Review of nanobubble experience at Sarah's Pond, Orleans, MA

Two year summary

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Contents

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) The pond has a “double bowl” that will permit 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 algae blooms in recent years, including cyanobacteria.

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 that the MassDEP regulatory minimum and virtually anoxic near the bottom 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 >10 ft (3 m) deep. Mean Secchi transparency depth is 9.1 ft (2.8 m), but clarity is lower most of the summer. The thermal profile suggests some stratification, with a thermocline between 10 and 13 ft (3-4 m) deep. Review of nutrient data shows strong evidence of summer sediment nutrient release. 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.

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 sets up a highly desirable test situation. While improvement of Sarah’s Pond is the specific goal, the OPC hopes to demonstrate an affordable technology for pond improvement that can compete with alternatives such as P inactivation 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 since May 2018, oxygen demand in the target volume to be addressed by an oxygenation system is 8-12 kg/day, including an induced oxygen demand of 2 to 2.5 times the measured base oxygen demand.

The OPC has provided monitoring for Sarah’s Pond and the same program was conducted in 2018 prior to oxygenation and in 2019 and 2020 during testing of the nanobubble system. Temperature and oxygen were assessed with a field instrument at 0.5 m 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.

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

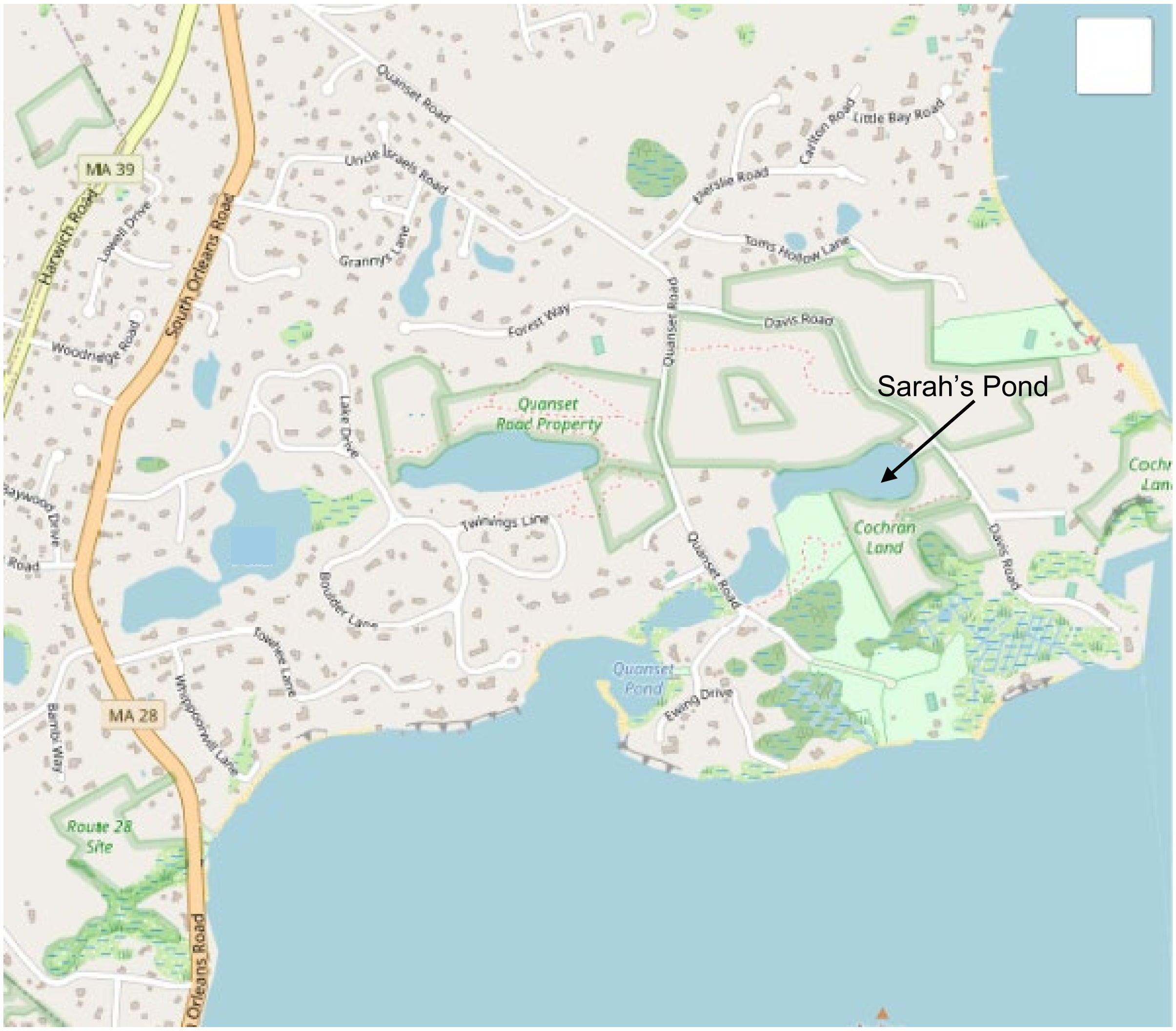


Figure 2. Sarah's Pond bathymetry

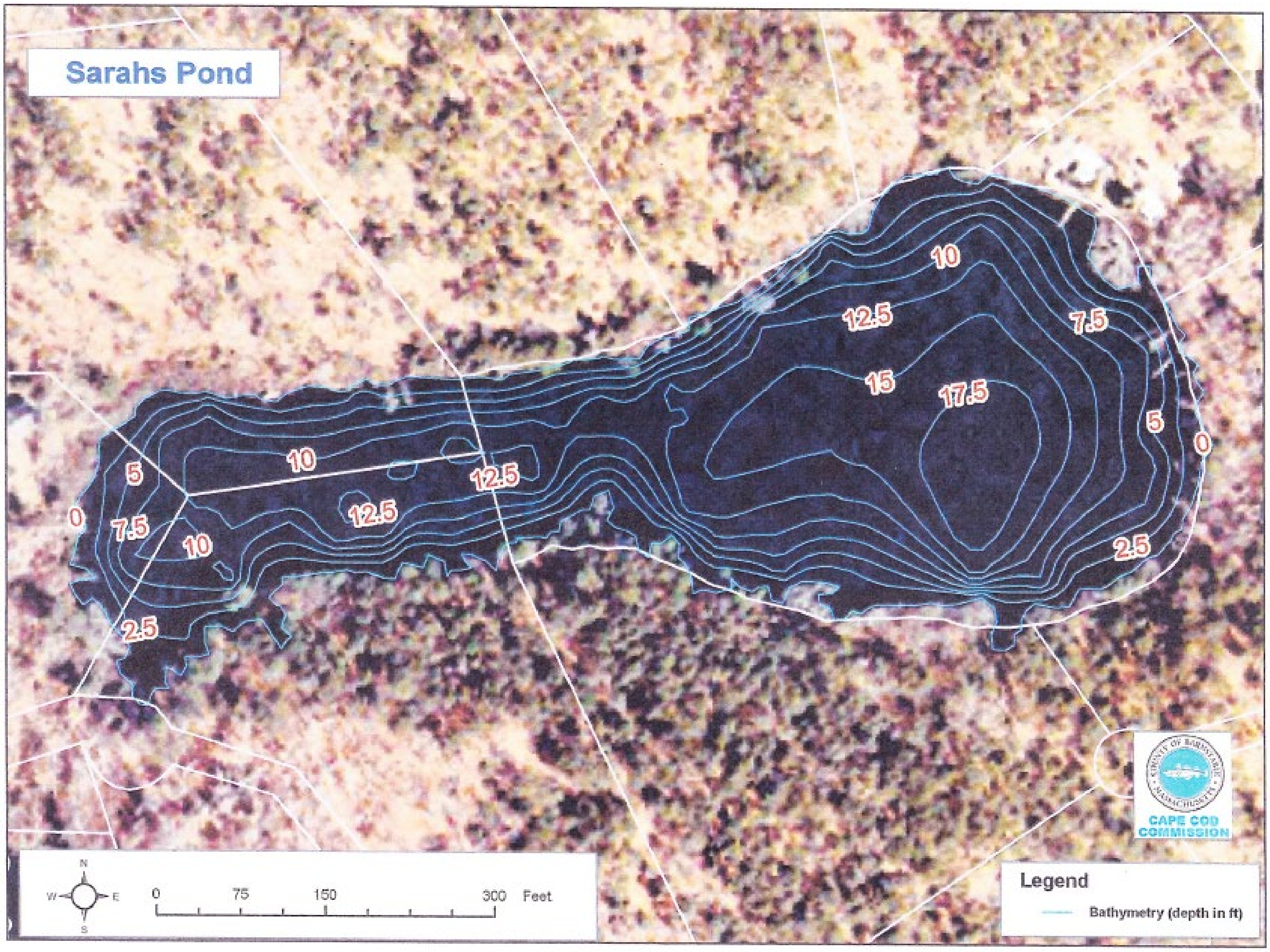


Figure 3. Target oxygenation area in Sarah's Pond

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 2019 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. However, for the purpose of evaluating equipment performance, the above criteria were offered as standards for possible vendors to meet.

SOLitude Lake Management, using equipment from Homeport and a design from Gaia, was selected to conduct this installation. OPC provided monitoring support and CCS provided laboratory support. WRS provided algal analysis, data interpretation and related support.

Installation and operation

A small shed was erected on the land occupied by the caretaker of the overall property and electricity was provided to it in early 2019. The oxygenation equipment was placed in that shed with an incoming and outgoing line for pond water. A pressure swing absorption (PSA) unit added oxygen to water pumped from the pond and proprietary equipment integrated into the unit created the nanobubbles. The treated water was then returned to the pond by gravity feed with a discharge point slightly above the deepest point in the pond.

