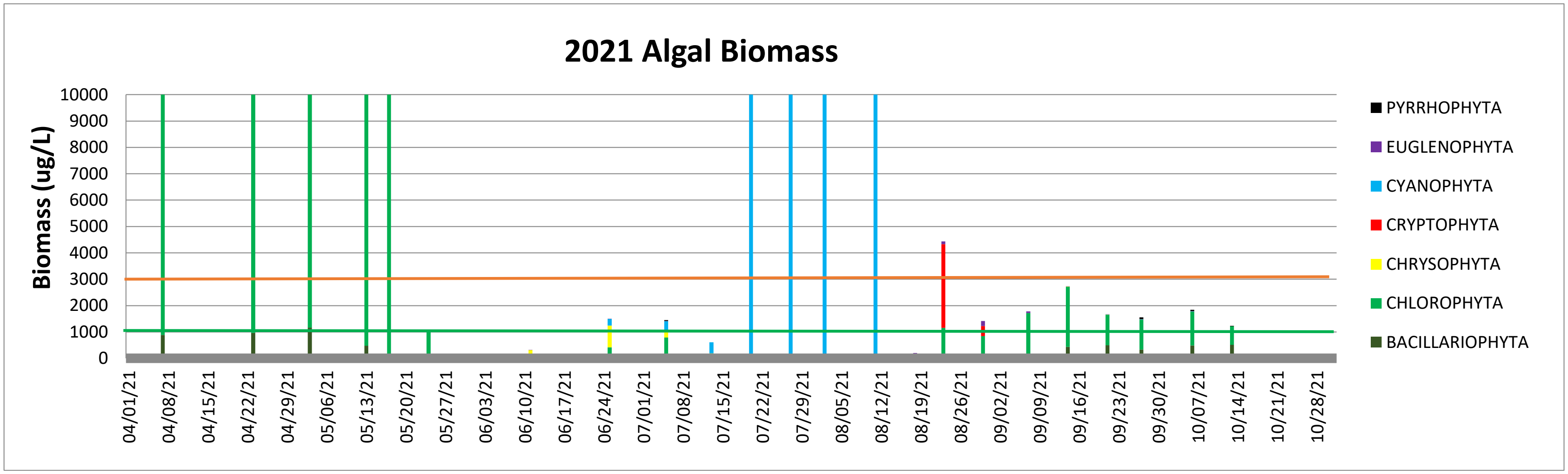
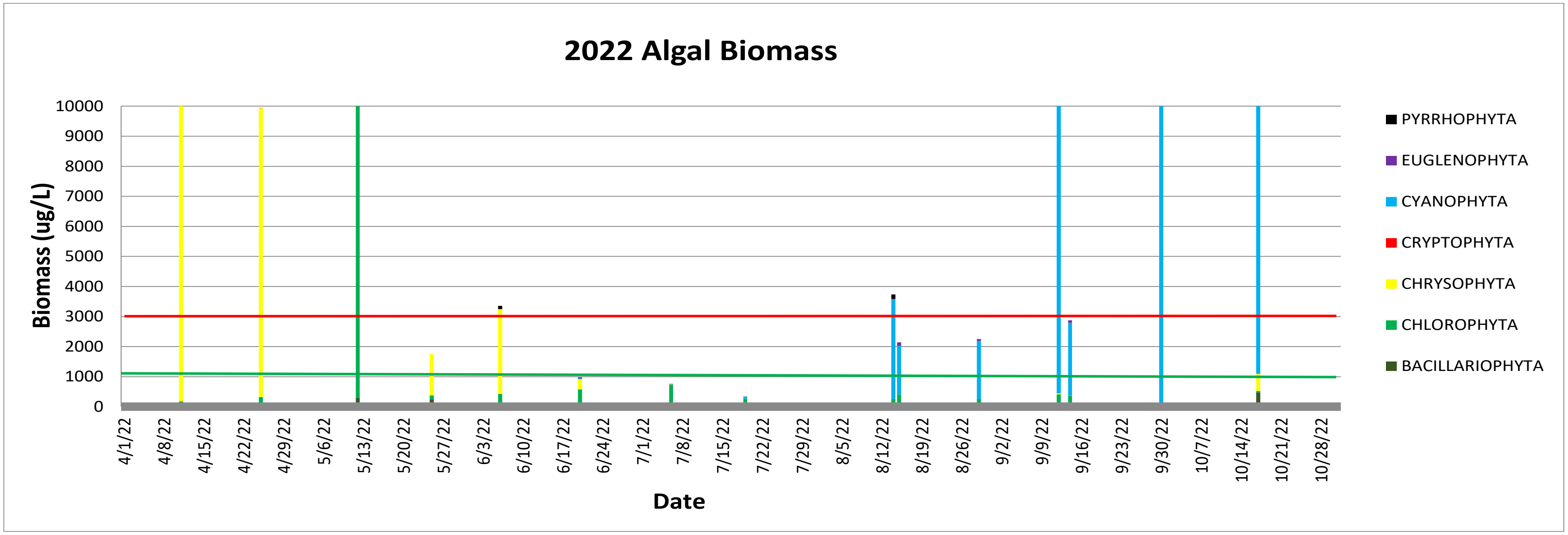


