INVESTIGATION OF ALGAL BLOOMS AND POSSIBLE CONTROLS FOR CLIFF POND, NICKERSON STATE PARK, BREWSTER, MASSACHUSETTS

BY WATER RESOURCE SERVICES, INC.

JUNE 2014

IN COOPERATION WITH AQUATIC CONTROL TECHNOLOGY

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Executive Summary

Cliff Pond in Nickerson State Park in the Town of Brewster on Cape Cod in Massachusetts is a valuable resource as part of this outstanding state park. For many decades it provided both habitat and recreational opportunity, including swimming, boating and fishing for trout and bass. Water clarity and aesthetic appeal were high. Starting sometime in the 1980s, oxygen loss in deep water accelerated, nutrient recycling increased, and algal blooms became increasingly frequent. Particularly troublesome have been cyanobacteria, or blue-green algae, some of which float and can produce toxins, creating a potentially dangerous situation at the surface and along shorelines where windblown accumulations can be substantial. Two dogs died in the late 1990s, but with monitoring and posting by the park management, human health impacts have been limited. However, the condition of Cliff Pond has deteriorated to the point where it is not useable for contact recreation for much of the summer and there is no suitable trout water (cold enough with adequate oxygen) in the pond through the summer months.

The cause of increased oxygen demand and the sources of elevated phosphorus in the fine sediments in water deeper than about 33 feet (10 m) are unknown. There is no evidence of current watershed problems that could be responsible over any period of a decade or less. Erosion on steep slopes around the pond is severe in places and warrants attention, but the sand does not have a high nutrient content or oxygen demand. The fine sediments in deep water are still mostly inorganic silts, but enough organic matter is present to express a fairly high oxygen demand of about 2.76 $g/m^2/day$, enough to cause depletion of oxygen (anoxia) in the bottom water layer. Phosphorus bound to iron in sediments can be released under anoxic conditions and both the phosphorus and iron are implicated in the increase and dominance of cyanobacteria. Levels of phosphorus in fine sediments average over 700 mg/kg, while values <50 mg/kg are preferred.

Over the last two decades the depth at which low oxygen is encountered by late summer has risen to the boundary between the upper and lower water layers. This exposes up to 78.5 acres (31.4 hectares) of pond bottom with phosphorus-rich sediment to anoxia and fuels cyanobacteria blooms. Eventual settling and decay of those blooms adds to both the oxygen demand and the phosphorus reserves, creating a self-sustaining cycle of declining water quality and overall pond condition that is independent of any watershed influences. This is a natural process that can be greatly accelerated by human actions, but any human influences at this time appear minor. Rehabilitation of Cliff Pond must focus on improving oxygen and reducing nutrient releases from water deeper than 33 feet (10 m). It would be preferable to address the entire lower water layer and associated sediment interface, but it appears sufficient to deal with the area and volume between 33 and 46 feet (10 to 14 m) of water depth.

The range of management actions has been reviewed and evaluated. Many approaches are not applicable to Cliff Pond, while some applicable methods are not feasible or affordable. Still others are not consistent with all use goals for the pond; for example, artificial circulation could oxygenate deep water and minimize algal blooms, but would also eliminate trout habitat. After analysis of goals and options for achieving them, only two techniques appear appropriate to this case: oxygenation and phosphorus inactivation.

Oxygenation could be accomplished by six different methods, but the use of diffused pure oxygen is most appropriate and least expensive for Cliff Pond. A diffused oxygen system would have few moving parts and minimal power needs. It would allow flexible application as warranted by ongoing, automated monitoring of oxygen in deep water. It would cost about $270,000 to install and between $15,000 and $25,000 to operate on an annual basis, inclusive of monitoring and maintenance, but with liquid oxygen as the primary operational cost. The anticipated cost over a 20 year period would be between $570,000 and $ 770,000.

Phosphorus inactivation would most likely involve a buffered application of aluminum compounds to deep pond sediment to transfer iron-bound phosphorus to aluminum complexes that do not release the phosphorus under anoxic conditions. It is possible to use lanthanum, recently applied under the tradename Phoslock. Insufficient case history data are available to comprehensively compare aluminum and lanthanum applications, but in general, it appears that lanthanum would be more expensive but would potentially strip phosphorus from the water column more effectively. Use of aluminum in a spring treatment would allow inactivation of sediment phosphorus at a time when water column concentrations are at their lowest, so the phosphorus stripping advantage of lanthanum may not be sufficient to overcome the cost differential. Based on experience to date, use of aluminum is recommended, but lanthanum could be considered if bid documents for a project were written based on performance rather than products.

Phosphorus inactivation would break the cycle of low oxygen, nutrient release, algal blooms, and deposition of oxygen-demanding organic particles that is the cause of pond deterioration. Aluminum can be toxic during treatment if dose and pH are outside a known range, but treatments have improved over the last two decades and can be conducted with minimal risk to fish and invertebrates. Multiple aluminum formulations are available and can be applied to avoid pH shifts and possible toxicity. Oxygen would be expected to increase near the top of the bottom water layer during summer stratification, but loss of oxygen near the bottom would still be expected. Water clarity in the upper water layer should be improved as much as with oxygenation, but less trout habitat would be created.

The anticipated total cost of a phosphorus inactivation project would be between $440,000 and $560,000. It has no ongoing operational costs and a 20 year period of benefit is expected. Consequently, the cost of oxygenation is between $130,000 and $210,000 more than the cost of phosphorus inactivation over a 20 year period, or between $6500 and $10,500 per year. The capital cost of oxygenation is less than that of phosphorus inactivation, but the operational costs of oxygenation increase its cost over the 20 year period of evaluation. If the operational costs can be covered in the park budget or by some separate allocation, the oxygenation system is recommended to maximize benefits for slightly more cost. If greater capital cost is tolerable, or operational costs simply cannot be guaranteed, the phosphorus inactivation treatment represents a viable alternative for rehabilitating Cliff Pond and improving water quality to support all designated uses. Oxygenation and inactivation are not mutually exclusive; both could be applied. The most logical sequence would be to inactivate first, then oxygenate as needed.

Project Background and Need

Cliff Pond is located in the Town of Brewster, within Nickerson State Park (Figures 1 and 2), and is the largest and deepest of over a dozen ponds in that state park. It is also the deepest pond on Cape Cod. Large sandy slopes adjacent to much of the shoreline give Cliff Pond its name. Cliff Pond has public access within the park, with two boat launches, a non-powered watercraft concession, and at least four beach areas. Sailing, kayaking, and windsurfing are all taught at the pond. Cliff Pond has been heavily stocked with trout and salmon for years, including brood stock. It has also been popular as a warm water fishery, mainly black bass (largemouth and smallmouth).

Swimming in the pond has been generally discouraged in recent years by blooms of cyanobacteria, also known as blue-green algae, and the pond has been posted for no contact in much of each of the last two summers. In the late 1990s at least two dogs died after consuming water and algae washed up at the shoreline; this was presumed to be related to toxic cyanobacteria. Further, oxygen levels in the deeper waters of the pond are depleted in most summers, causing the release of a number of undesirable compounds from deep sediments, including phosphorus, iron, and manganese, as well as putting considerable stress on cold water fish.

This project was undertaken to evaluate current sources of nutrients to Cliff Pond, to assess the factors responsible for algal blooms, and to evaluate alternative means to reduce algal blooms and improve the condition of Cliff Pond overall.

Cliff Pond Features

Cliff pond is a classic kettlehole lake, formed by stranded ice at the end of the last glacial period over 10,000 years ago. The pond covers 206.7 acres (82.7 ha) by most recent measurement, but has been listed at between 200 and 210 acres (80-84 ha) in a variety of reports and fact sheets. The volume is just under 5900 acre-feet (7.3 million m^3), suggesting a mean depth of 28.5 feet (8.6 m). The maximum depth is about 88 feet (26.7 m) when the pond is at its normal elevation (Figure 3), but the water level can rise or drop over a foot in response to precipitation or drought. There are no surface water inlets or outlets associated with Cliff Pond; inflow is by precipitation and ground water inseepage, while outflow is by evaporation and ground water outseepage. Flax Pond is just to the north and Little Cliff Pond is just to the east, but neither has a surface water connection to Cliff Pond. Smaller nearby ponds are shallow and mostly weedy, and even at the highest observed water levels they are unconnected to Cliff Pond.

The shoreline and nearshore area of Cliff Pond is mostly coarse sand. There are some areas of rocks, including a few glacial erratic boulders, and other areas of gravel, but sand is the dominant substrate in water <20 feet (6 m) deep. In the southwestern cove of the pond, where the primary boat launch is located, there is a silty to mucky layer at depths >20 feet, but outside of this cove the substrate is sandy to depths as great as 40 feet (12.1 m), after which inorganic silt and organic muck sediments become dominant. The surrounding land is sandy, and erosion from the steep slopes is evident, adding more sand to the margin of the pond.