Actual installation did not meet the target of the start of May 2019 due to delays in equipment delivery and complications with installation. The pump was not able to pull water from the target depth of the lake at the rate necessary to meet the oxygenation specifications. The return water pipe separated at joints. Soundproofing was necessary to meet decibel targets at the nearby residence of the caretaker. The actual start up was in the second week of June but there were still problems and the system was not operable for most of July. A variety of equipment replacements and adjustments were made to improve performance. Consistent operation was achieved at the start of August and the system ran until mid-September 2019 when natural destratification occurred.

The oxygenation system was started up in mid-April of 2020 and ran almost continuously until early August. The water level in Sarah's Pond was very high as a consequence of a clogged outlet pipe in 2020 until it was cleared by the Mosquito Control Commission about May 6, 2020. It took about two weeks for the water level to return to its normal elevation. This did not affect system operation but may have influenced the results and overall conditions in the pond. The system was off in the first half of August, adjustments were made, and several tests were run to assess actual oxygen delivery to the pond. An additional oxygenation unit was added, and the system ran in an enhanced mode for about three weeks, being shut down by the end of the first week of September. The enhanced system barely met the minimum oxygen specification and the electrical cost to run it was high. At that point it was felt that sufficient data had been collected to evaluate performance.

System performance was not evaluated through direct testing until early August of 2020, following sub-optimal results through 2019 and much of 2020. The vendor team agreed to conduct a well-controlled validation study of the nanobubble equipment. The test protocol was generated by SOLitude and approved by all parties. Key measures included electrical consumption, pump flow rate, water temperature, and dissolved oxygen delivery. One complication was difficulty measuring oxygen in nanobubble form, necessitating vibration of the test container to enhance transfer of oxygen from bubbles to the water to facilitate complete measurement of oxygen input without waiting many hours to days. The transfer of oxygen from bubbles to water is a complex function of differential oxygen concentration, bubble size, temperature and other variables, but if oxygen in the receiving water is low one would expect a fairly large and rapid increase in oxygen in treated water. Equipment adjustments were made in response to testing results to increase oxygen delivery to the pond and the system was run for several more weeks in August and September of 2020.