Figure 21 continued. Phytoplankton of Sarah's Pond



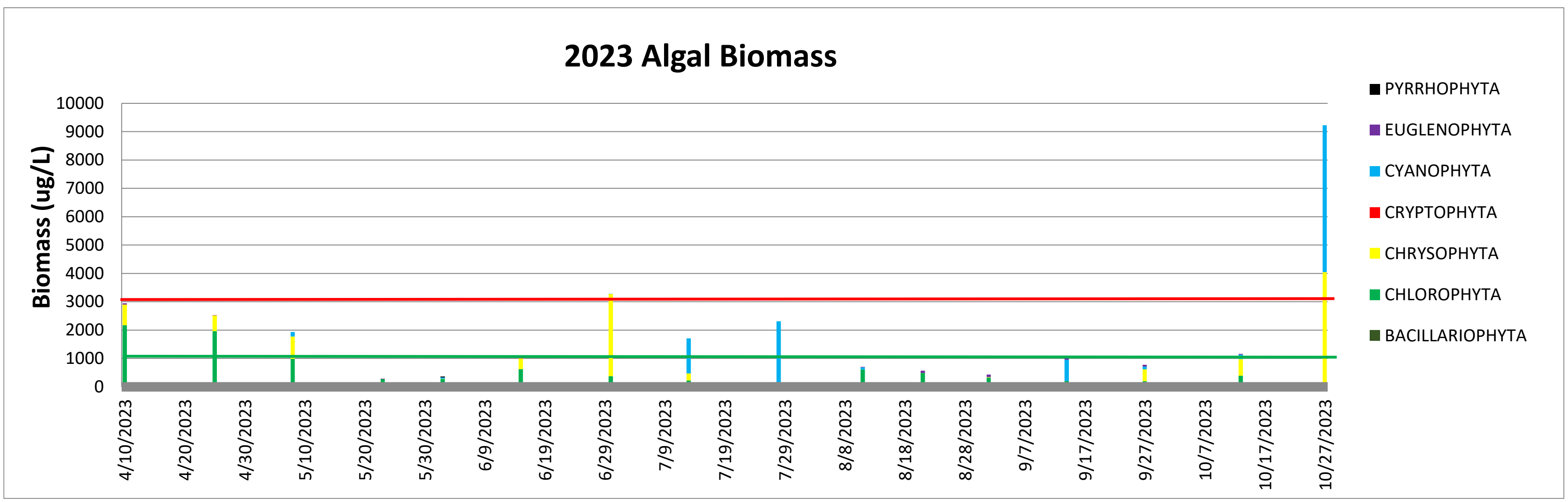


Figure 21 continued. Phytoplankton of Sarah's Pond

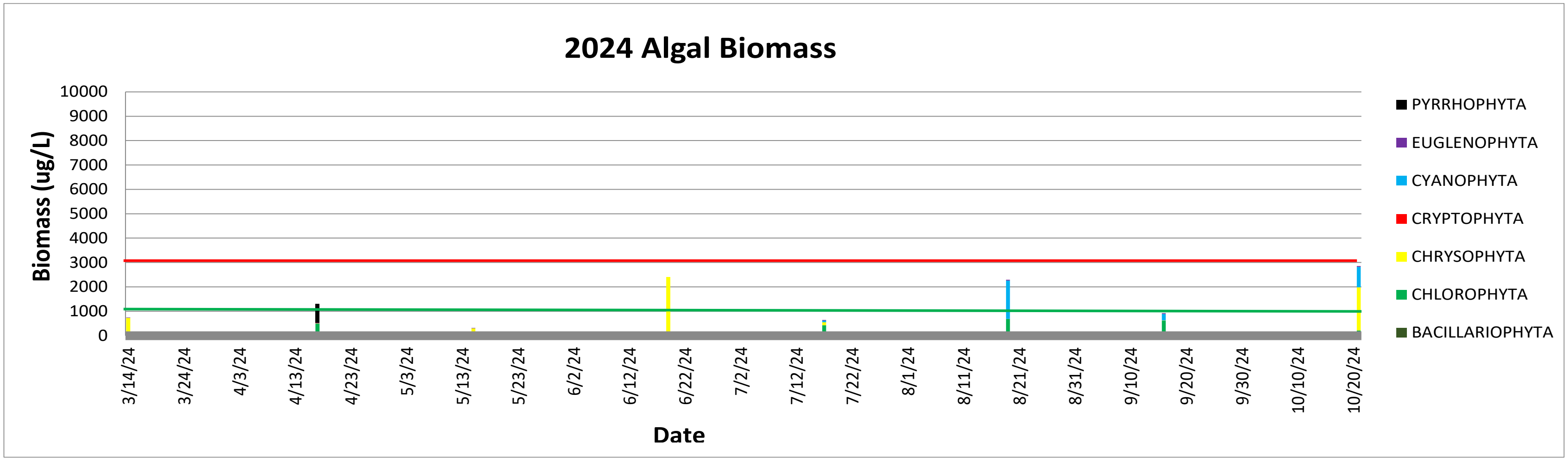
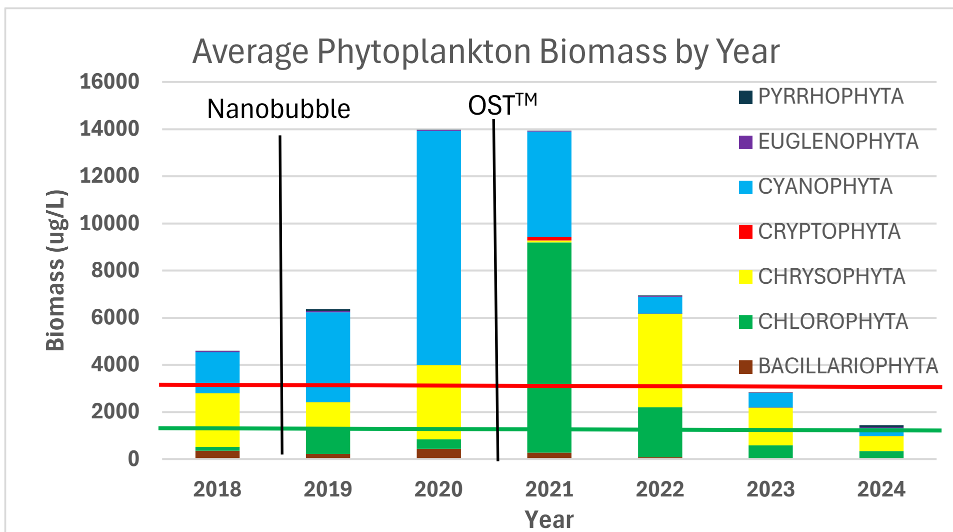


Figure 22. Average phytoplankton biomass for Sarah's Pond samples from individual years



A primary driver for cyanobacteria is the release of P from the sediment at low N to P ratio, as some cyanobacteria can utilize dissolved N gas and do not depend upon other N compounds in the water column. As light penetrates to the bottom everywhere in Sarah's Pond unless a bloom is in progress, algae can grow at the sediment-water interface, utilizing P as it is released without it accumulating in the overlying water. With high nitrate levels it is often filamentous green algae that form mats in such situations, but in many cases nitrates are quickly used up and the N to P ratio will be low, favoring cyanobacteria. When enough P has been stored in cells, many cyanobacteria are able to generate gas bubbles within cells and float upward, gaining more access to light and forming the blooms that have been observed. This appears to be a major mechanism for cyanobacteria blooms in Sarah's Pond, but one that has been suppressed by OST™.

The types of cyanobacteria that have been abundant have been fairly consistent, with *Dolichospermum* providing the greatest biomass in most years. *Aphanizomenon* was abundant in 2019 and *Woronichinia* became dominant later in 2022, after a *Dolichospermum* bloom. In 2023, *Aphanizomenon* was the most abundant cyanobacterium in mid- to late summer, while the biomass spike in late October was comprised of *Dolichospermum* and *Woronichinia*. *Aphanizomenon* and *Dolichospermum* were the most abundant cyanobacteria in 2024, with smaller amounts of other genera present. *Microcystis* has also been present but not dominant in this monitoring program. All of these cyanobacteria are known to grow at the sediment-water interface before rising in the water column to form blooms. All are considered possible toxin producers, although actual toxin production is erratic among cyanobacteria and should not be assumed without direct testing.