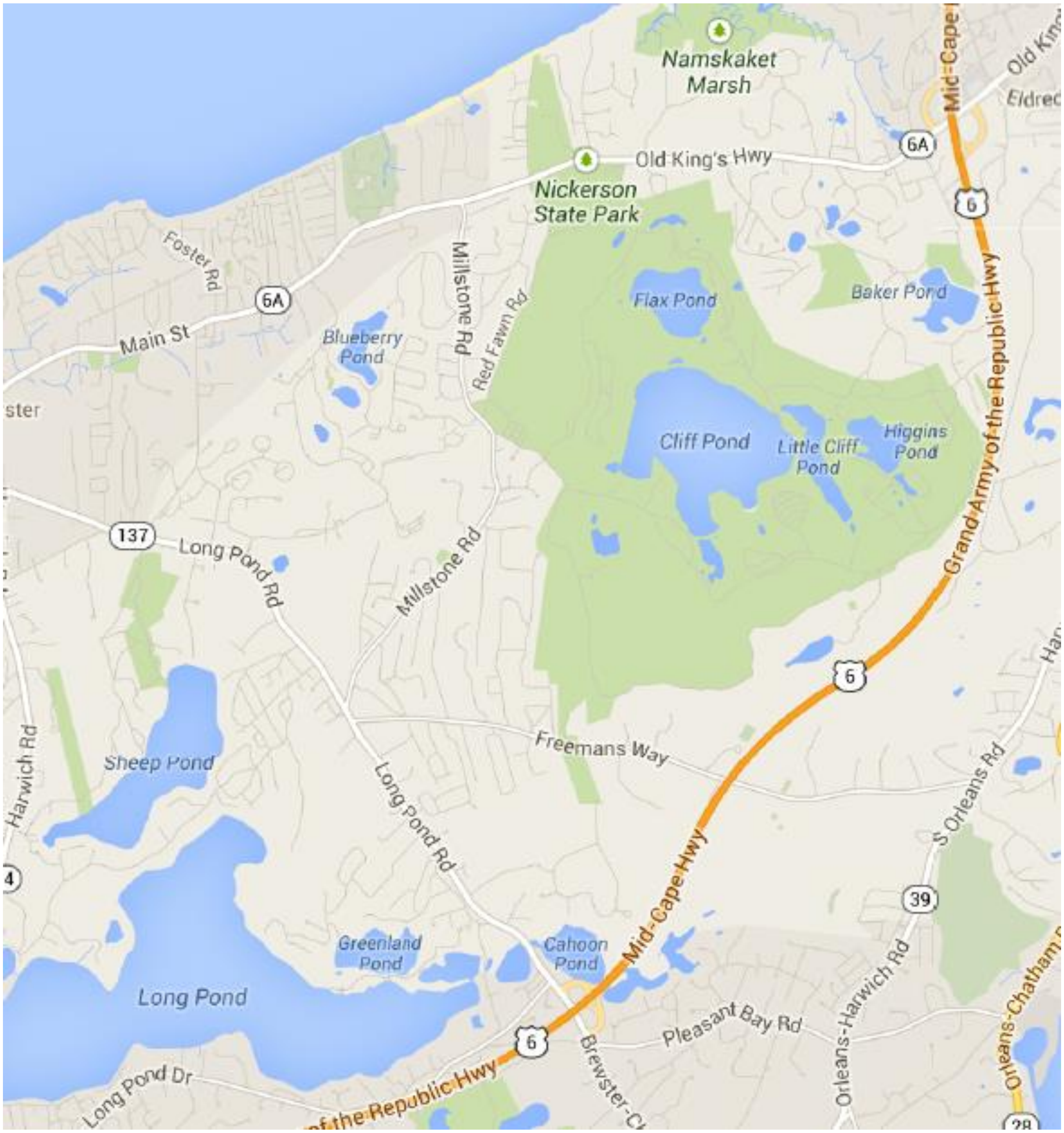


Figure 1. Cliff Pond and Nickerson State Park location on Cape Cod

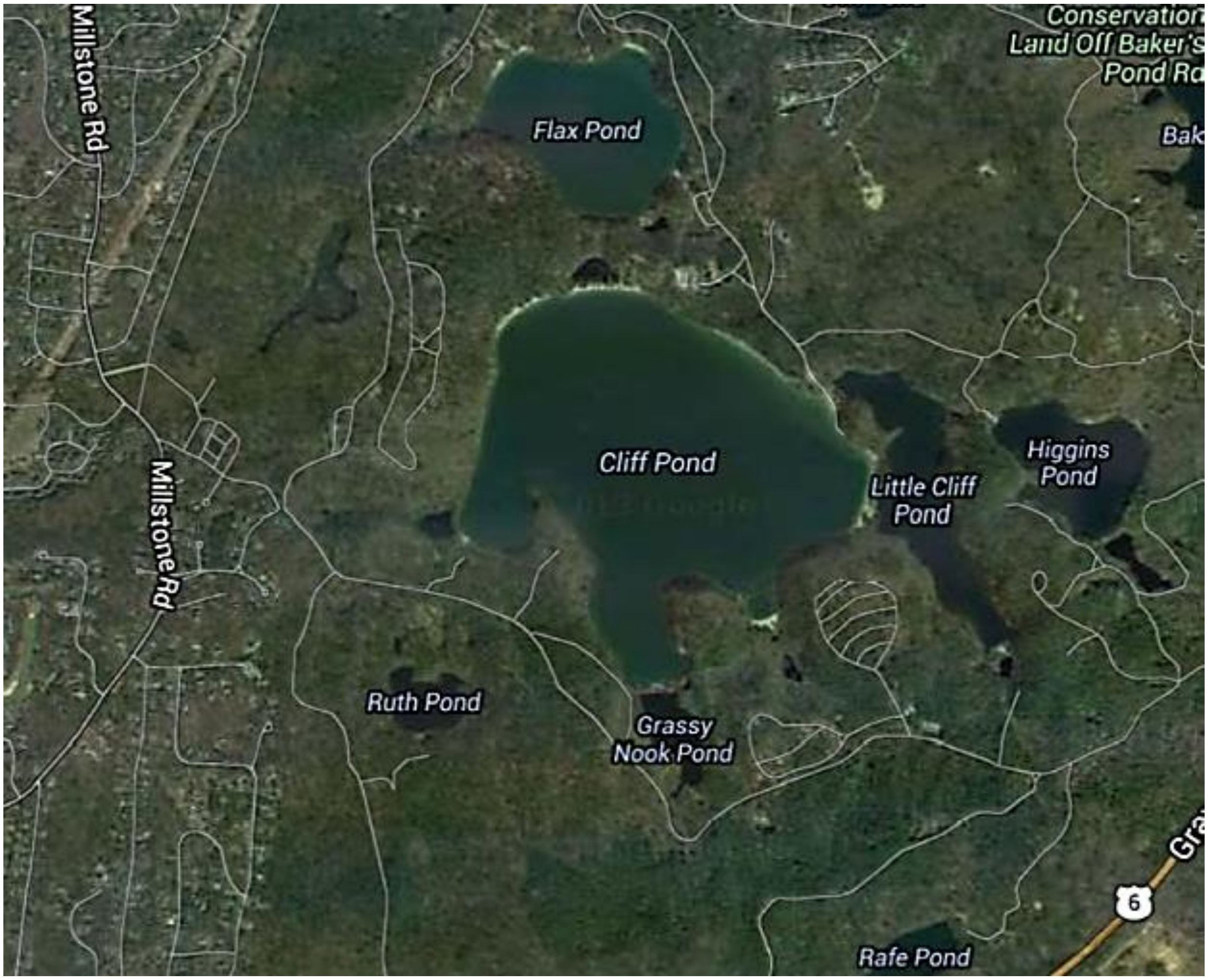
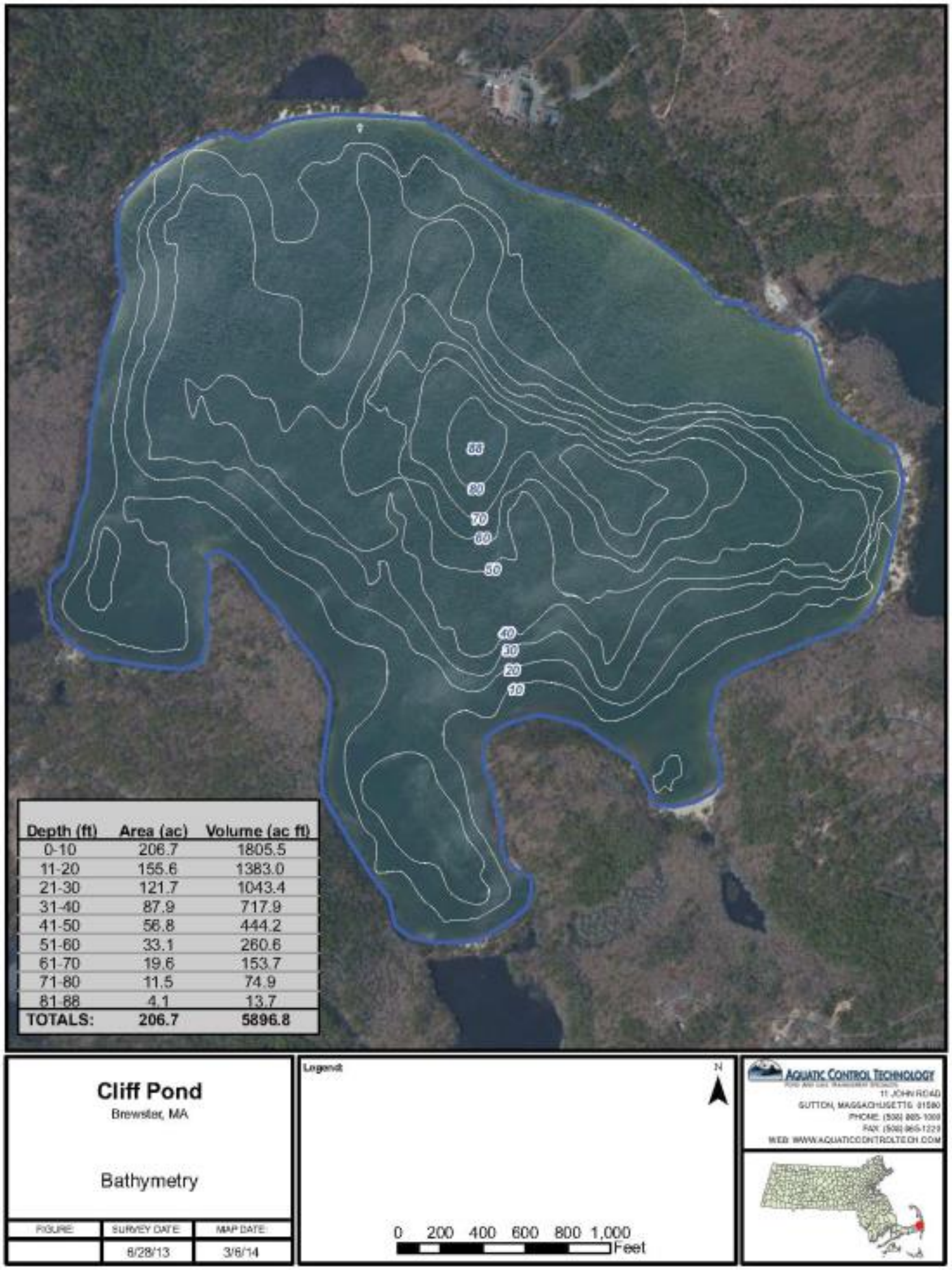


Figure 2. Cliff Pond immediate area



Depth (ft)	Area (ac)	Volume (ac ft)
0-10	206.7	1805.5
11-20	155.6	1383.0
21-30	121.7	1043.4
31-40	87.9	717.9
41-50	56.8	444.2
51-60	33.1	260.6
61-70	19.6	153.7
71-80	11.5	74.9
81-88	4.1	13.7
TOTALS:	**206.7**	**5896.8**

Figure 3. Bathymetric map of Cliff Pond

Watershed Features

The Cliff Pond watershed is difficult to delineate, as it has separate ground water and surface water components that are not congruent. Ground water flow on Cape Cod has been studied extensively, and while there is variation in both the location of high points and the localized flow paths, the general direction of ground water flow through the Cliff Pond area (Figure 4) is from the southwest to the northeast. The peak elevation of ground water to the west of Cliff Pond is about 31 feet above mean sea level (FMSL), the elevation of Long Pond and Sheep Pond. The elevation of the surface of Cliff Pond is normally about 26 FMSL, with Ruth Pond to the west at 27 FMSL, Little Cliff Pond to the east at 25 FMSL, and Flax Pond to the north at 24 FMSL. The elevated land around Cliff Pond may cause some anomaly in ground water topography, with adjacent land all around the pond providing inseepage near the edge of Cliff Pond, but in general ground water will move from the southwest side to the northeast side. The swath of land between Long Pond and Cliff Pond will be the largest contributing area (Figure 5). Certainly Flax Pond and Little Cliff Pond will not contribute water to Cliff Pond.

Figure 4. Ground water contours on east Cape Cod (Cliff Pond shown as red square). After Guswa and LeBlanc 1985

Figure 5. Ground water contours and drainage boundary (red) and surface water drainage boundary (yellow) for Cliff Pond

The surface watershed is rather small, based on local topography around Cliff Pond (Figure 5), and with such sandy soils, not much runoff generation would be expected anywhere but on the steep slopes near the lake. Erosion on some of those slopes is pronounced (Figure 6); some of it is natural, but some is related to foot traffic disturbing minimally vegetated soils and destabilizing them. All of the approximately 170 acres (68 ha) of potential surface drainage area is within Nickerson State Park, and includes woodland, trails, roads and campsites.

The swath of land through which the ground water flows from the southwest is woodland and low density residential development, terminating at Long Pond and potentially including water from Long Pond. Unlike many more heavily developed areas, there is no obvious major threat from the land below which the ground water passes. Wastewater disposal is a likely issue, but at the observed density of housing, severe impacts on ground water quality would not be expected.

Figure 6. Erosion on slopes around Cliff Pond in 2013

Designated Uses

Cliff Pond is listed as Class B waters. Under the Massachusetts system, this means that the water is not intended for direct potable water supply, but is expected to meet water quality standards for recreational and habitat uses. The designated uses of Cliff Pond include swimming, boating, fishing, and habitat for fish and wildlife. Those uses are impaired by low oxygen and algal blooms.

Rehabilitation Needs and Objectives

Improving water clarity and oxygen in deep water are the two primary needs, and these appear to be linked. Water clarity is largely reduced by algae blooms, and those blooms represent an organic mass that will contribute to oxygen demand in deeper water. The blooms may be supported by internal recycling of phosphorus brought on by low oxygen in the deep waters of the pond. Therefore, a logical primary objective would be to improve oxygen throughout the pond, thus reducing the availability of phosphorus from sediments and limiting algal blooms.

Additional Data Needs

The key data needs to reach management oriented conclusions for Cliff Pond include:

1. Assessment of current conditions in the pond, especially with regard to oxygen status and nutrient levels.
2. Quantification of external sources of phosphorus and nitrogen to the pond to the extent possible with existing data.
3. Quantification of the amount of phosphorus in the surficial sediments that could be released into the water column, and assessment of the build-up over the course of the summer.
4. Assessment of the area of the pond subject to anoxia and potentially contributing to the internal phosphorus load.
5. Documentation of the algae in the pond that are impairing water clarity.
6. Inventory of biological components of the pond that may have bearing on which alternative actions can be implemented under current regulatory limits and that could affect the outcome of any action under consideration.
7. Assessment of water quality that might affect choice of management alternatives or constrain implementation.

The sampling and investigation program carried out in 2013 sought to provide the data necessary to address the above considerations within the time and financial constraints imposed.

Study Approach and Methods

Historic Data Review

Data from past studies by the Division of Fisheries and Wildlife and Department of Environmental Protection (and forerunners) was obtained through those agencies. Data from the Ponds And Lakes Stewards (PALS) program was obtained from the Town of Brewster and the School of Marine Science and Technology at UMASS Dartmouth, which provides all analytical services. The value of the PALS program and the contribution made by SMAST cannot be overestimated and the involved staff and volunteers are to be commended for creating this important data base and making it available. While there have been no intensive investigative studies, the body of data spanning over 60 years and providing annual data for over a decade is extremely valuable for tracking the progression of problems in Cliff Pond.

Watershed Assessment

The watershed was evaluated through field observation. We drove or walked nearly all of the potential contributory area to assess likelihood of any contribution and possible sources of contaminants, with a focus on phosphorus and nitrogen. GPS was used to map the distribution of wastewater disposal facilities in Nickerson State Park and other features of interest.

In-Lake Investigations

Water Quality

Cliff Pond was visited and assessed to varying degrees on 9 dates in 2013. On four dates field water quality assessment was conducted and samples were collected for nutrient analysis by a certified laboratory, Envirotech Labs of Sandwich, Massachusetts. On two other dates only field water quality features were assessed and plankton samples were collected. On an additional three dates, temperature and dissolved oxygen measurements were the only tests performed.

Field water quality measures included profiles of temperature, dissolved oxygen, pH, conductivity, and turbidity, measured with a Hydrolab DS5 multi-probe sonde, plus assessment of alkalinity by titration at surface and bottom locations and Secchi transparency from the surface, Phytoplankton and zooplankton samples were also collected with nutrient samples for later lab analysis. Laboratory nutrient measures included total and dissolved phosphorus, ammonium nitrogen, nitrate plus nitrite nitrogen, and total Kjeldahl nitrogen.

Measurements were made and samples were collected at the surface and every 10 feet (3 m) to the bottom of the pond. With the bowl-like shape of Cliff Pond, a single sampling site in the center of the lake was deemed sufficient to characterize pond conditions on each date (Figure 7). However, on the last sampling date three stations (southeast, north and west) were added to the central station and fewer depth locations were sampled to evaluate horizontal spatial variability.

Sediment Assessment

Soft sediment distribution was assessed by underwater viewing system (a Marcum 820 series videocam on a cable, with a viewing screen in the boat). This allowed delineation of where muck sediment began to accumulate and where cover by muck was complete, but does not provide data on the depth of soft sediment. Surficial sediment quality was assessed by collecting samples with an Ekman dredge in 5 areas (Figure 8), with each area represented by a composite sample created from 3 to 5 individual samples. Areas were selected based on the visual survey, with sampling in areas where muck cover was complete and muck depth was at least 6 inches (15 cm). Each individual sample was obtained from the upper 2 inches (5 cm) of the retrieved muck. One of the individual samples in area 5 (southern end of the deep basin) had a much higher sand content from visual observation and was packaged as a separate, sixth sample.

Sediment testing included measurement of total phosphorus, iron-bound phosphorus, percent solids, and percent organic matter by a certified laboratory, Spectrum Analytical Laboratory of Agawam, Massachusetts. A critical calculation derived from these measures is the amount of available phosphorus in the surficial sediments. Phosphorus bound to iron can be released under anoxic conditions, and is a key component of internal load. Addition of aluminum transfers phosphorus from iron to aluminum, and resulting aluminum-phosphorus complexes are not subject to release under anoxia. Since aluminum treatment could be used to inactivate surficial sediment iron-bound phosphorus, aluminum dose testing was also conducted by Spectrum Analytical Laboratory. In this test, a known quantity of sediment is exposed to an aluminum solution representing one of several chosen doses in g/m^2. The treated sediment is settled and dried, then re-tested for iron-bound phosphorus. As the dose of aluminum rises, the fraction of phosphorus remaining in an iron-bound form declines, and the most effective and/or efficient aluminum dose can be determined for possible application.

Figure 7. Map of water quality sampling stations

Figure 8. Map of sediment sampling stations

Seepage Assessment

The flow of ground water into or out of the pond was assessed with seepage meters according to the method of Mitchell et al. 1988. Seepage meters were deployed (Figure 9), each with a known quantity of water in an attached bag, allowed to incubate for multiple hours, then the bags were extracted and seepage was calculated as the difference in the water volume in the bag, adjusted for area covered and time of incubation to derive seepage in liters per square meter per day. Seepage work was carried out in mid-June and early July, at a time of relatively high water as a consequence of a very wet June, so seepage may have been reduced by the increased water level in the pond, but estimates were obtained and can be adjusted as warranted.

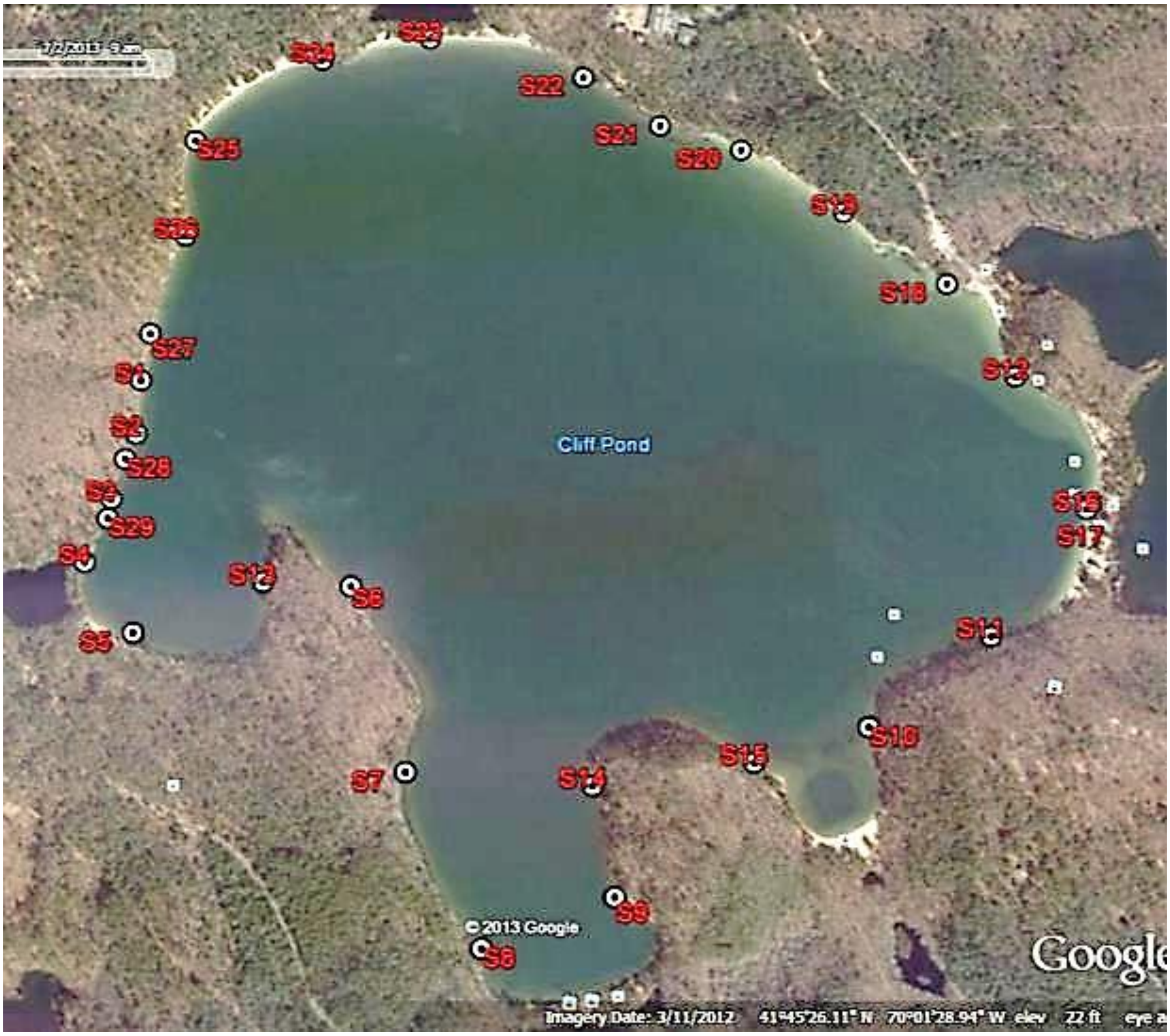


Figure 9. Map of seepage stations

Seepage quality was determined separately by the methods of Mitchell et al. 1989, using littoral interstitial porewater (LIP) samplers. These are basically mini-wells, inserted into peripheral sediments to extract porewater that represents the ground water seeping into (or out of) the pond at that time. LIP samples were tested by a certified water testing lab, Envirotech Labs of Sandwich, Massachusetts. Testing included ammonium nitrogen, nitrate plus nitrite nitrogen, dissolved iron, and dissolved phosphorus. Shoreline segments were established (Figure 10) and a sample for each was obtained as a composite of at least four individual LIP samples. Seepage meters could be matched to these shoreline segments to allow quantity and quality of seepage to be combined into load estimates for nitrogen, phosphorus and iron.