Program Results

Comparing the temperature and oxygen data for the two monitoring stations in Sarah's Pond, there are differences between the two stations with and without the oxygenation system running. Station 2 (untreated) data were subtracted from station 1 (treated when system was running) data to generate the data in Table 1. Without the oxygenation system running, the temperature at the 10 ft depth is not much different between the two stations. There is a difference at the bottom, which is <12 ft at station 2 and about 16.5 ft at station 1, with station 1 being colder. This is logical as the sample location is deeper for station 1. Oxygen at 10 ft is similar with the oxygenation system off between stations 1 and 2, with slightly more oxygen at station 1. This is also logical, as the 10 ft depth is further from the oxygen demanding bottom sediments at station 1 and the impact of that sediment is slightly less. Using the deepest points at stations 1 and 2 for the comparison, oxygen is much lower at station 1 without the oxygen system running. This is likely a consequence of the greater depth, less mixing, and greater oxygen demand at that station.

With the oxygenation system running, there was no difference on average between the temperature at 10 ft at either station, and the temperature at the bottom of station 1 was cooler than the temperature at the bottom of station 2, as expected and consistent with depth. There was not much difference in oxygen at 10 ft but there was considerably less oxygen at the bottom of station 1, even with the oxygenation system running.

Statistical comparison of data with and without the oxygenation system running (Table 1) suggests no significant difference in the temperature at 10 ft but a significant difference was detected (95% probability that the difference is real) in temperature at the bottom, with the temperature warmer with the oxygenation system running. This means that the oxygenation system is either adding heat (the water may warm during the oxygenation process) or causing vertical mixing that raises the temperature at the bottom.

The difference in the difference in oxygen between stations 1 and 2 with and without the oxygenation system running at either 10 ft or the bottom is not significant at the 95% probability level but is significant at the 90% probability level. For the 10 ft depth, there is actually less oxygen with the system running, but the difference is not striking. For the bottom location, there is more oxygen with the system running, as desired, just not a lot more oxygen. Variation is fairly high over time, leading to lower statistical power and the lack of significance at a very high level of confidence (>95%). The oxygenation system did not meet the goal of raising the oxygen level to >2 mg/L on a consistent basis and rarely achieved a concentration of 5 mg/L.

Another way to look at the data is to graphically compare the mass of oxygen in the water column under a square meter of area in the deepest area, the target zone for oxygenation. As the upper 8-9 ft of water tend to mix freely with shallower water throughout the year, we restricted the calculation of oxygen mass in the water to depths of >2.5 m. Mixing slows near the thermocline and there is very little exchange between the deeper water and the shallower water during stratification. If the oxygenation system is working well, no major decrease in oxygen mass should be observed as spring and summer proceed. Slight shifts are possible with temperature changes, but oxygen demand should be counteracted.

Table 1. Comparison of station 1 (treated) and station 2 (untreated) temperature and oxygen with and without the oxygenation system running (station 2 data subtracted from station 1)

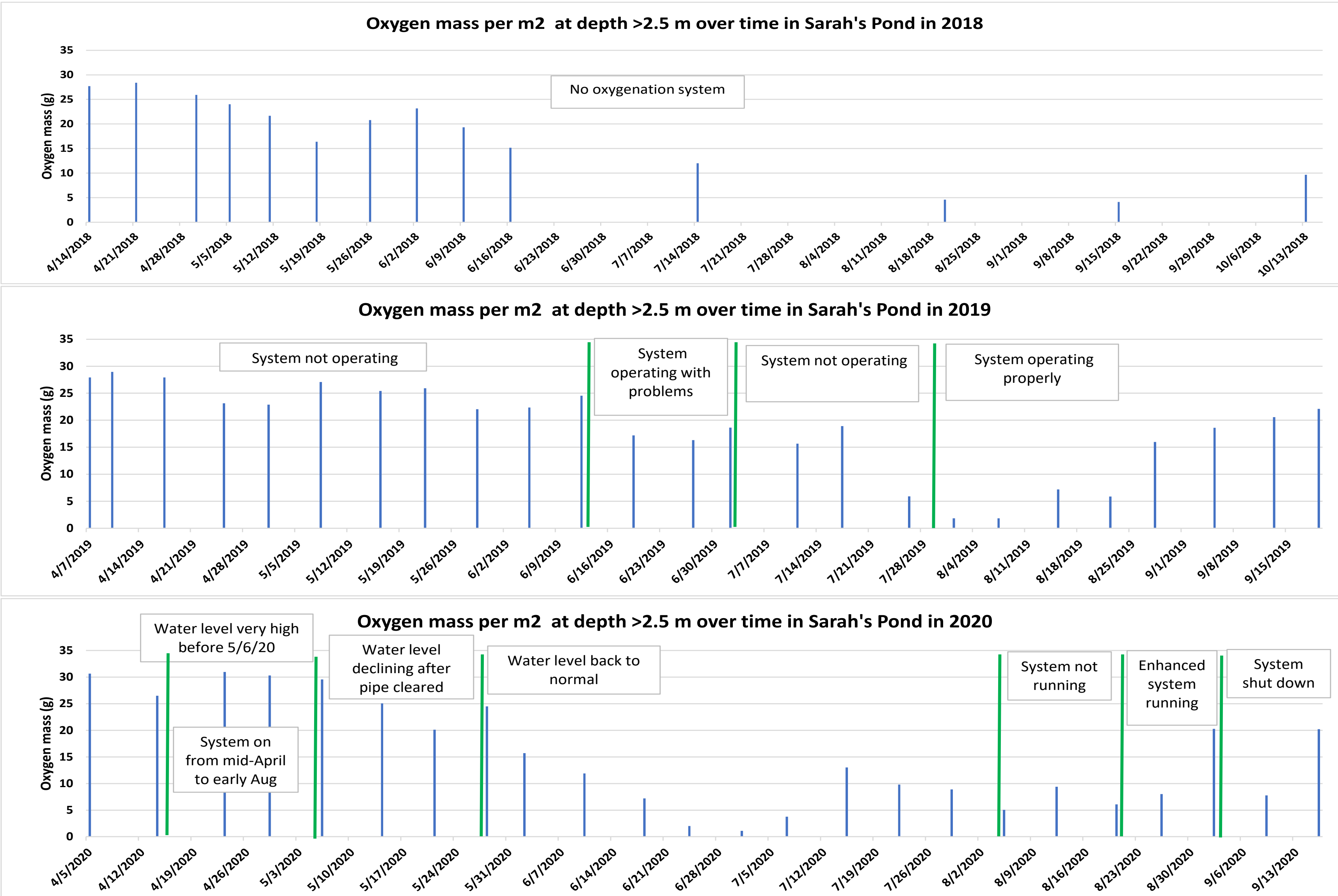
Treated vs Untreated Station	Avg	Median	Std Dev	n			
Temp @ 3 m, system off	0.3	0.0	1.47	18			
Temp @ bottom, system off	-3.3	-2.7	2.44	18			
DO @ 3 m, system off	0.7	0.8	2.28	18			
DO @ bottom, system off	-6.3	-7.1	4.37	18			
Temp @ 3 m, system on	0.0	0.0	0.28	25			
Temp @ bottom, system on	-2.0	-2.0	1.31	25			
DO @ 3 m, system on	-0.2	0.1	1.02	24			
DO @ bottom, system on	-4.2	-3.9	3.15	24			
Statistical Comparison by T-Test	**P =**	**Interpretation**					
Temp @ 3 m, system on vs off	0.323	Temp @ 3 m not different when treated					
Temp @ bottom, system on vs off	0.047	Temp at bottom is warmer when treated (mixing or heat addition indicated)					
DO @ 3 m, system on vs off	0.093	Oxygen is not different at 3 m when treated at a probability of 95%, but is lower when treated at probability of 90%					
DO @ bottom, system on vs off	0.078	Oxygen is not different at the bottom when treated at a probability of 95%, but is higher when treated at probability of 90%					