The primary type of golden algae that has been abundant is *Dinobryon*, a colonial flagellate that colors the water brownish. Abundant green algae are mostly from the orders Chorellales and Sphaeropleales, small colonial or unicellular forms that color the water greenish. In a few cases cryptomonads (small flagellates) and pyrrhophytes (larger flagellates) have been abundant, but not as frequently as the three algae groups (goldens, green, and cyanobacteria) that bloom in Sarah's Pond. None of these non-cyanobacteria pose any threat of toxicity but they can discolor the pond and reduce clarity.

Conclusions and recommendations

Much has been learned over the seven years of more intensive monitoring and six years of oxygenation experimentation in Sarah's Pond. While better results in terms of sustained pond condition are desirable, this has been a remarkably insightful program that is advancing the science of oxygenation of lakes and ponds.

Sarah's Pond has elevated nutrient levels, particularly phosphorus (P), that allow algal blooms to form and lower clarity in the pond on a regular basis. Of particular concern is the triggering of cyanobacteria blooms by low oxygen at the sediment-water interface, this condition causing P to be released from the sediment at a low N to P ratio. The problem cyanobacteria are all forms known to initiate growth on the sediment surface then rise in the water column by forming gas bubbles in cells after sufficient P has been absorbed. Consequently, the release of P from sediment is likely stimulating these blooms. While elevated P in the water column is a chronic problem in Sarah's Pond, it appears that the most troublesome blooms and associated water quality impairments are the result of anoxia at the sediment-water interface and cascading effects that lead to cyanobacteria growth and dominance. In that regard, maintaining adequate oxygen near the pond bottom is viewed as a critical step in minimizing cyanobacteria blooms and maximizing pond quality.

The nanobubble system installed and operated in 2019 and 2020 did not provide sufficient oxygen to satisfy oxygen demand in the pond and was therefore unable to reduce cyanobacteria blooms. There were some nominal benefits from the system, but it did not achieve the target conditions under normal operating conditions even with expansion of its capacity. The nanobubble system was therefore discontinued in favor of oxygenation saturation technology (OST™) system installed and operated in Sarah's Pond in 2021 through 2024 and is still present to continue operation as desired. The OST™ system was able to achieve desired oxygen conditions consistently when operating, but there have been operational interruptions that allowed low oxygen conditions to develop at some point through 2023, and there are shallower parts of the pond that experience low oxygen and which are not addressed by the OST™ system. Cyanobacteria did bloom in all four years of OST™ operation, but at declining intensity and later in the summer each year.

Periods of successful OST™ operation clearly indicated the potential to maintain high oxygen near the pond bottom and demonstrated benefits that can be achieved by such operation. However, unreliable operation in 2021 and to a lesser extent in 2022 with a variety of equipment issues led to brief periods of anoxia near the pond bottom. There were five periods of system shutdown over a roughly six-month operation period in 2021, two over a similar spring-fall period in 2022, and only one period of poor operation in 2023, ranging from a few days to two weeks. There were no known shutdowns in 2024 and oxygen remained high at the bottom of the deepest part of the pond through the summer. Shutdowns lasting a few days do not appear to cause substantial impact, as it takes time for oxygen to be lost and redox reactions to release iron-bound phosphorus from the surficial sediment. Failure to maintain oxygen >2 mg/L near the sediment-water interface for more than a few days, however, appears to promote enough P release to trigger cyanobacteria blooms.

The OST™ system provides enough oxygen to keep the pond well oxygenated at depths greater than about 14 feet under the range of weather conditions and the automated system for turning the

OST™ on and off allows for efficient operation while maintaining an oxygen buffer that should provide adequate time to make repairs in the event of some kind of equipment failure. The OST™ was not designed to provide oxygen to shallow areas or the western basin of the pond. There may indeed be enough oxygen capacity in the current OST™ system under all but the most extreme conditions, but the distribution system is not set up to feed those peripheral shallower areas. The system could be altered to meet that need or a supplemental unit could be installed, but the progression of improving conditions over the last four years suggests that just maintaining the current system for a few more years is worthwhile before considering any further adjustments.