Figure 10. Map of littoral interstitial porewater sampling stations

Water Depth Assessment

A side scanning sonar unit was deployed by Aquatic Control Technology on a boat that made many passes across Cliff Pond, generating overlapping images and supporting data for the depth and bottom features of the pond. The data are fed into a geographic information system and the primary result was a new water depth contour (bathymetric) map for the pond (Figure 3).

Biological Assessments

Plankton samples were collected with temperature and dissolved oxygen profiles at the central station. Phytoplankton were collected as grab samples slightly under the water surface. Zooplankton were collected by vertical tows of an 80 µm mesh net until 380 liters of water were collected (30 m of tow with a 13 cm diameter net). Plankton samples were preserved with glutaraldehyde in the field (0.5% for phytoplankton, 2% for zooplankton) and concentrated in the lab prior to quantitative assessment under phase contrast microscopy.

Macrophytes were not a primary focus of this study, and are in fact not abundant in Cliff Pond. General assessment of types and abundance of aquatic vascular plants was made during a general survey of peripheral pond conditions and by viewing with the Marcum underwater video system while assessing soft sediment distribution in the pond. Further assessment was conducted with side scanning sonar in the course of development of the bathymetric map. Mussels were also noted during these observational efforts.

Assessment of current fish community features was based on effort conducted on August 21, 2013. Boat access was achieved through the boat ramp at the area known as Fishermen's Landing by a Division of Fisheries and Wildlife team, with assistance from WRS staff. A variety of gear types were used to sample Cliff Pond including boat electrofishing, experimental gill nets, seining and angling. Five experimental gill nets (125 feet total length, five 25-foot panels of 1, 1.25, 1.5, 1.75 and 2 inch bar mesh monofilament nylon) were set for 2.5-2.75 hours during the day for a total effort of 13.5 net-hours (Figure 10). The seine was 45 feet x 6 feet with ¼ inch mesh and used to capture fish in an arc from shore in two locations (Figure 10). Electrofishing runs were made along shore in two locations (Figure 10).

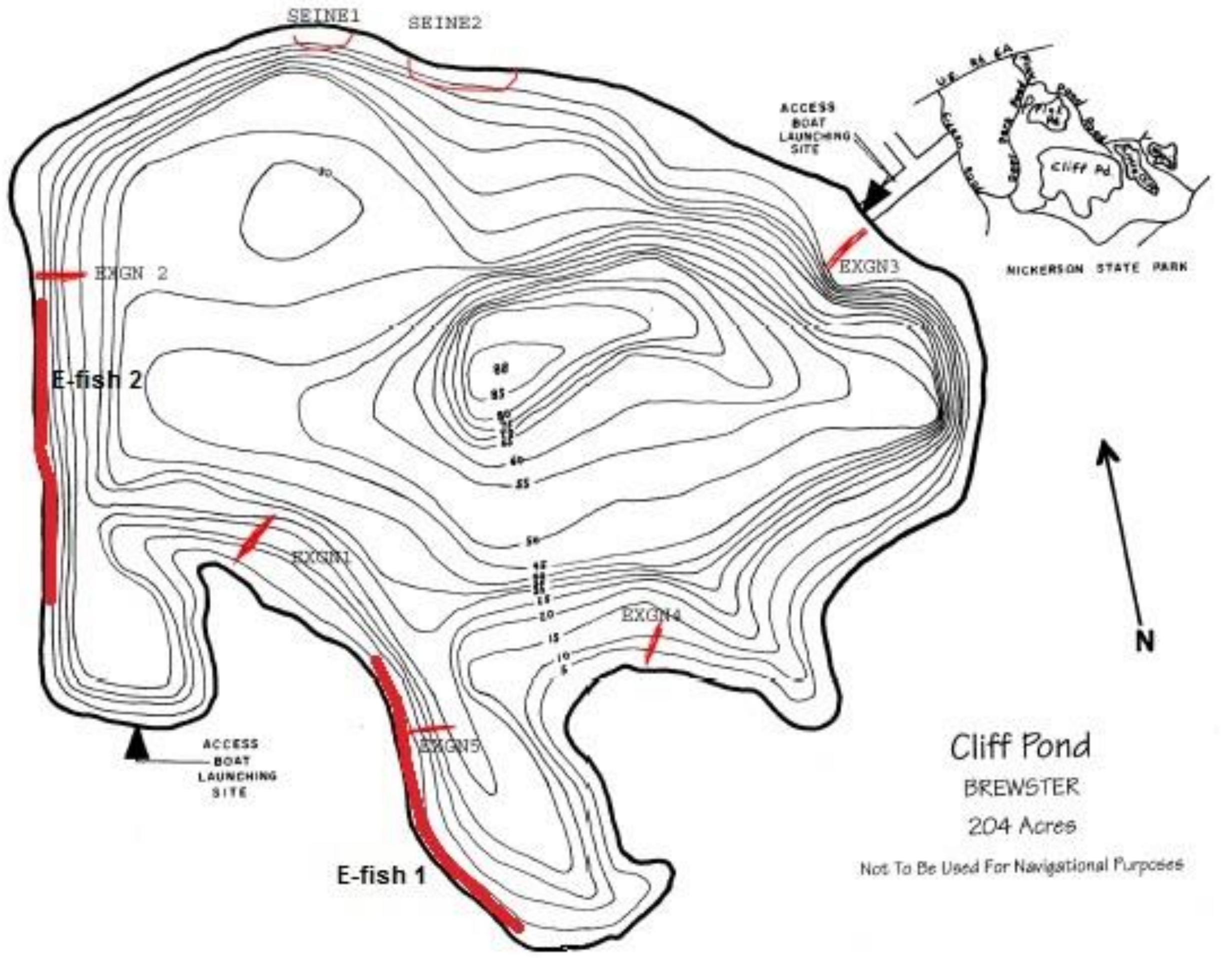


Figure 11. Fish survey locations

Investigative Results

Historic Data Review

Data for water clarity extends back to 1948, although only a few data points exist for the period prior to 2001 (Figure 12). The sparse early data do not suggest a water clarity problem prior to about 2002, although algal blooms were reported in the late 1990s that apparently included toxic cyanobacteria, based on the death of at least two dogs after exposure to algae in Cliff Pond. Low water clarity in mid- to late summer is evident in 2002 through 2005, with decreased clarity only at the very end of summer in 2006 and no apparent problems in 2007 through 2010. Clarity was the lowest ever reported in 2011 and 2012, however, with values below the former swimming standard of 4 feet (1.22 m). The lack of an observable trend suggests multiple overlapping influences, none of which may be sufficient by itself to dictate conditions, but together can allow severe algae blooms when facilitating factors align. Those factors may include influences for which we do not have data, but we will be examining possible factors for which we do have data to elucidate possible mechanisms of bloom formation.

Chlorophyll has not been monitored as often as water clarity, but enough data exist through the PALS program since 2001 to observe shifts in this key water quality variable (Figure 13). Low to moderate levels with relatively even distribution over the three identified depth intervals between 2001 and 2003 gave way to increasingly erratic chlorophyll concentrations between 2004 and 2010 with higher levels most of the time at mid-depth or the deeper sampling area than near the surface. In 2011 and 2012 chlorophyll levels were much higher in the surface water than in other years or in the other two depth intervals, creating the worst blooms in the period of PALS record. We know that there were blooms in the late 1990s, and they were apparently cyanobacteria blooms, but detailed data are unavailable. Based on limited water clarity data, it does not appear that there were algal blooms prior to the 1990s.

Total nitrogen in Cliff Pond surface water has increased in recent years (Figure 14), with 5 of the 6 highest values in the last 4 years. For total phosphorus in Cliff Pond surface water (Figure 15), 3 of the 4 highest values have been recorded in the last two years, the two lowest clarity years between 1948 and 2012. Total nitrogen in deep water has fluctuated but has not been extremely variable, whereas total phosphorus in deep water has been highly erratic over the period of 2001 through 2012 (Figures 14 and 15). Surface values for nitrogen and phosphorus are generally moderate, but deep water values are often quite high by late summer.

Oxygen levels have changed over time (Figure 16), with depressed oxygen (<5 mg/L) and anoxia (<1 mg/L) found at shallower depths more often in recent years. Oxygen problems are not expected and do not appear to occur in fall, winter or spring, when the pond is not stratified. During summer stratification, however, there is a clear decline in the depth at which oxygen decreases to <5 mg/L between 1948 and 2000, and it appears that the bottom started experiencing anoxia sometime between 1980 and 1987. From the 1980s on there is variability in the depth at which anoxia occurs, but it does appear to occur in all years, sometimes at depths which involve a large portion of the bottom of the pond. Anoxia reached the thermocline in 2009 and 2011 and was close in 2012.