The mass of oxygen per square meter between 2.5 m of depth and the bottom in the oxygenation target zone in 2018, before the oxygenation system was installed and operated, exhibits an obvious decline through spring and into summer (Figure 4). Only a few summer measurements were made, but all demonstrated low oxygen in water >2.5 m deep. Oxygen increased in October after the weather cooled and stratification ended. Based on the volume of water involved, the oxygen mass under a square meter needs to be at least 5.6 g to have an oxygen concentration of 2 mg/L and 14 g to have a concentration of 5 mg/L. The former should limit P release from sediment while the latter supports most aquatic life forms.

The decline in oxygen mass in 2019 (Figure 4) was actually slower in 2019 before the oxygenation system went into operation than in 2018 without any oxygenation system. With late installation and problematic operation in June and July, the mass of oxygen became very low, although the rate of decline was still slower than in 2018. With operation of the system in August, oxygen mass showed some recovery and reached an acceptable level by early September. Whether or not the continued improvement was due to the system or natural destratification is not determinable from the data and a combination of influences is likely.

In 2020 the oxygenation system was turned on in mid-April when oxygen mass was naturally high. Despite operation, the pattern of oxygen mass exhibited a strong decline with low levels reached by late June. The water level was higher and inputs of oxygen-demanding organic matter may have been higher in 2020, possibly overtaxing the oxygenation system, but the rate of decline was still

Figure 4. Oxygen mass in the treated area of Sarah's Pond in 2018-2020



much faster than expected. Some recovery was observed in the second half of July, but not to the desired level. Oxygen mass declined when the system was shut down in the first half of August but rebounded substantially in late August and early September when the oxygenation capacity was doubled. Oxygen mass again declined when the system was shut down in early September but increased in later September with destratification. Clearly the oxygenation system added oxygen and improved conditions, but the target levels of oxygen were not consistently achieved in 2019 and 2020.