Phosphorus concentrations have declined and water clarity has increased over the last four years of OST™ operation, and a similar if slightly lesser decline has been observed for total nitrogen. The typical late spring/early summer cyanobacteria blooms observed in 2018-2020 were delayed to late July in 2021, mid-August in 2022, and late October in 2023. A cyanobacteria bloom occurred in late August of 2024, but the severity of blooms, based on both chlorophyll-a measures and phytoplankton biomass, has been declining since the OST™ system was installed. This suggests that cyanobacteria growth at the sediment surface, supported by P release under anoxic conditions, is the critical driver for cyanobacteria blooms, which are then responsible for increased nitrogen and phosphorus in surface water as the algae rise in the water column.

What is striking about the pattern of the data is that the changes have been gradual. Most other P management techniques, such as inactivation with aluminum or removal by dredging, are expected to have more immediate effects with benefits declining over time. One might expect a more pronounced improvement from the start with adequate oxygenation, but there are multiple factors at work that limit the response. From an operational perspective, there were problems to be worked out that caused poor performance at times during the first two years and slightly impaired performance in the third year. But even with adequate oxygenation, there are reactions that must take place involving a lot of sediment, ongoing inputs to the pond, and stimulation of decomposition that facilitates nutrient releases that must be processed. Furthermore, the OST™ system was not designed to handle the whole pond, leaving some areas as possible contributors of nutrients and algae even under the best possible operational scenario. The observed improvement over the four-year period of OST™ operation may therefore be a product of multiple influences and can be expected to continue for several more years.

Projection of when a new and acceptable equilibrium condition may be reached is complicated, and in fact there is rarely any true equilibrium for pond conditions, given variation in weather. Yet the pattern exhibited by the data can provide insights. Based on the bottom P concentration progression and a target of an average concentration of 15 ug/L, another three years of successful operation would be needed. Based on the surface P progression and a target of 10 ug/L, that target could be reached as early as next year. The targets are relevant but somewhat arbitrary, and since cyanobacteria tend to start their growth cycle on the bottom, the projection from bottom P data is probably the better choice in this case. If we use the same approach with surface chlorophyll-a data, a low chlorophyll-a value of about 2 ug/L could be reached as soon as next year, but with variation, probably more like three years. Using water clarity and seeking an average of 14 ft (4.24 m), the projection is for that to be achieved in three years. Achievement of the target averages does not mean that there will be no unacceptable values, but conditions should be acceptable nearly all the time.

Detection and response to equipment problems and operational constraints have improved system reliability. Advancements in OST^{TM} have helped improve Sarah's Pond. Key aspects of successful operation include:

1. Starting the system before any low oxygen conditions can develop; this could involve operation over the winter but start up in April should be sufficient. With operation automatically triggered by oxygen sensors, there is no pressing need to actually turn the system off, as it will not run when oxygen is sufficient, but it may be advantageous to lower the oxygen threshold above which the OST^{TM} does not operate in the absence of stratification.
2. Maintaining a large oxygen buffer over the pond sediment to drive the anoxic interface well into the sediment where light is sufficient to allow algae growth and to prevent anoxia while any shutdown scenario can be addressed; keeping the system running if oxygen is <15 mg/L near the sediment-water interface appears appropriate, but a threshold of 10 mg/L may be adequate.
3. Operating the system in an "on demand" mode, such that the system runs whenever oxygen drops below the target oxygen level (currently 15 mg/L) at the chosen sensor depth (currently 17 ft but adjustable to other sensor depths as desired).
4. Proper ventilation of any shore-based equipment to dissipate heat to the maximum practical extent. Note that new versions of OST^{TM} equipment place the oxygen transfer container in the target lake for improved cooling and oxygen transfer efficiency. Use of adequate ventilation and a fan in shore-based installations is recommended, but heat buildup during warmer months is still possible and equipment should be monitored regularly at such times.
5. Use of durable, high-quality materials for all system components to minimize downtime for repairs or replacement; at this point most of the original components of the system have been replaced or altered to maximize performance. The cost of better materials is worthwhile when it minimizes system downtime.
6. Equipping pipelines and headers with flotation capacity so that they can easily be brought to the surface for inspection and cleaning, with at least one mid-season cleaning recommended.
7. Frequent monitoring of in-situ, remotely accessible, sensor data to assess oxygen levels and detect any failures or abnormalities, facilitating timely action when needed.