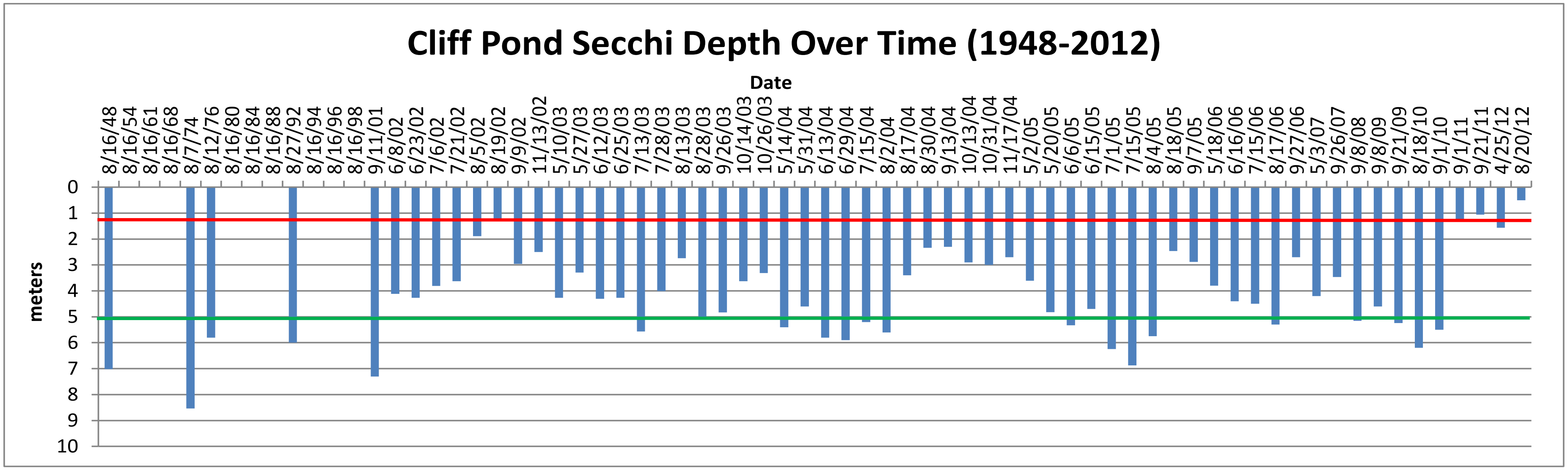


Figure 12. Secchi transparency for Cliff Pond between 1948 and 2012

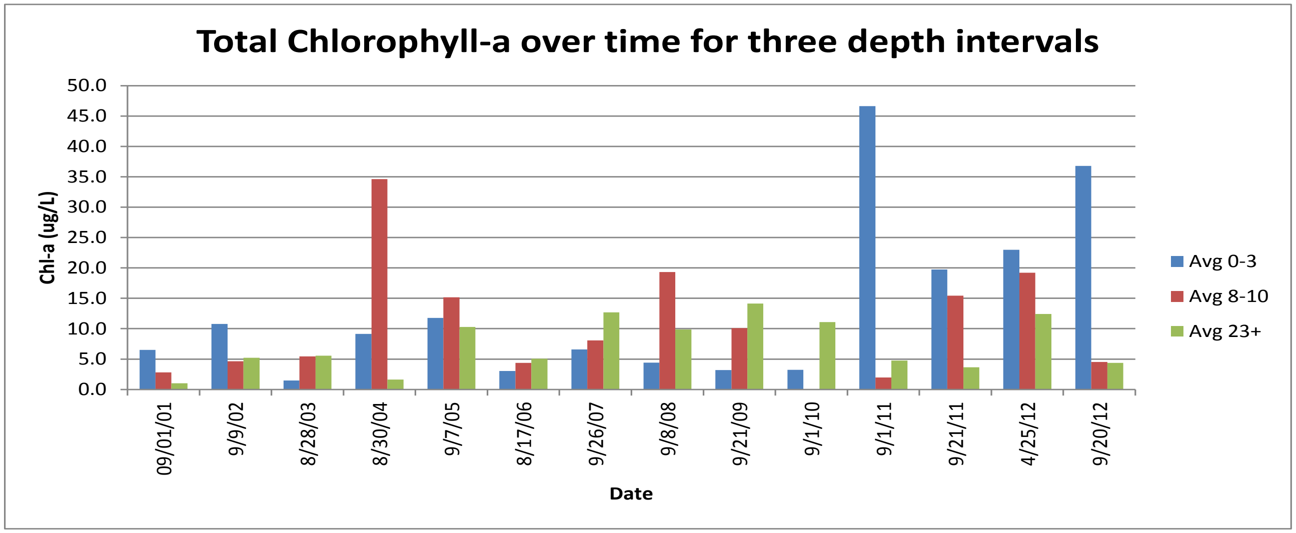


Figure 13. Secchi transparency for Cliff Pond between 1948 and 2012

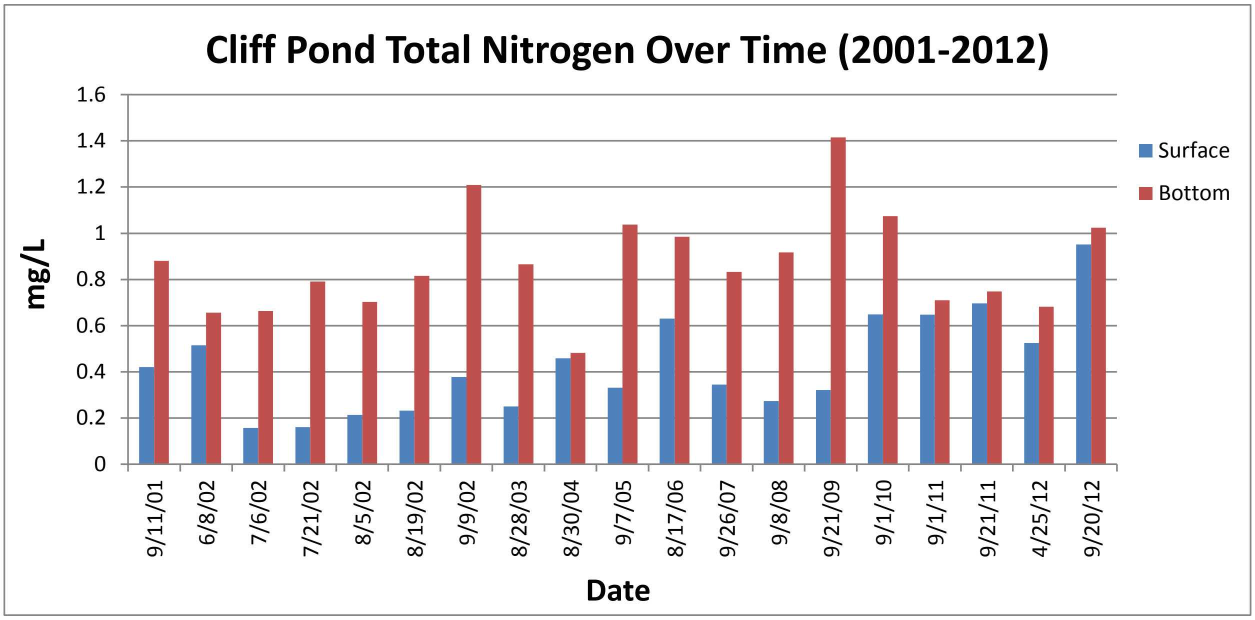


Figure 14. Total nitrogen in Cliff Pond between 2001 and 2012

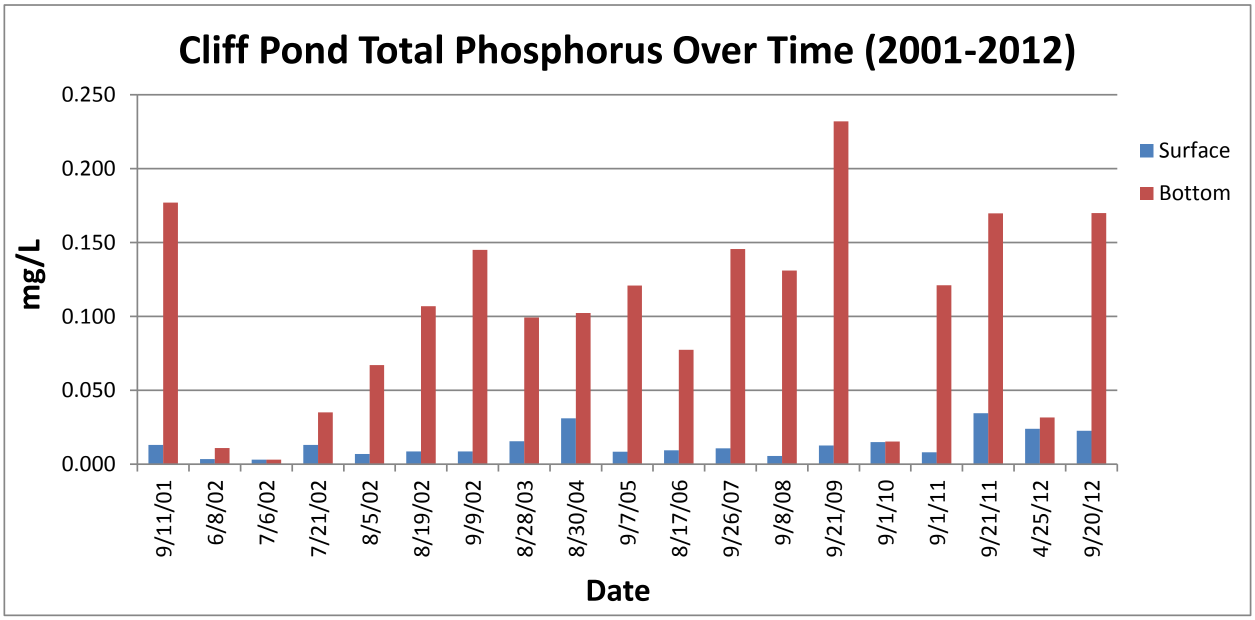


Figure 15. Total phosphorus in Cliff Pond between 2001 and 2012

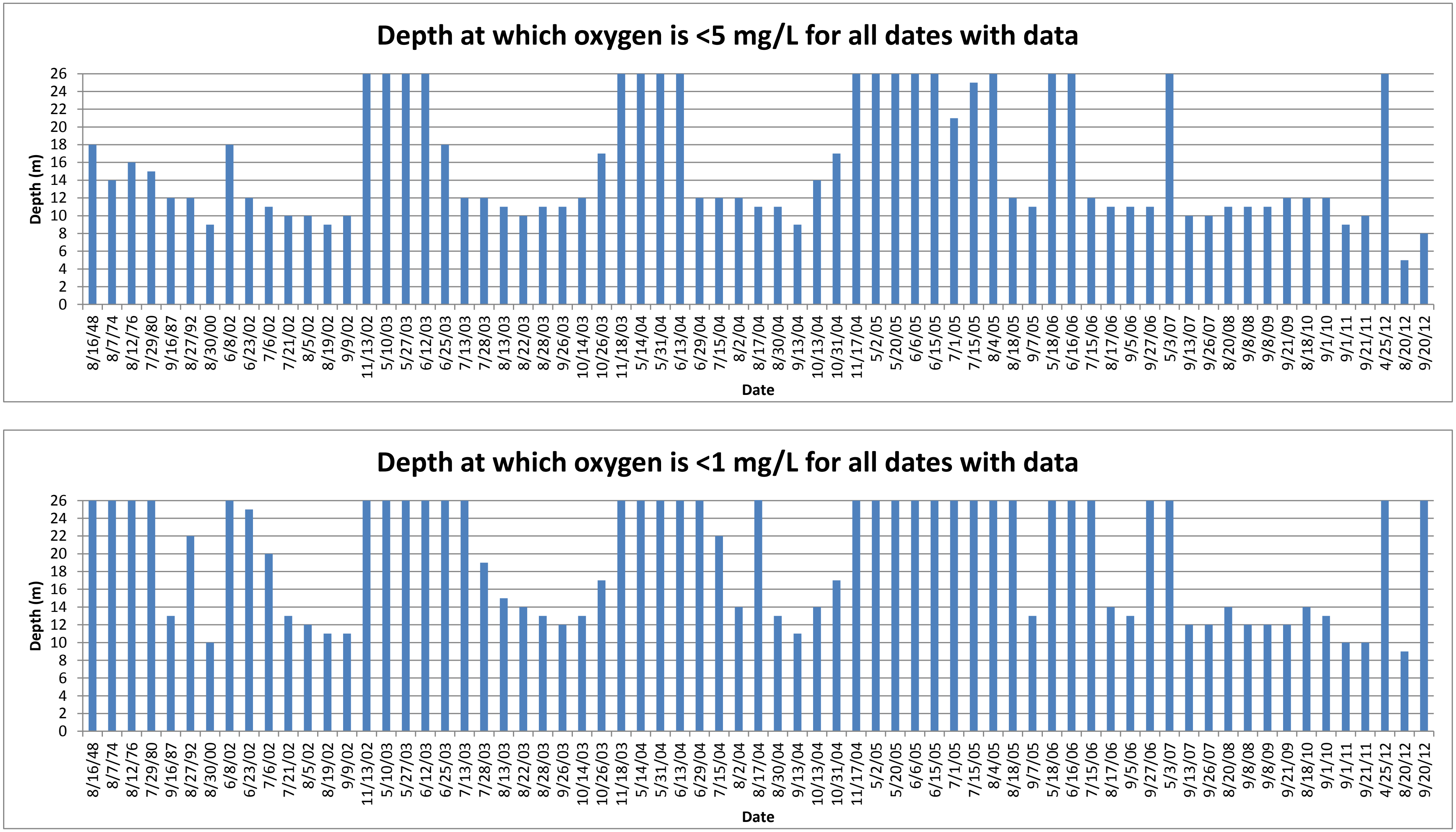


Figure 16. Depth at which oxygen declines below 5 mg/L (top) or 1 mg/L (bottom) in Cliff Pond

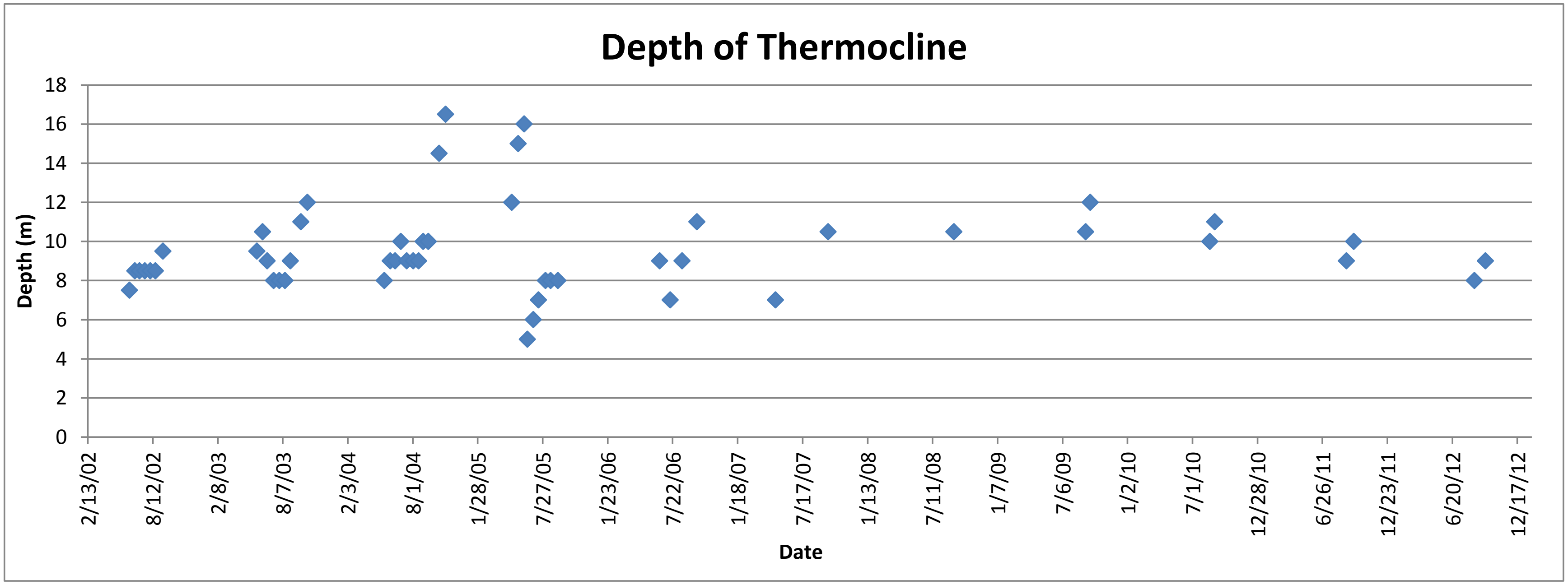


Figure 17. Depth of the thermocline in Cliff Pond over time

The depth of the thermocline, the depth that marks the boundary between upper and lower water layers during stratification, has been mostly between 26 and 40 feet (8 and 12 m) since 2002 (Figure 17), with occasional deviations to extremes of 16.5 and 54 feet (5 and 16.5 m). The transition zone between the upper and lower layers tends to be 3 to 7 feet thick (1-2 m) when the pond is strongly stratified, but the thermocline is a useful concept for considering how much of the bottom will be in each layer. The range is substantial, and considered in light of oxygen loss in the lower layer, may be very important to sediment-water interactions that affect algal bloom formation. There is no strong pattern over time, although the depth of the thermocline has been steadily decreasing since 2009 and may relate to increased algae over that time period, leading to lower light penetration.

Watershed Assessment

Cape Cod has experienced major land use changes over the 20th century, going back to the farming period at the turn of the century through a development boom in the 1980s, but Nickerson State Park has remained relatively unchanged. It was a private game preserve in the early 1900s and became a state park in the 1940s, so it has not experienced many of the pressures found elsewhere. A portion of the ground watershed has been developed over time, but is not intensely developed, and originates in Long Pond. Long Pond experienced sporadic cyanobacteria blooms, but was not in extremely poor condition. It was treated with aluminum in 2007 and has enjoyed increased clarity since then, the same period in which significant deterioration has been noted in Cliff Pond. The ground watershed is not especially large, but the surface watershed is quite small, only about 170 acres (68 ha). The surface watershed is entirely within Nickerson State Park and is mostly wooded. There are steep slopes adjacent to the pond, some of which are eroded, but overland flow to the pond is minimal.

The most obvious current source is wastewater disposal within the park, and the locations of all facilities that might conceivably have a leachfield within the ground water drainage area of the pond were mapped by GPS (Figure 18, Table 1). Combining the surface and ground watersheds to produce the maximum area near the pond, most facilities are outside the possible zone of influence. The camper pump station is marginally within the border, but is a sealed facility and should not be contributing to ground water. The Department of Youth Services buildings are partly within the border, but the leachfield is well downhill on the north side of the pond and would not be expected to contribute to it. Six bathrooms, three in camping area 4 and three in camping area 6, are within the border, but are about as far from the pond as they can be and are well above it, providing a very large volume of sand to absorb phosphorus. Nitrogen might be expected to move more freely through ground water. Loads can be estimated based on projected bathroom use and position.

Vegetation in the watershed is mostly pine, oak and shrubs like blueberry and sweet pepperbush. The soils are quite sandy and do not produce much runoff. Acidity is high. Erosion on the steep sloped adjacent to the pond can be severe, and there will be nutrients associated with sand inputs, but the actual mass of nutrients is calculable and would appear to be low. There are roads in the park and rest of the watershed, but there are no storm water drainage systems that route runoff to Cliff Pond or anywhere near it. The park can be heavily used, but is generally well policed and few significant sources of contaminants are evident. People have been observed bathing in the ponds, using soap and shampoo, but not in Cliff Pond (at least recently) and it is hard to envision enough abuse of this kind to impact water quality in a pond with a volume of almost 6000 acre-feet (7.3 million m^3).

While all inputs deserve attention to minimize impacts to Cliff Pond, there is nothing in the watershed that stands out as a major source at this time or at any time in its documented history. Nutrients do accumulate in all water bodies, and in the absence of any surface outlet, retention will be complete; ground water outflow and evaporation are negligible means of departure from the pond for nitrogen and phosphorus, most of which will wind up in particulate matter.