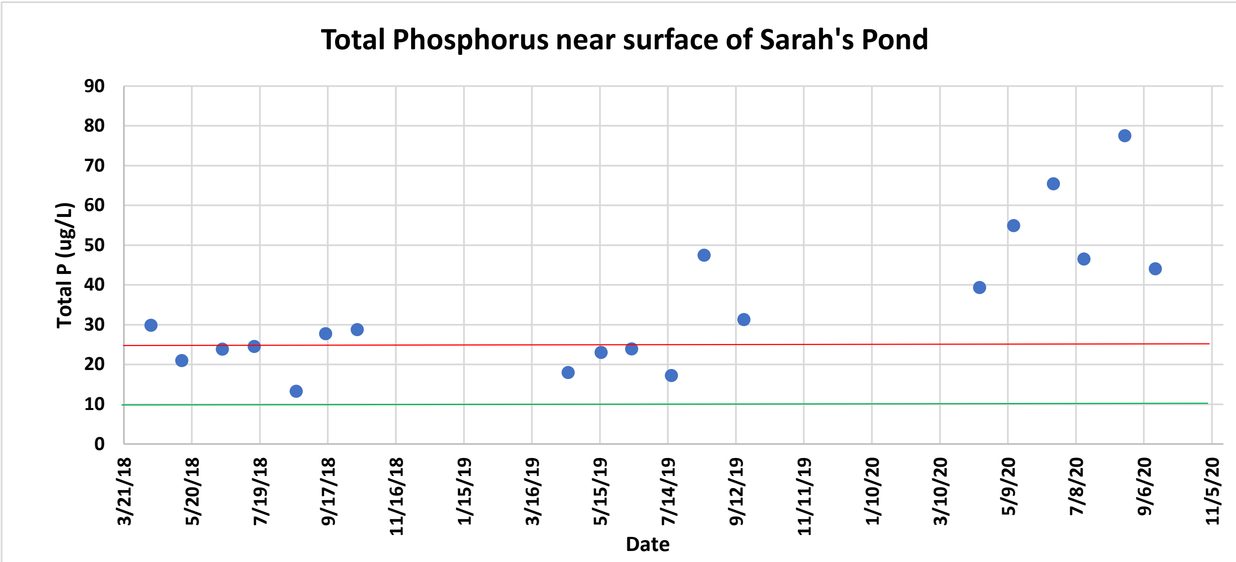
An important but indirect intended effect of oxygenation was a reduction in the internal loading of P, which occurs as P bound to iron in surficial sediments is released as a function of chemical (redox) reactions at low oxygen levels. By keeping oxygen high enough, much of this release can be prevented. P concentrations in the target zone of Sarah's Pond did not exhibit a decrease in 2019 or 2020 compared to 2018 before the oxygenation system was installed (Figure 5). The target level for minimal algal blooms of 10 ug/L was not achieved and the problem level above which blooms are common (25 ug/L) was often exceeded. Concentrations did tend to be higher in deeper water, suggesting ongoing release from the sediment. Concentrations were distinctly higher in 2020 but this may be a function of higher water level and additional loading unrelated to the oxygenation system. Still, better results were expected of a fully functional oxygenation system.

Total nitrogen is not greatly affected by oxygenation and no major changes were noted over time (Figure 6). Values are higher than desired, but if P is kept low this should not be a major problem. In fact, an elevated N to P ratio often limits cyanobacteria. The pond might still be green, but green algae would dominate instead of cyanobacteria.

The ultimate desired effect of oxygenation is reduced algal abundance, especially by cyanobacteria, with a commensurate increase in water clarity. Clarity remained low most of the time in 2018-2020 and Chl concentrations were elevated beyond the desired limit of 4 ug/L on almost all dates and exceeded the somewhat arbitrary threshold of 20 ug/L for a bloom on about half the sampling dates (Figure 7). Conditions were not improved in 2019 or 2020 with the oxygenation system running over 2018 before it was installed. The highest values occurred during summer.

Actual phytoplankton biomass and composition (Figure 8) reflect Chl levels to a degree, but as the Chl content of different types of algae varies, the correspondence is not exact. Spring tends to be dominated by golden algae that prefer colder water. Cyanobacteria can occur at any time but tend to peak as the water warms during summer. A variety of algae are observed later in summer, with greens and goldens most common, although cyanobacteria remain present in many samples. It is more typical for cyanobacteria to remain dominant through late summer, and that was true in 2018, so it is possible that the oxygenation system produced some changes that favored other algae over cyanobacteria in Sarah's Pond. But algae blooms in general and cyanobacteria blooms in particular were not prevented by the oxygenation system run in 2019 and 2020.

Figure 5. Total Phosphorus at the surface and bottom of Sarah's Pond



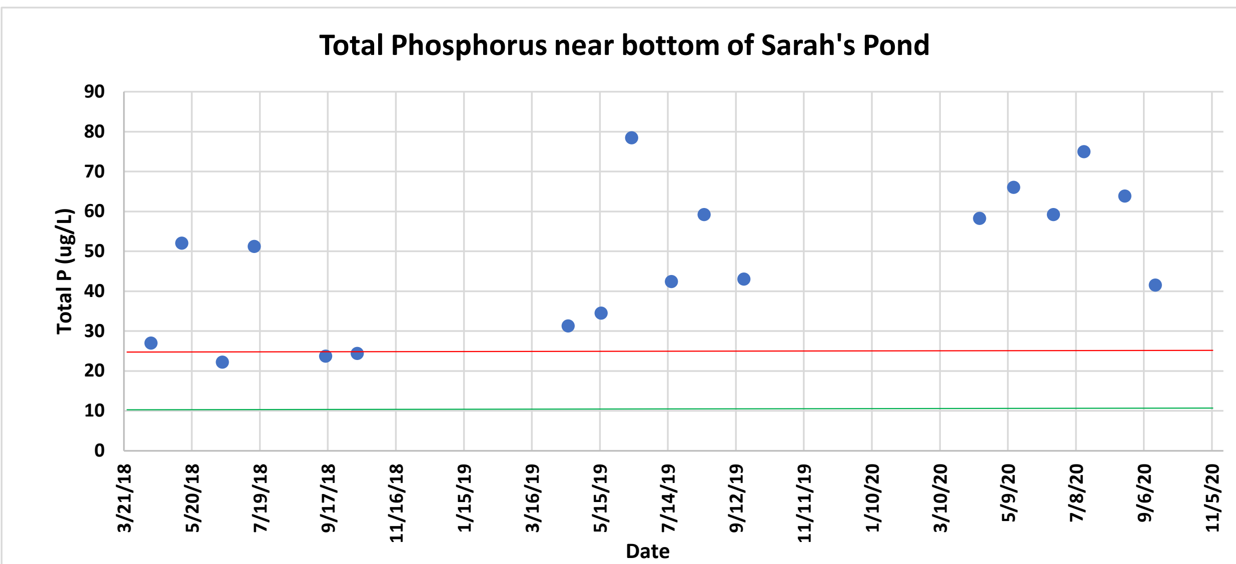
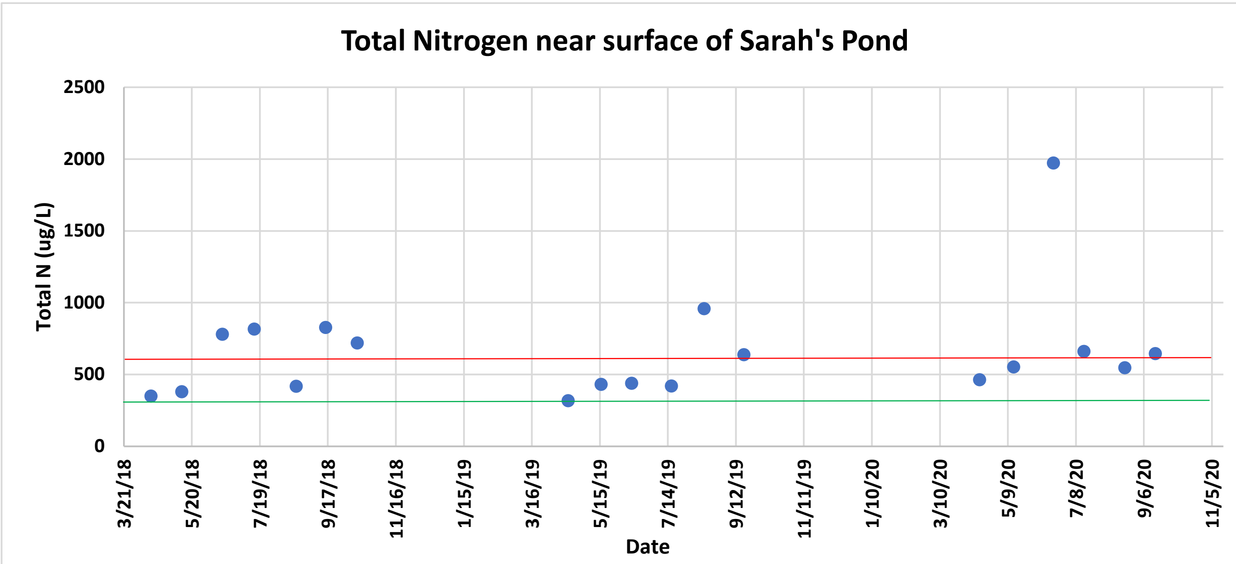