Oxygenation differs from other P control techniques in that it is almost entirely preventive. If oxygenation fails to prevent significant P release due to insufficient oxygen input for any reason, it is unlikely that increased oxygen input will be able to prevent algae blooms resulting from P releases during inadequate oxygenation. Further, resumed proper operation after a period of shutdown can be expected to oxidize released iron, creating a precipitant that can clog the distribution system for oxygenated water, leading to reduced performance. Consequently, the ability of any oxygenation system to continuously deliver the design oxygen quantity is a primary concern in its design, construction, and operation.

Yet where properly designed and operated, oxygenation systems have the potential to provide additional benefits not often available by other means. Habitat improvements related to adequate oxygen are the most obvious benefits not attainable by most other techniques. P inactivation by aluminum or other inactivators may reduce oxygen demand but rarely eliminate anoxia to the extent achievable by a well-functioning oxygenation system. Removal of sediment by dredging can eliminate oxygen demand but will have many collateral impacts that can be avoided by oxygenation. The gradual changes in sediment potentially induced by oxygenation are both beneficial in nature and desirable in terms of a gradual rate of change; aquatic ecosystems will sustain less “shock” impacts under the gradual improvement observed to date in Sarah’s Pond.

Virtually all oxygenation systems require a period of site-specific adjustment to meet project goals and the Sarah’s Pond experience has been no different. Improvements have been made in system materials, system layout, and operational controls that have improved reliability and results. However, shutdowns or impaired performance periods are almost inevitable with oxygenation, and it is essential to have a checklist of things to evaluate when oxygen drops below the established threshold, with an on-call, designated party to conduct that evaluation and take appropriate action. Problem resolution within 3 to 5 days seems necessary to reliably avoid oxygen depletion.

The issue of high oxygen having potential negative impacts on aquatic life forms such as fish has been raised, but reviews through 2014 indicate no evidence that any oxygenation program has ever caused mass mortality. Many lakes experience oxygen concentrations approaching 20 mg/L as a result of excessive photosynthesis without fishkills or invertebrate mortality unless very low overnight oxygen occurs in the absence of photosynthesis, and that would not be an issue with an oxygenation system. Oxygen does not have to regularly be 15-20 mg/L for the system to work, but higher oxygen levels will enhance control of P release from the sediment and act as a buffer if the system is shut off for more than a few days. Adjustment over time through experience is advised.

While oxygen >4-6 mg/L throughout the pond should provide all desired benefits, that is a lower threshold, not an average, and maintaining a higher oxygen level, particularly near the bottom, will provide some security. An occasional shutdown for any of a myriad of reasons is to be expected and having a higher base level of oxygen will maximize the window of opportunity to correct any problems without adverse impact on the pond. It should be noted that higher oxygen levels do not necessarily result in higher operating cost and, while higher oxygen levels could allow more uptake, they will drive redox reactions deeper into the sediment and ultimately decrease oxygen demand.

While operation of the oxygenation system is not necessary until oxygen drops below about 80% saturation near the pond bottom, keeping the oxygen higher provides a margin of safety and allows oxygen to penetrate deeper into surficial sediments, satisfying oxygen demand and minimizing P release. Low oxygen near the bottom has occurred in early April and operation through October may be necessary to minimize low oxygen and related P release. Year-round OST™ operation is a possibility with potential benefits but does not appear necessary at this time in Sarah’s Pond.

It appears worthwhile to operate the current system for at least three more years, based on the projections from the data for the period of record. Improvement has occurred and more can be expected with proper OST™ system operation. A single technique such as oxygenation may not be able to solve all pond problems or guarantee acceptable conditions at all times, but the pattern of improvement demonstrated over the last four years suggests that the pond has not yet reached a new and stable condition.

The monitoring program as conducted for the last seven years has served the project well. As the OPC relinquishes control and responsibility for this project, consideration of minimum necessary monitoring is appropriate. The greatest need is daily review of oxygen sensor data to detect any problems and consistent adherence to sampling protocols when hands-on monitoring is conducted. The monthly program of field measures and nutrient testing remains appropriate, along with clarity measurements. Ortho-phosphorus, nitrate-nitrogen, silica, and turbidity assessment can be dropped and algae assessment could be limited to whenever clarity declines in a manner indicative of a possible algal bloom. The excel tables used to generate graphics for key pond features displayed in this report can be used to continue that reporting and an abbreviated annual summary can be generated rather than this lengthier report.