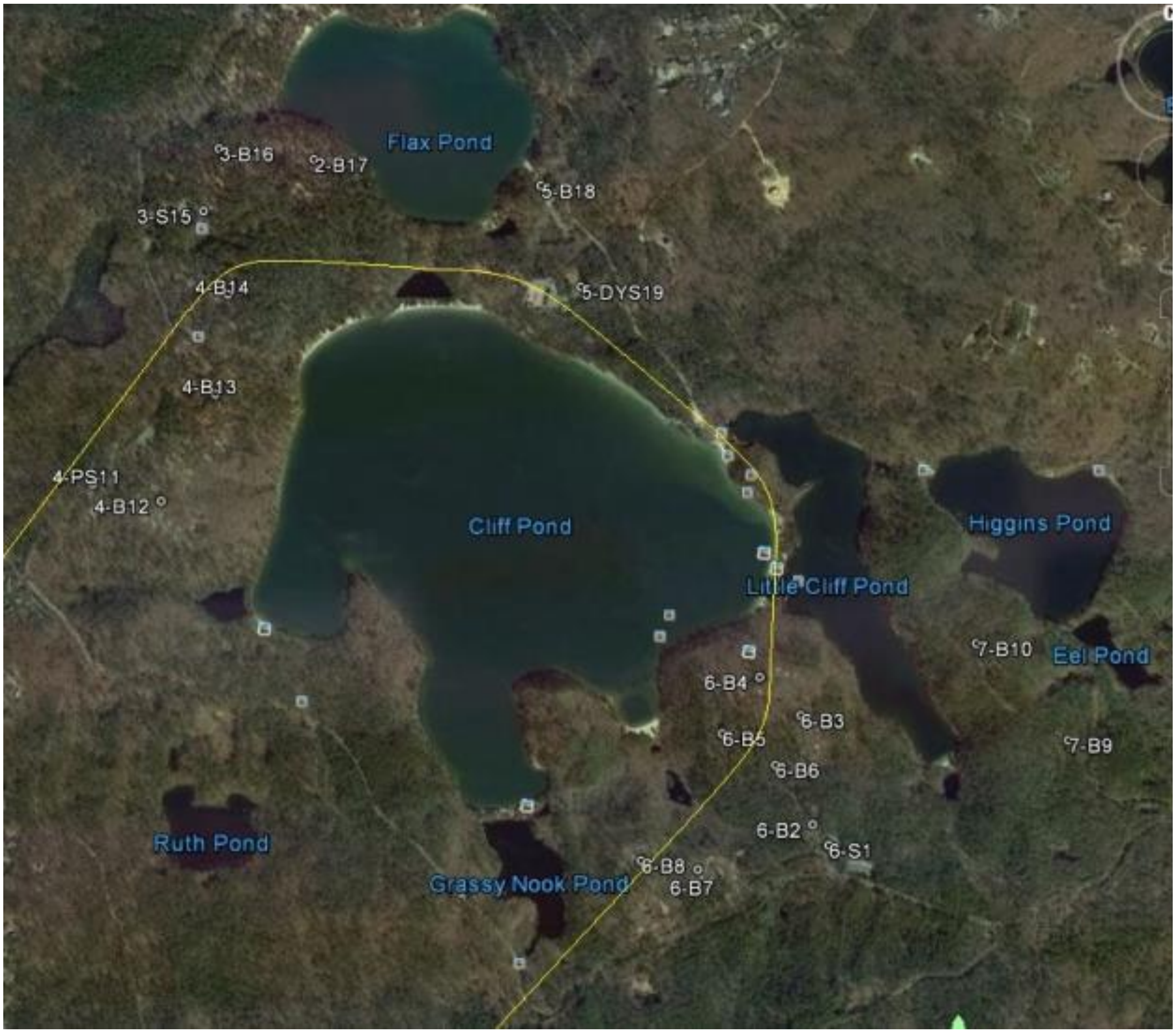


Figure 18. Map of wastewater disposal system locations with drainage boundary for Cliff Pond

Table 1. Locations of wastewater disposal facilities near Cliff Pond.

Area	GPS #	Waypoints map	Point of Interest
6, 6 Ex	329	6-S1	bathroom / showers
6, 6 Ex	330	6-B2	bathroom
6, 6 Ex	331	6-B3	bathroom
6, 6 Ex	332	6-B4	bathroom
6, 6 Ex	333	6-B5	bathroom
6, 6 Ex	334	6-B6	bathroom
6, 6 Ex	336	6-B7	bathroom
6, 6 Ex	337	6-B8	bathroom
7	338	7-B9	bathroom
7	339	7-B10	bathroom
4	340	4-PS11	pump station
4	341	4-B12	bathroom
4	342	4-B12	bathroom
4	343	4-B13	bathroom
3	344	4-B14	bathroom / showers
3	345	3-S15	bathroom
2	346	3-B16	bathroom
5	347	2-B17	Flax Pond beach bathroom
5	348	5-B18	DYS camp
5	349	5-DYS19	Leachfield at DYS camp

In-Lake Investigations

Bathymetric Assessment

A new bathymetric map (Figure 3) was produced from the side scanning sonar survey. GIS work up of the data suggests an area of 206.7 acres (82.7 ha) and a volume of 5896.8 acre-feet (7.27 million m^3). The water level can vary a foot or more up or down, however, so the area and volume are not static. The water level was high to normal for most of this investigation, owing to a very wet June.

Water Quality Data

Complete water quality data can be found in Appendix A. Water clarity was low when the investigation started in April (Figure 19), owing to a bloom of a filamentous golden alga (*Tribonema*). Clarity gradually increased as those algae died off, peaking in mid-June at almost 14 feet (4.2 m). A cyanobacteria bloom (*Anabaena*) arose quickly in late June, but was not severe and affected mostly areas downwind where particles accumulated. The north and northwest nearshore areas were most affected. This bloom died out and by mid-July the water clarity reached a study high near 16.5 ft (5 m). Clarity remained high into early August, but another cyanobacteria bloom

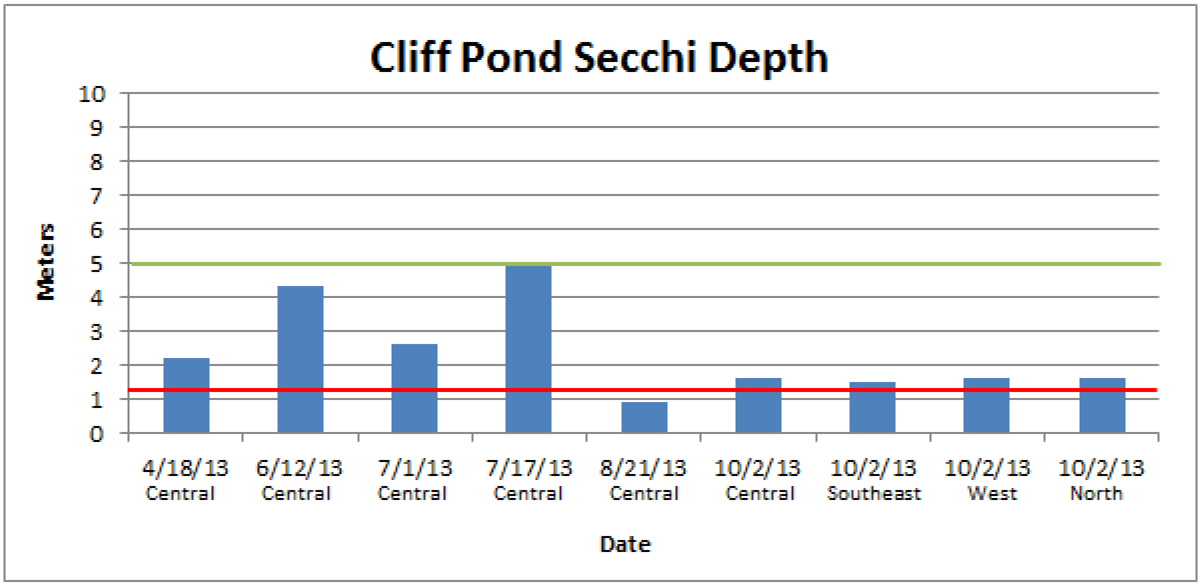


Figure 19. Secchi transparency

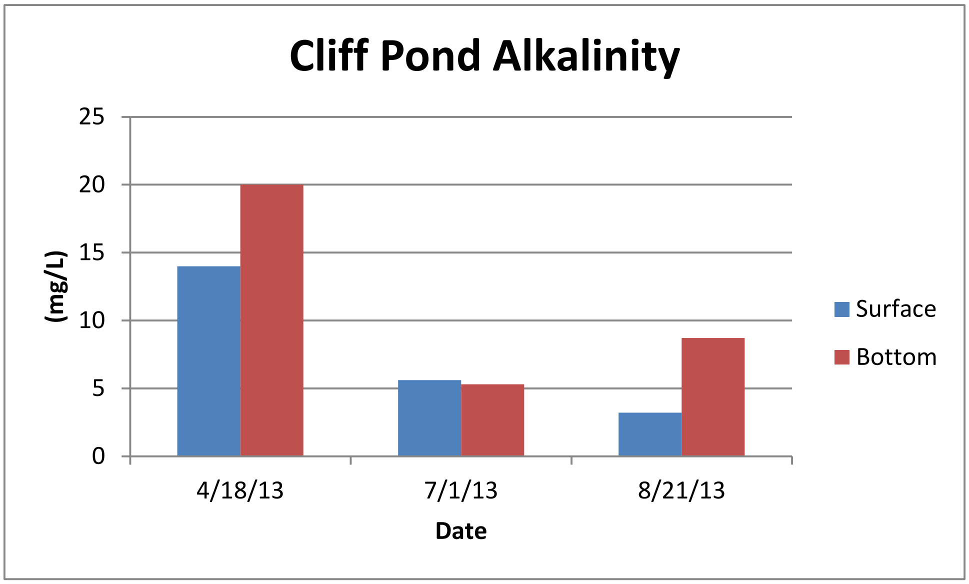


Figure 20. Alkalinity

(*Aphanizomenon*) developed and clarity was low from mid-August through the rest of the study period to early October. The pond was closed for contact recreation for part of June and most of August and September. While more measurement elucidated more of the seasonal pattern of clarity, the 2013 results were consistent with data from recent years.

Alkalinity was assessed only three times, as this water quality variable is not prone to wide variation in most ponds. Values were generally low in Cliff Pond, with slightly higher values in April than in July and August (Figure 20). Surface water values were lower than deep water values in April and August and similar between water depths in July. This is not a well buffered pond, but is typical of most Cape Cod ponds.

Profiles over the range of pond depth at the central deep hole station (Figure 21) exhibited a typical pattern of temperature progression for deep water bodies, with nearly isothermal conditions in April giving way to thermal stratification in June and through the summer. The thermocline formed at 26 to 30 feet (8 to 9 m) and became very sharp by early October at 33 feet (10 m).

Oxygen in the upper water layer remains near saturation, having access to the atmosphere and accepting oxygen from algal photosynthesis; decreases in oxygen are mostly related to increasing temperature, which controls the saturation level for oxygen in water. Oxygen in the lower water layer is gradually depleted, approaching zero in the bottom few feet by the end of June and eventually having no oxygen below a depth of 33 feet (10 m) (Figure 21). With the thermocline at the same depth and representing a very sharp boundary, the whole lower water layer was unsuitable for fish, a volume of approximately 1450 acre-feet (1.8 million m^3) or 25% of the pond volume.

Additional temperature and dissolved oxygen profiles (not shown) were collected and used in the assessment of oxygen demand discussed later in this report. Oxygen demand is more reliably calculable from profile with oxygen levels all above 2 mg/L, as demand is harder to satisfy when oxygen is low. These profiles were collected in May and early June and were intermediate to those of April and mid-June.

The pH was similar from top to bottom and near neutral in April 2013, but diverged in upper and lower water layers after stratification (Figure 21). Upper water pH, affected by intense algal photosynthesis that removed carbon dioxide and raises the pH, increased to 9.6 standard units in August. Deep water pH, subjected to acid accumulation from decomposition under aerobic and later anaerobic conditions, declined to 4.9 standard units in August. These are widely divergent values, as pH is on a logarithmic scale (a pH of 5 indicates 10,000 times more acidity than a pH of 9), and are not beneficial to pond ecology.

Specific conductivity, a measure of the dissolved substances in water, was fairly uniform and low at around 50 µS/cm until late July, but then increased in both upper and lower water layers (Figure 21). The increase in deeper water was more pronounced, but values were still <100 µS/cm. Values <100 µS/cm are often associated with low fertility, but as conductivity does not indicate what the solids are, this is not always true.

Turbidity was variable over depth but always <4 NTU through July, but increased near the surface and decreased in deeper water in August through September (Figure 21). Values exceeded 10 NTU at the start of October in the upper waters, declining sharply at the thermocline to the lowest values of this study in deeper water. The increased turbidity appeared related to the cyanobacteria bloom, which was a highly buoyant species concentrated in upper waters.

Values for temperature, oxygen, pH, conductivity and turbidity were assessed at the three other pond stations at the top and bottom on October 2, 2013 as a check on horizontal variability of water quality. Values matched those at the central station closely (Figure 22).