Figure 6. Total Nitrogen at the surface and bottom of Sarah's Pond



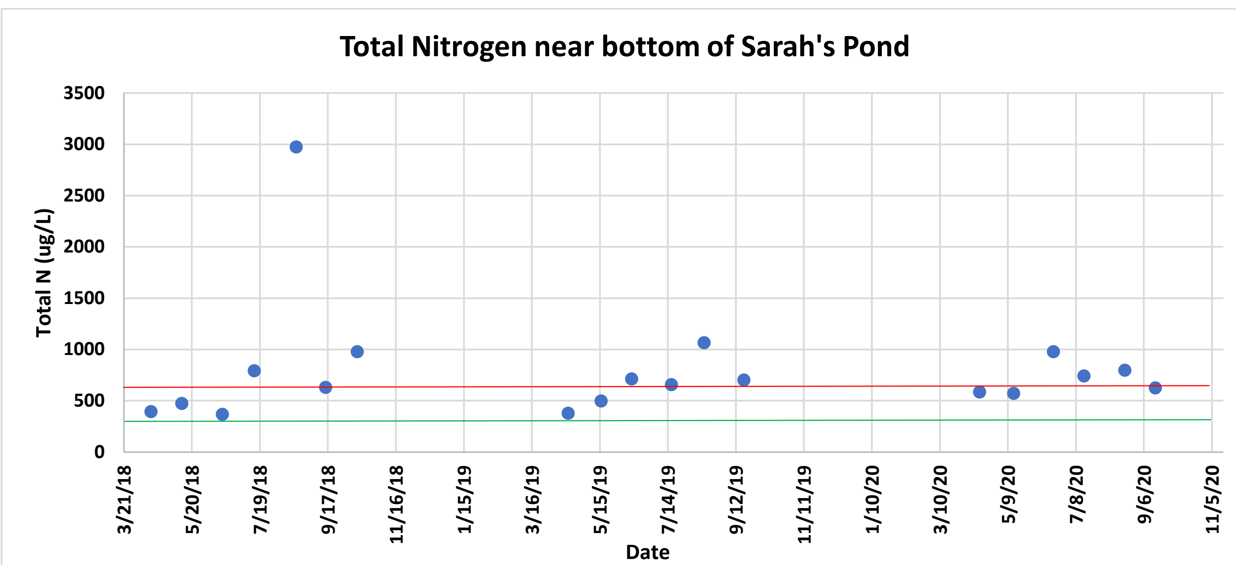
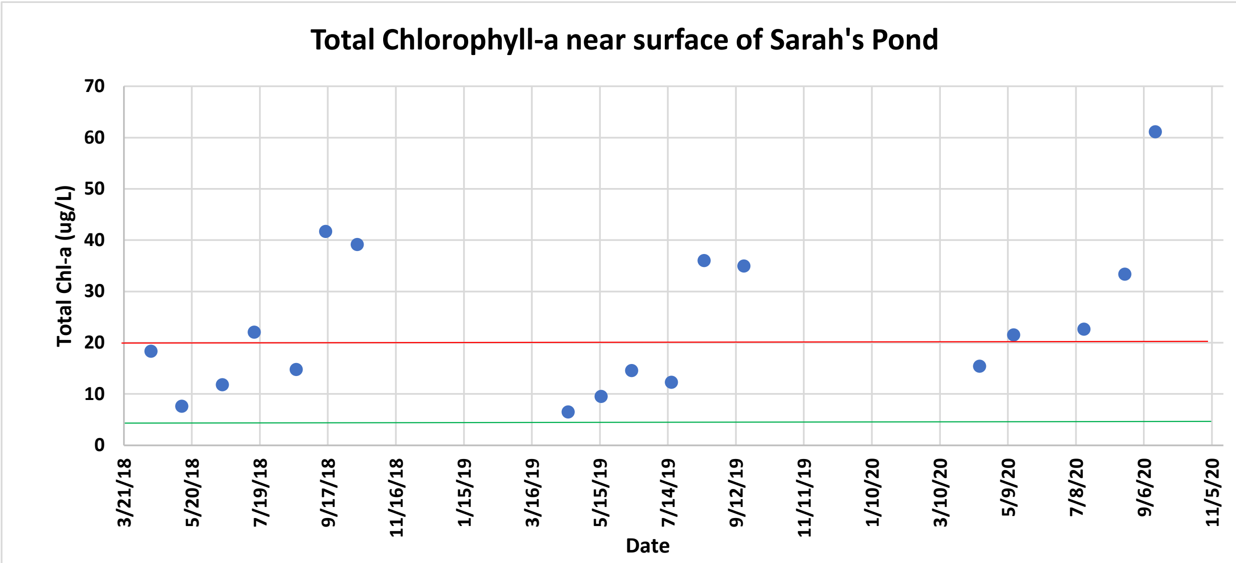