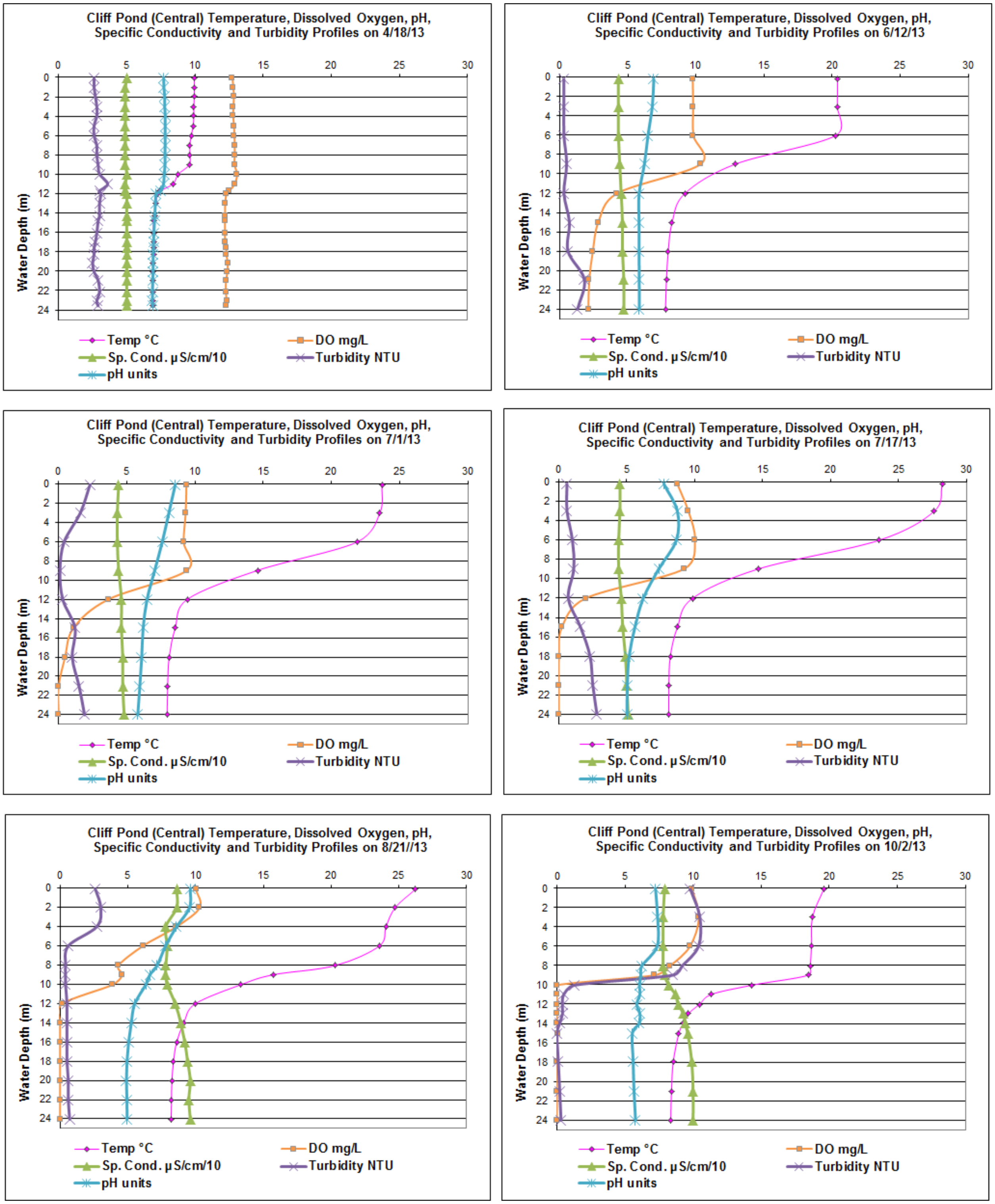


Figure 21. Central Station Temp, DO, pH, Spec. Cond. and Turbidity Profiles

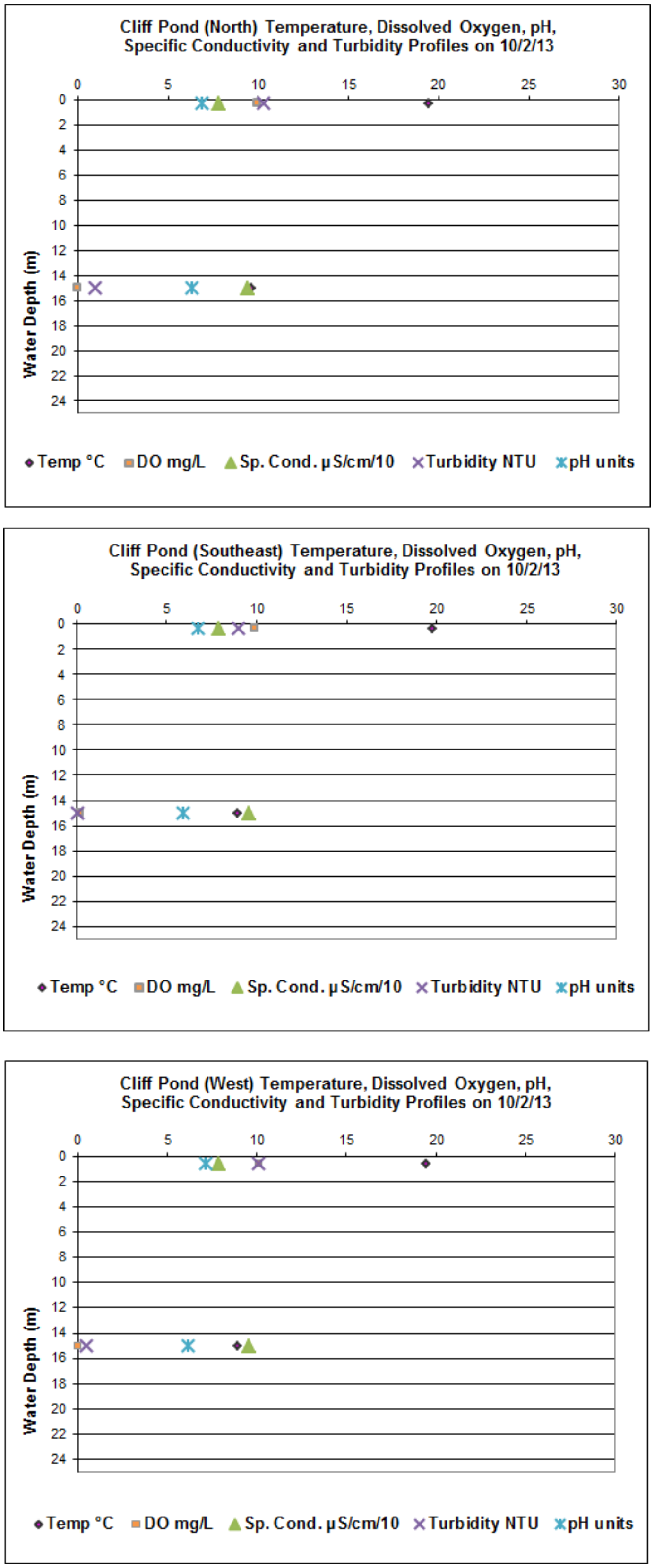


Figure 22. North, Southeast and West Stations Temp, DO, pH, Spec. Cond., Turbidity Profiles

Ammonium nitrogen, nitrate plus nitrite nitrogen, total Kjeldahl nitrogen, dissolved phosphorus and total phosphorus were assessed at 10 foot (3 m) intervals from top to bottom at the central sampling station in April, July and August. Samples were collected at the surface, thermocline, and deepest location at the central station in early October, while samples were collected from the surface and bottom at three additional stations in early October to assess horizontally spatial variation. A quality control sample was collected at the 40 foot (12 m) depth in July and the values agreed closely with the duplicate sample.

Nitrate was low to moderate in concentration throughout the study, while ammonium was low to moderate at all depths to start and increased through the summer as it accumulated in deep water (Figure 23). Total Kjeldahl nitrogen (TKN) generally tracked the ammonium level, with added organic nitrogen, such that ammonium and organically bound nitrogen (mostly amino acids in living or dead algae) were the dominant forms of nitrogen in Cliff Pond in 2013. This is the only investigation to split nitrogen fractions, but it is likely that all recent years have a similar split. Once the bottom becomes anoxic in deep water, anaerobic decay will lead to ammonium accumulation. That decay is not rapid, so a mix of organic and ammonium nitrogen will be present. The ammonium is completely soluble and very mobile, and becomes a source of nitrogen for algae.

A fraction of the ammonium is un-ionized (NH3-N, ammonia, rather than NH4-N, ammonium) and toxic. At low pH and temperature such as encountered in deep water, this fraction would be low, but at higher temperature and pH such as observed in upper waters, there could be toxicity. As ammonium is fairly rapidly converted to nitrite and then nitrate in the presence of oxygen, toxicity in the upper waters would be expected to be minimal. However, at the thermocline there could be toxicity by ammonia, and this represents a serious issue for stocked salmonids, as any holding over into summer will be squeezed into the thermocline area as a consequence of high temperature above and low oxygen below.

The values for the three additional stations sampled in October indicate similar results as for the central station (Figure 24). Values for nitrate were generally low, while ammonium and TKN increased to high levels in deeper water.

Total and total dissolved phosphorus were assessed from the same samples as nitrogen forms. Total dissolved phosphorus is tested the same way as total phosphorus, except that the sample is filtered first, so algae and associated particulate phosphorus will have been removed. Despite this difference in the testing and the presence of substantial quantities of algae at least in August and October, total dissolved phosphorus tracked closely with total phosphorus (Figure 25). Based on the variance in the quality control samples, we suspect that the total dissolved phosphorus sample was either not filtered or was filtered after digestion, but we have been unable to get confirmation from the lab. The total phosphorus level is most important and is what we rely on for loading calculations.

Phosphorus values were moderate and not excessive in April, July and August, increasing to high levels only in the deep water in the early October samples (Figures 25 and 26). Given algal blooms

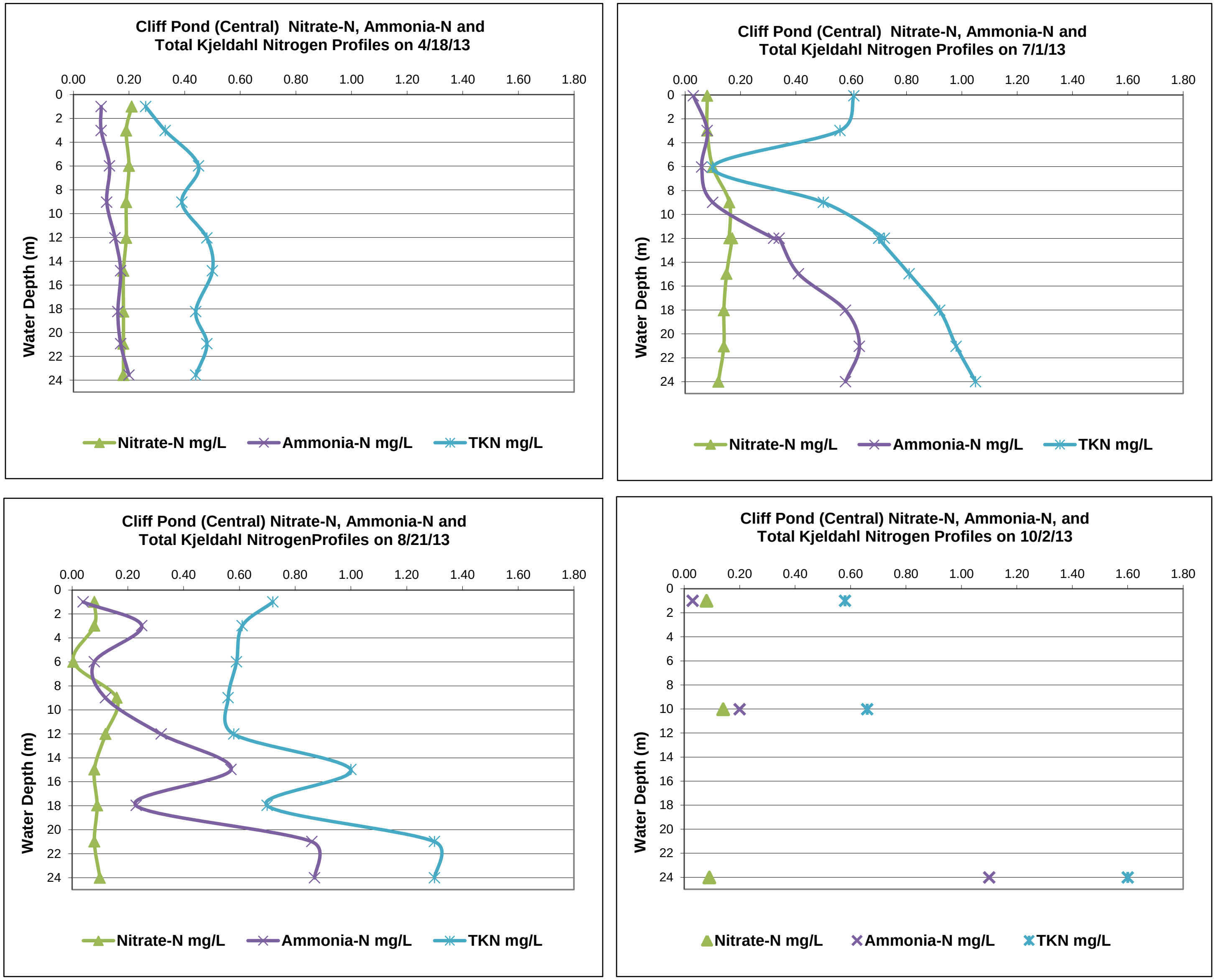
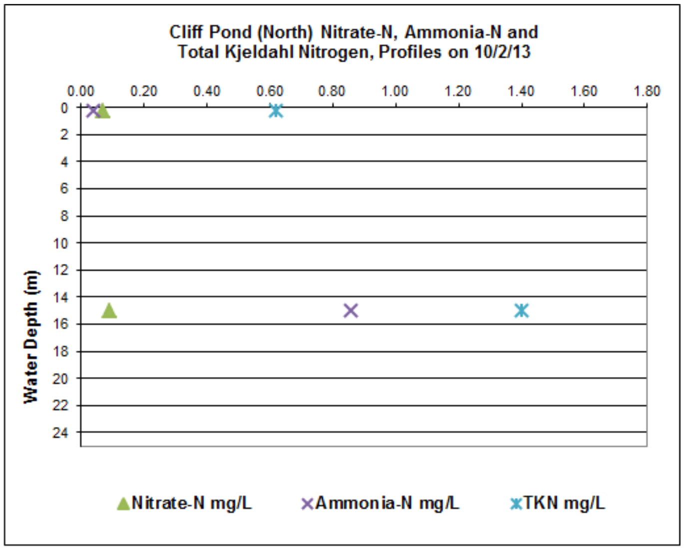
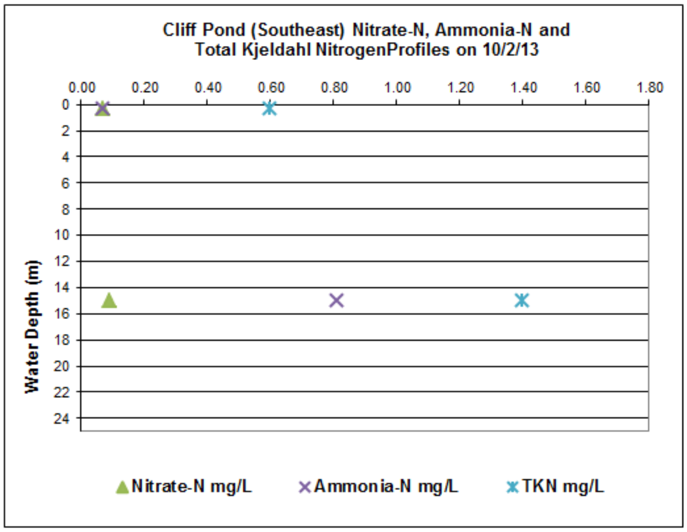


Figure 23. Central Station Nitrate-N, Ammonia-N, TKN Profiles





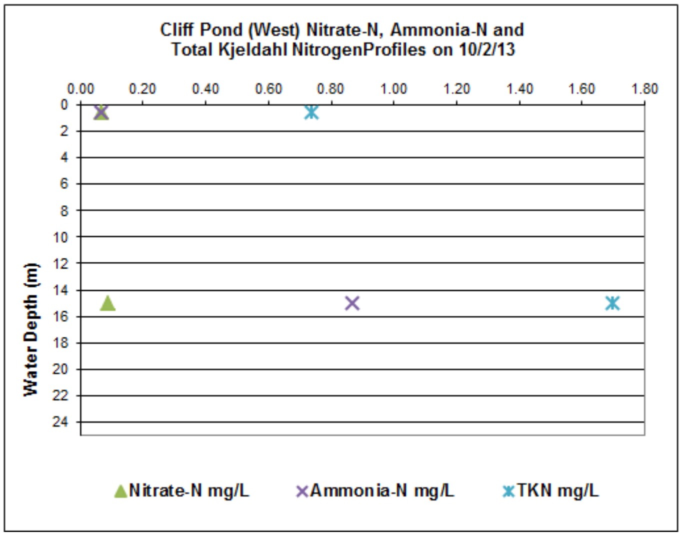


Figure 24. North, Southeast and West Station Nitrate-N, Ammonia-N, TKN Profiles

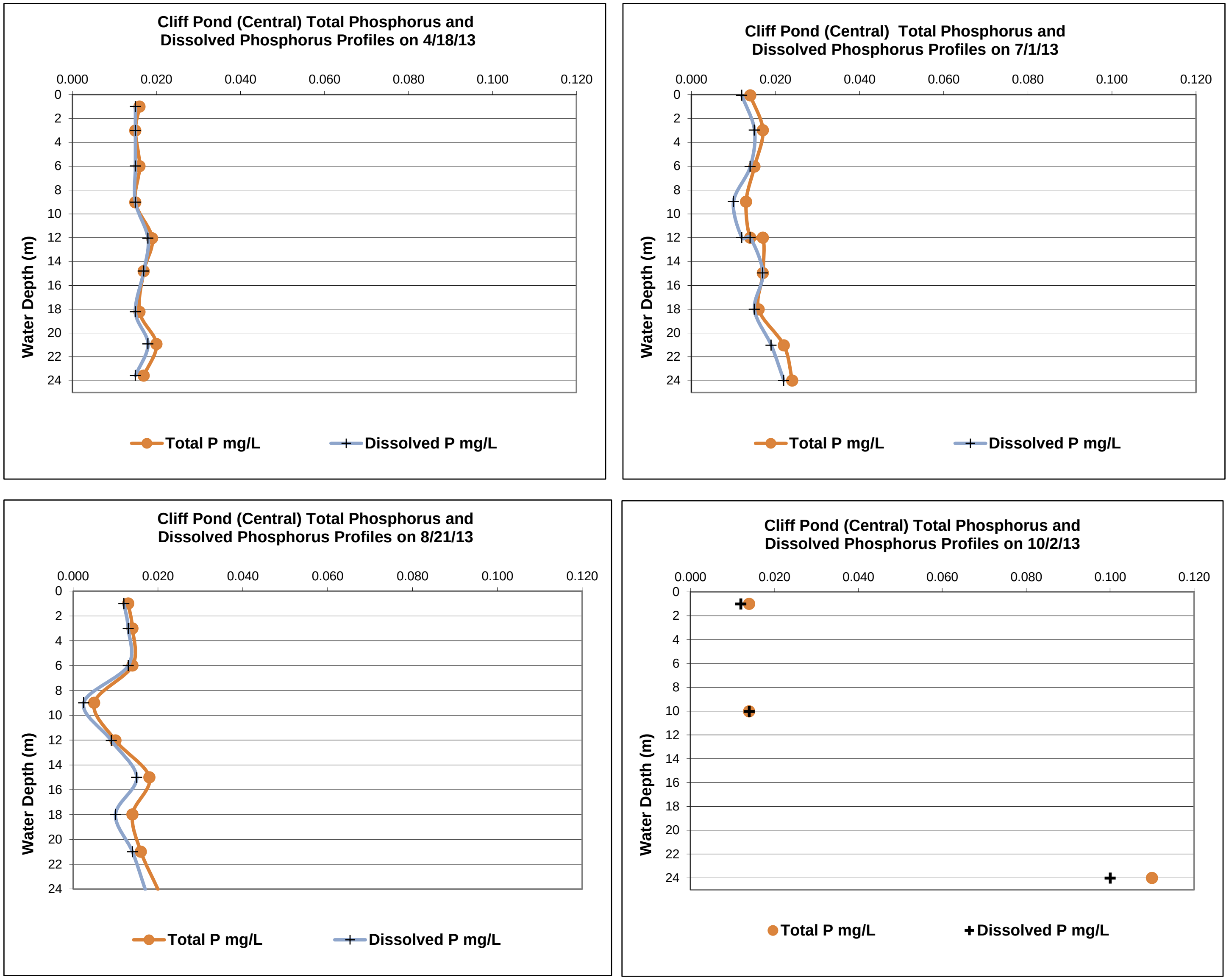
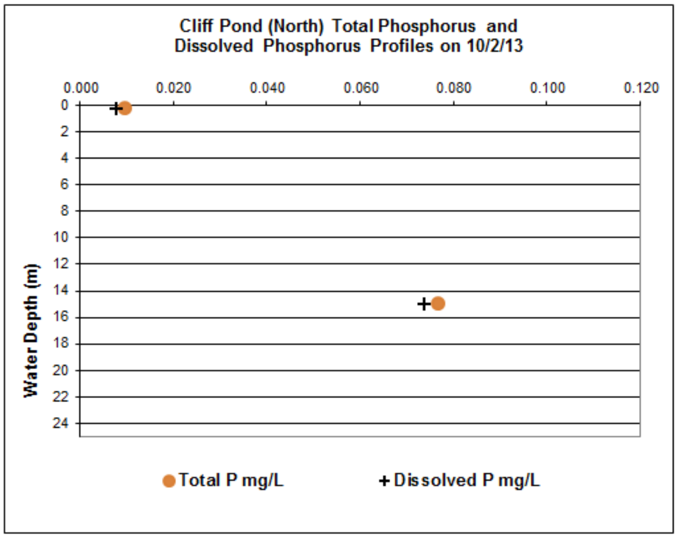
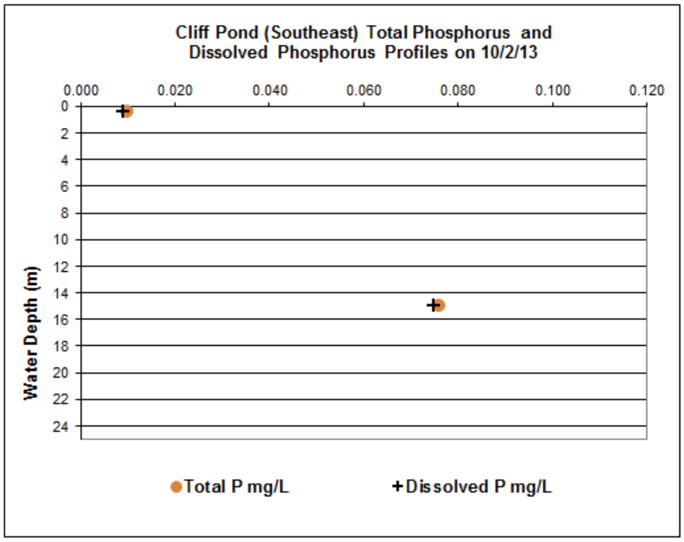


Figure 25. Central Station Total Phosphorus, Dissolved Phosphorus Profiles





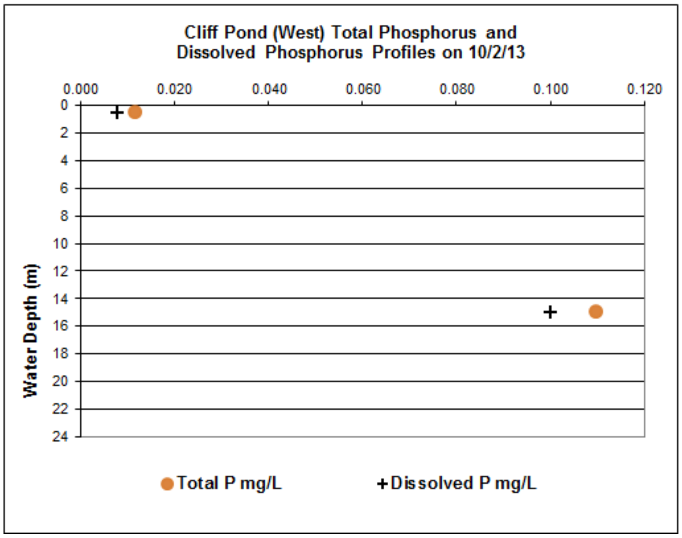


Figure 26. North, Southeast, and West Stations Total Phosphorus, Dissolved Phosphorus Profiles

on each sampling date for nutrients, the less than excessive phosphorus levels are confusing. Either the algae are extremely efficient at producing biomass with limited phosphorus (largely true for the cyanobacteria, which were the bloom forms on 3 of 4 dates), or phosphorus at the sediment-water interface (not measured by water column tests) was being used to generate substantial biomass, which then moved into the water column and was reduced in concentration by expanding biomass (also likely for cyanobacteria). Phosphorus levels <0.01 mg/L rarely cause blooms, while blooms are entirely possible at levels >0.02 mg/L. Phosphorus values for Cliff Pond surface waters in 2013 were between 0.010 and 0.016 mg/L.

While the substantial algae blooms at only moderate phosphorus levels in 2013 are disconcerting, the results are consistent with other years. The grand average phosphorus concentration in Cliff Pond surface waters since 2001 is 0.013 mg/L, with a high of only 0.035 mg/L in 2012. As some portion of total phosphorus in most lakes is unavailable to algae, and the values in Cliff Pond surface waters are not high, this suggests very high availability of phosphorus that is in the water. Such availability would not be expected from overland watershed sources (e.g., tributaries, which don't exist at Cliff Pond, and runoff, which is minor, which are high in particulate forms) or atmospheric inputs (about half of rainfall and dryfall inputs are available on average). If ground water was highly anoxic, phosphorus mobility would be high and much of the input would be available. As will be demonstrated in the next sections, seepage inputs are not extreme. This leaves internal loading, release from iron in anoxic sediments, as the likely primary source of phosphorus in Cliff Pond.

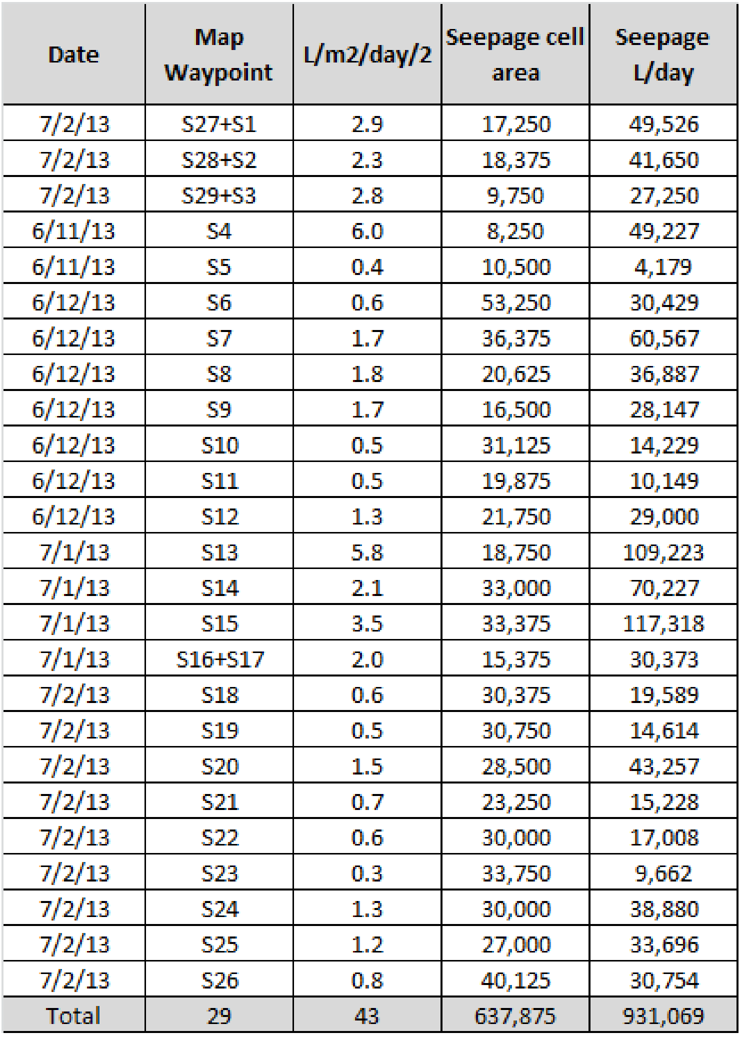
Seepage Quantity Assessment

Seepage quantity was assessed with seepage meters deployed on four days in June and early July of 2013. Seepage meters measure the amount of water gained or lost from the covered area of pond. Seepage is usually highest near the pond margin, declining exponentially with distance from shore and water depth, although geologic and soil anomalies can create zones of greater or lesser seepage in any area than might be expected. However, overall seepage can be estimated by a simple ring of meters around a water body, and that was what was done at Cliff Pond (Figure 9).

The detailed results of seepage measurements can be found in Appendix A. Individual seepage measurements were almost all positive (indicating inseepage) but also low (<5 L/m^2/day), and these were further divided by two (to account for maximum seepage at the pond edge where meters were placed) when calculating flow through areas which extend out to the point where muck was thick enough to impede seepage. Resulting inseepage for each defined cell (Table 2) was calculated, and summed to slightly less than a million liters per day, <1000 m^3/day or about 340,000 m^3/yr. Given a pond volume of almost 7.3 million m^3, this is not a large daily inseepage volume.

As the water level was high at the time of all measurements, inseepage could have been impeded (the localized ground water slope would have been altered), but very few negative seepage values were obtained (loss from the bags attached to meters, indicating outseepage). Water was still seeping into the pond, just not at the maximum rate possible. Water was seeping in all around the pond, indicating that despite the prevailing southwest to northeast direction of regional ground water flow, localized topography allows Cliff Pond to capture ground water from most of its perimeter. It is easy to envision an inflow rate higher than calculated, but at even triple the measured inseepage the total would be <3000 m^3, about 1 million m^3/yr, compared with 7.3 million m^3 of pond volume. There may be areas of greater inflow in deeper water, and Cliff Pond is sandy to depths of >40 feet (12 m), but ground water seepage is not large relative to pond volume.

Table 2. Seepage measurements for Cliff Pond in 2013



Date	Map Waypoint	L/m2/day/2	Seepage cell area	Seepage L/day
7/2/13	S27+S1	2.9	17,250	49,526
7/2/13	S28+S2	2.3	18,375	41,650
7/2/13	S29+S3	2.8	9,750	27,250
6/11/13	S4	6.0	8,250	49,227
6/11/13	S5	0.4	10,500	4,179
6/12/13	S6	0.6	53,250	30,429
6/12/13	S7	1.7	36,375	60,567
6/12/13	S8	1.8	20,625	36,887
6/12/13	S9	1.7	16,500	28,147
6/12/13	S10	0.5	31,125	14,229
6/12/13	S11	0.5	19,875	10,149
6/12/13	S12	1.3	21,750	29,000
7/1/13	S13	5.8	18,750	109,223
7/1/13	S14	2.1	33,000	70,227
7/1/13	S15	3.5	33,375	117,318
7/1/13	S16+S17	2.0	15,375	30,373
7/2/13	S18	0.6	30,375	19,589
7/2/13	S19	0.5	30,750	14,614
7/2/13	S20	1.5	28,500	43,257
7/2/13	S21	0.7	23,250	15,228
7/2/13	S22	0.6	30,000	17,008
7/2/13	S23	0.3	33,750	9,662
7/2/13	S24	1.3	30,000	38,880
7/2/13	S25	1.2	27,000	33,696
7/2/13	S26	0.8	40,125	30,754
Total	29	43	637,875	931,069

Seepage Quality Assessment

Seepage quality was assessed with littoral interstitial porewater (LIP) samplers that produced a sample of ground water just before it enters the water body. Multiple samples from each established shoreline segment (Figure 10) were composited and tested for nitrate, ammonium, dissolved iron and dissolved phosphorus in the lab (Table 3). Multiplying by the seepage estimate for each shoreline segment, a load for each nutrient can be estimated (Figure 27). The combining for seepage meter results for shoreline segments results in a lower overall seepage quantity estimate, but only by 7%.

Table 3. Seepage quantity and quality for delineated shoreline segments

Location	Seepage L/day	Nitrate-N mg/L	Nitrate-N kg/yr	Ammonia-N mg/L	Ammonia-N kg/yr	Dissolved Iron mg/L	Dissolved Iron kg/yr	Dissolved Phosphorus (P) mg/L	Dissolved Phosphorus (P) kg/yr
A	122,306	0.11	4.91	0.07	3.12	1.00	44.64	0.012	0.54
B	112,993	0.05	1.96	0.11	4.54	0.07	2.89	0.018	0.74
C	169,069	0.07	4.42	0.12	7.61	0.11	6.99	0.034	2.12
D	197,694	0.08	5.41	0.08	5.77	0.12	8.66	0.019	1.37
E	65,034	0.01	0.12	0.04	0.95	1.57	37.27	0.150	3.56
F	200,219	0.08	5.85	0.06	4.38	0.58	42.39	0.014	1.02
Total	**867,314**		**22.67**		**26.38**		**142.84**		**9.35**