Figure 7. Total Chlorophyll-a at the surface and bottom of Sarah's Pond



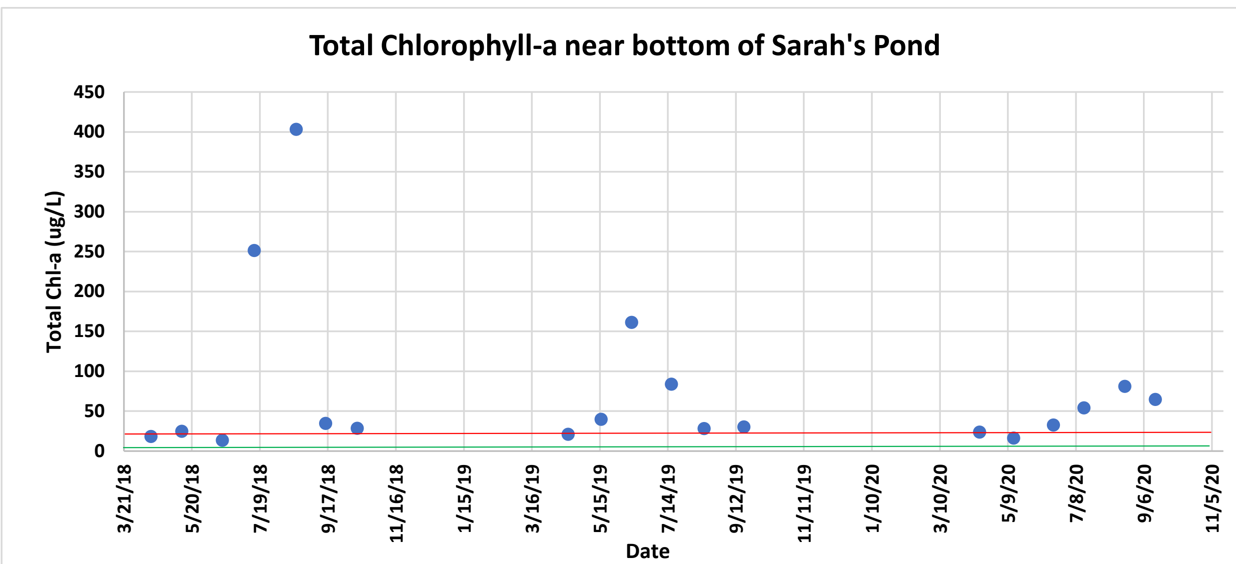
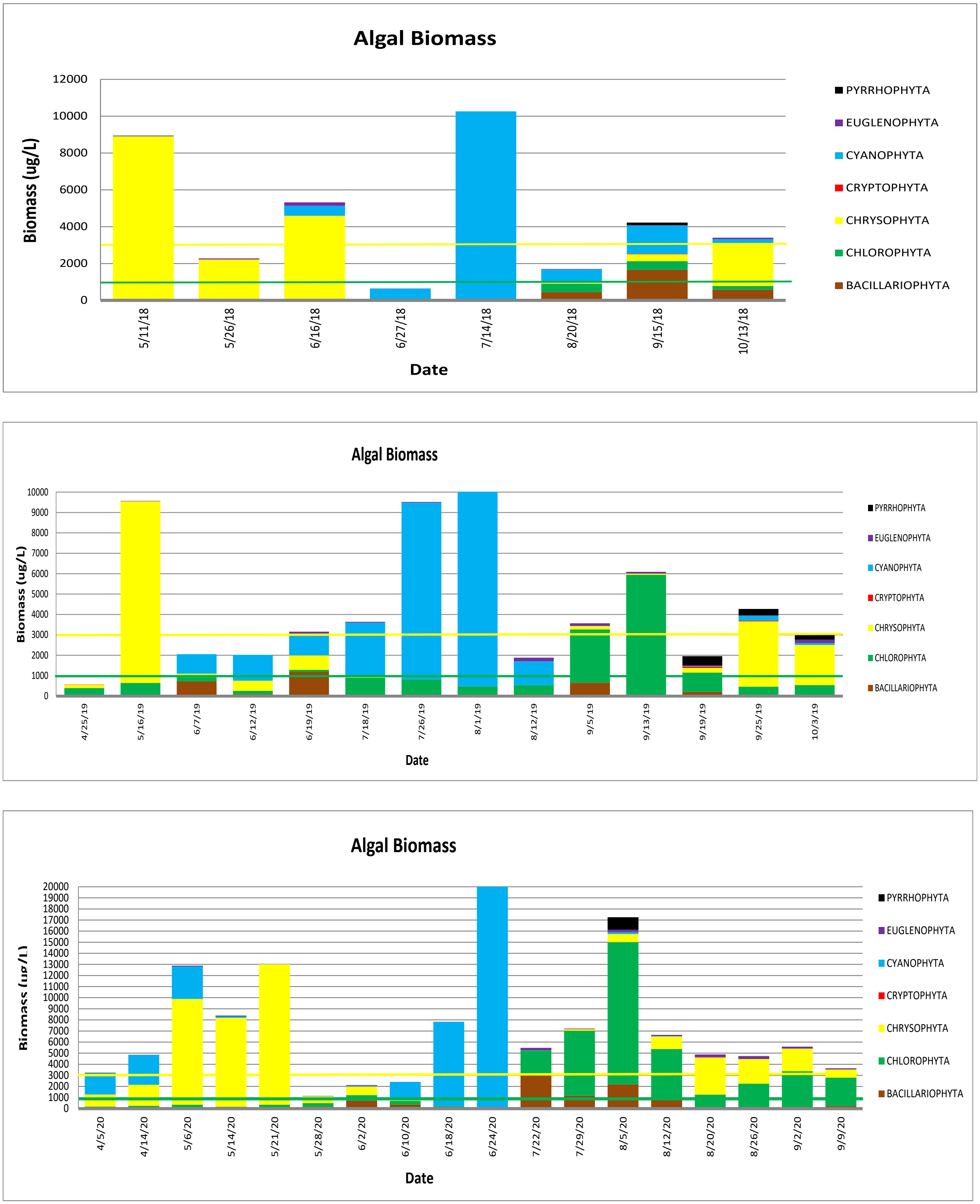


Figure 8. Phytoplankton of Sarah's Pond in 2018-2020



Oxygenation system performance testing

It is unfortunate that oxygen output tests were not conducted when the system was first installed, but after most of two years of operation, a test was designed and conducted and shed light on why results were less than expected. The target condition was a flow rate of 180 gal/min with an oxygen concentration in return water of 12 mg/L above the ambient level. Water pulled from the pond was run through the oxygenation system and routed to a closed container rather than back to the pond. Vibration was used to aid transfer of oxygen from nanobubbles to the water. Oxygen in the container was then measured.

The first validation protocol was conducted on August 6, 2020. The desired pumping level was achieved, and the oxygenation process appeared to operate as intended, but oxygen content in the return water was significantly below the target level. Intake concentrations ranged from 0.06 to 1.35 mg/L while return water ranged from 4.61 to 7.22 mg/L. The net increase of 4.85 mg/L translates into about 4.8 kg/day delivered to the pond, while an input of 8-12 kg/day was needed.

Proprietary equipment which creates the nanobubbles was replaced and the validation protocol was repeated with no significant change in results. A second oxygenation unit was added, and another validation run was conducted on August 20, 2020. The new set up was expected to have the potential to add up to 35 kg/day. Results from the August 20th validation study showed a slight increase of oxygen compared to the first set of runs but still less than the target. The maximum concentration of oxygen observed was a net increase of 8.25 mg/L, representing an input of 8.2 kg/day, at the low end of the success criterion. Oxygen in Sarah's Pond did improve with the increased oxygenation capacity, but with a commensurate increase in power cost.

The problem appears related to the transfer of oxygen to the water via nanobubbles. Either the conversion of gas to nanobubbles is much less efficient that claimed in product literature or the transfer of oxygen from the nanobubbles to the water is much slower than expected. In either case, available oxygen is not being delivered to the target zone at a rate sufficient to counter the oxygen demand. The system is rather inefficient in its delivery of oxygen to the pond.

Cost considerations

The capital cost of the installed unit was about half of the bid price for the closest competing technology, sidestream supersaturation, but technology and related costs can change fairly rapidly in a developing field like oxygenation. Of greatest concern is the ongoing operational cost, which is largely a function of power cost. The monthly electrical cost averaged $800 per month at a usage of slightly more than 4.1 kwh during operation from June 2019 through July 2020. For the annual period of operation, the cost was projected at $3600 and did not meet the oxygen objectives. The system enhancements of August 2020 resulted in a monthly electrical cost in excess of $1000, an increase approaching 30%. The oxygen objective might be achievable with the enhanced system, but barely meets the low end of the oxygen delivery specification and does so with a theoretical capacity more than four times the actual oxygen delivered. The increased cost and low efficiency were not viewed as acceptable.

Conclusions and management options

The installed nanobubble oxygenation system did not achieve the target conditions of 8-12 kg oxygen per day over two years of operation. There were installation and operational challenges, but even when running in accordance with the plan, not enough oxygen was delivered to the target zone of Sarah’s Pond to counteract the oxygen demand. Testing of the equipment in an enclosed system revealed that the efficiency of oxygen transfer was about 25% of the expected value. Oxygen was either not transferred to the return water at the expected rate or the transfer from the nanobubbles was lower than expected. A doubling of the theoretical oxygenation capacity resulted in an available oxygen mass very close to the lower end of the specified range under the best testing results at a power cost that was considered unsustainable. The nanobubble system was therefore removed in fall of 2020.

The nanobubble system did deliver oxygen to the pond and there were resultant increases in oxygen concentration, but the increases were insufficient to prevent internal P loading, algae blooms, and low water clarity. Nanobubble technology has enjoyed some success in other aquatic applications, but based on the experience at Sarah’s Pond, we conclude that the efficiency of oxygen delivery will need to be increased to make nanobubbles a competitive approach for oxygenation of the bottom water layer in lakes.

During the two years of nanobubble testing there have been developments with sidestream supersaturation that have lowered the capital cost of such systems and make it a possible approach for Sarah’s Pond. The OPC is currently planning to install a sidestream supersaturation system at Sarah’s Pond in spring of 2021 and evaluate its performance over the spring-summer period of 2021. Testing of the system by SOLitude personnel in another location has provided promising results and it is hoped that this oxygenation system will provide the desired conditions in Sarah’s Pond.