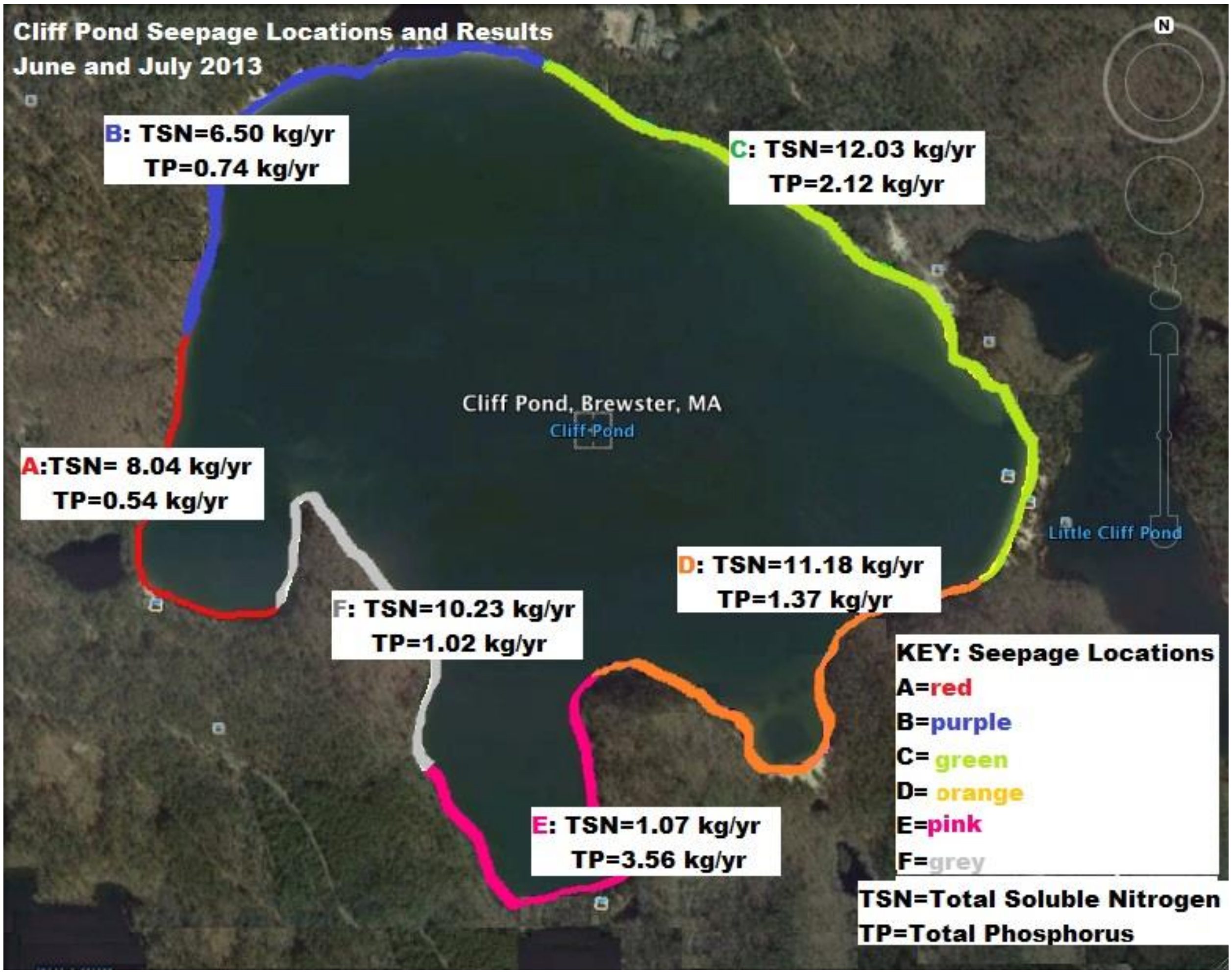


Figure 27. Seepage segments and calculated N and P loads

Nitrate and ammonium nitrogen levels were low in all samples; the sum of these two soluble nitrogen fractions was never >0.2 mg/L, and the resulting total load is not large. Even tripling that load to account for lower inseepage due to a wet June and high water levels does not yield an elevated load. Likewise, only one phosphorus value was elevated, and the calculated loads of phosphorus from each defined shoreline segment are not large. Additionally, the amount of iron is always >10 times the phosphorus concentration, suggesting that there is plenty of iron to bind the phosphorus once it enters the pond. Loading from ground water will be further considered in the construction of nutrient budgets, but it is apparent that the ground water is not a large source of nitrogen or phosphorus to Cliff Pond.

Sediment Distribution Assessment

The margin of Cliff Pond ranges from cobble to sand, grading to sand at intermediate depths and transitioning to finer sediments (inorganic silt and organic muck) at greater depths (Figure 28). Cobble, gravel and sand hold negligible quantities of phosphorus in an available form, so the emphasis is on fine grained sediment when considering potential internal loading. Using an underwater viewing system, we mapped the edge of the fine sediment layer in Cliff Pond. While lesser slopes allow fine sediment to accumulate in the boat launch cove (southwest part of the pond), there are no major accumulations of fine sediment anywhere else in water <30 feet (9 m) deep. A fine coating of silt can be found in some areas, and an occasional muck deposit may occur where local bottom topography allows accumulation, but stable and expansive coverage by fine grained sediment is not consistently found at depths >35 feet (10.6 m). Even then, fine sediment thickness is not substantial in all areas. No effort was made to measure fine sediment volume, but the Ekman dredge used to collect surficial sediment samples sometimes returned sand in water as deep as 50 feet (15.2 m). It is the area of fine sediment that determines potential interactions with the overlying water, however, not its thickness.

For the purpose of considering the soft sediment that may harbor substantial phosphorus reserves and be exposed to low oxygen levels during summer, we mapped the edge of the fine sediment layer where it represented the dominant bottom coverage (Figure 29). The affected area was about 73 acres in area (29.4 ha or 294,000 m^2). This equates to the area of the pond covered by water somewhere between 33 and 36 feet deep, but no depth contour is closely followed. In areas of steep slope the depth of accumulated fine sediment is as deep as 45 feet (13.6 m), while in areas of more gradual slope fine sediment can be found at a water depth of 30 feet (9 m). If dredging, phosphorus inactivation, or some other sediment treatment was to be implemented, the 73 acre area in Figure 29 would be the primary target zone.

Sediment Quality Assessment

This investigation did not include any detailed assessment of sediment characteristics as would relate to dredging, but surficial sediment samples were examined for features relating to phosphorus inactivation (Table 4). Five composite samples from defined areas (Figure 8) were collected, plus one sandy individual sample from one of those areas that provided a comparison with coarser sediments. Testing for percent solids, percent organic content, total and iron-bound phosphorus revealed a range of conditions generally consistent with expectations for this pond.

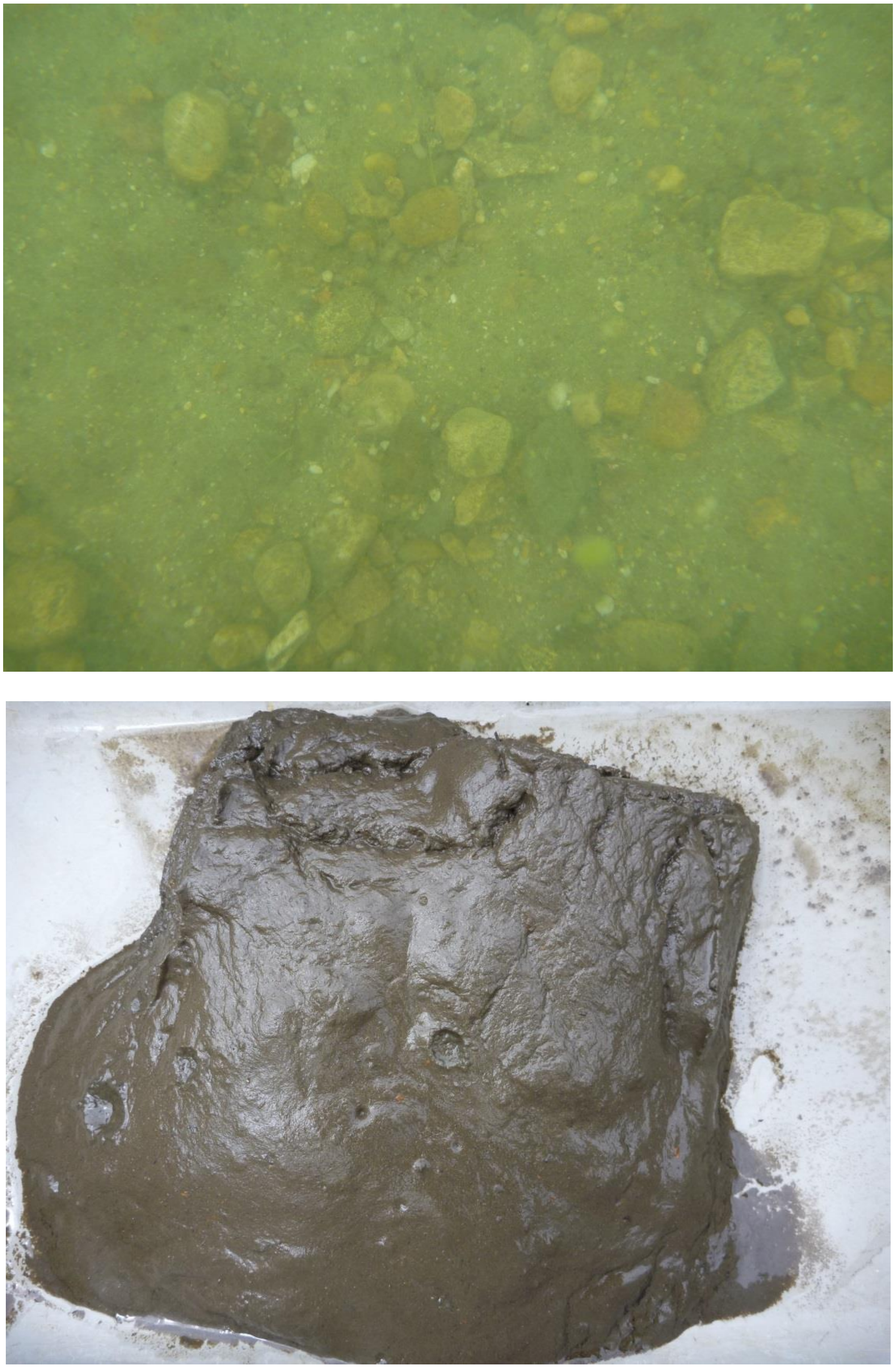


Figure 28. Shallow water substrate (top) and deeper water sediment (bottom) in Cliff Pond

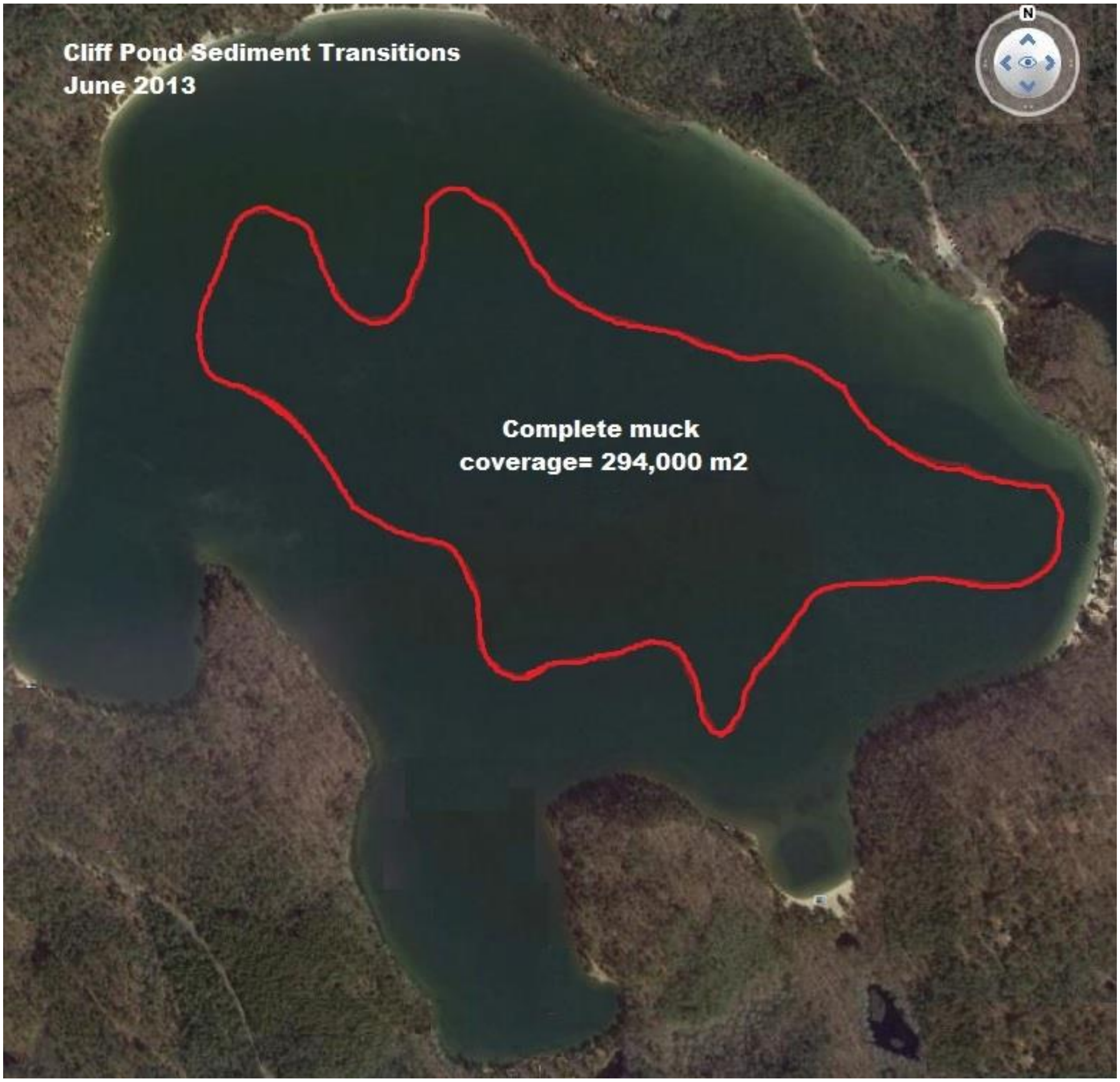


Figure 29. Map of pond areas completely covered by muck sediment

Table 4. Results of sediment quality testing and aluminum dosing assays.

Parameter	Unit	Treatment	CP- S1	CP- S2	CP- S3	CP- S4	CP- S5	CP- S5 Special
% Solids	%	None	12.5	21.3	22.3	27.0	24.2	53.3
% Organic matter	%	None	8.0	16.5	17.8	14.6	17.3	5.77
Total phosphorus	mg/kg dry wt	None	1980	2080	2020	1740	2180	475
Iron bound Phosphorus	mg/kg dry wt	None	731	1020	712	513	658	161
Iron bound Phosphorus	mg/kg dry wt	Al at 25 g/m2	381	557	522	253	343	<23.4
Iron bound Phosphorus	mg/kg dry wt	Al at 50 g/m2	138	323	252	111	228	<23.4
Iron bound Phosphorus	mg/kg dry wt	Al at 75 g/m2	< 99.6	242	197	97	172	<23.4

Percent solids ranged from 12.5% at the central station to 53.3% for the sandy sample, with all the other stations in the range of 21.3 to 27%; the central area is very "soupy", while the sandy sample was much more solid, and the other stations represented very typical values for deep pond sediments. The organic content was a little surprising, being at the low end for most deep pond sediments. The sand sample was 5.8% organic matter, about what would be expected, while the other samples ranged from 8 to almost 18%, the low end of the observed range in Massachusetts. Values >20% are common, and often values >30% are obtained in ponds subjected to algal blooms and rooted plant problems. It appears that the soft sediment of Cliff Pond is still largely inorganic silts. The lack of rooted plants and historic infrequency of algal blooms (despite relatively recent problems) have kept the organic content of the deep water sediment fairly low.

Total phosphorus was fairly consistent among the non-sandy samples at 1740 to 2180 mg/kg. The sandier sediment value was lower at 475 mg/kg. These values are of limited utility, as they do not convey information about phosphorus availability. Phosphorus attached to aluminum or refractory organic matter will remain in the sediment indefinitely. Phosphorus bound to iron is of greatest interest, as it can be released under anoxic conditions. Iron-bound phosphorus values for non-sandy samples were all in a range considered high at 513 to 1020 mg/kg. Iron-bound phosphorus represents 29 to 49% of the total phosphorus, a large percentage that suggests high potential for internal recycling under anoxic conditions. The sandier sample contained 161 mg/kg of iron-bound phosphorus, a moderate value, but still a third of the total phosphorus in that sample.

Aluminum Dose Testing

Since inactivation of the iron-bound phosphorus is under consideration as a rehabilitation technique, aluminum dosing tests were conducted to determine the appropriate dose of aluminum. The starting level for each test is the untreated iron-bound phosphorus concentration, and treatment of sediment aliquots with varying aluminum doses moves phosphorus from iron to aluminum. Re-testing for iron-bound phosphorus allows comparison with the original level and determination of the reduction in available phosphorus (Figure 30).

Iron-bound phosphorus values <100 mg/kg are acceptable, although values <50 mg/kg are desired. The sandier sample showed a pronounced decline in iron-bound phosphorus to a desirable level at the lowest dose, equivalent to 25 g/m^2 of aluminum. Other samples did not decline to <50 mg/kg at even the highest dose, equivalent to 75 g/m^2 of aluminum, but 2 of 5 samples were below 100 mg/kg. If aluminum treatment is pursued, additional testing would be warranted, and it may be necessary to increase the dose beyond 75 g/m^2. Yet the lab tests provide an indication of expected results, and suggest that at the 75 g/m^2 dose about 75% of the available phosphorus could be inactivated. This could make a big difference to pond condition.

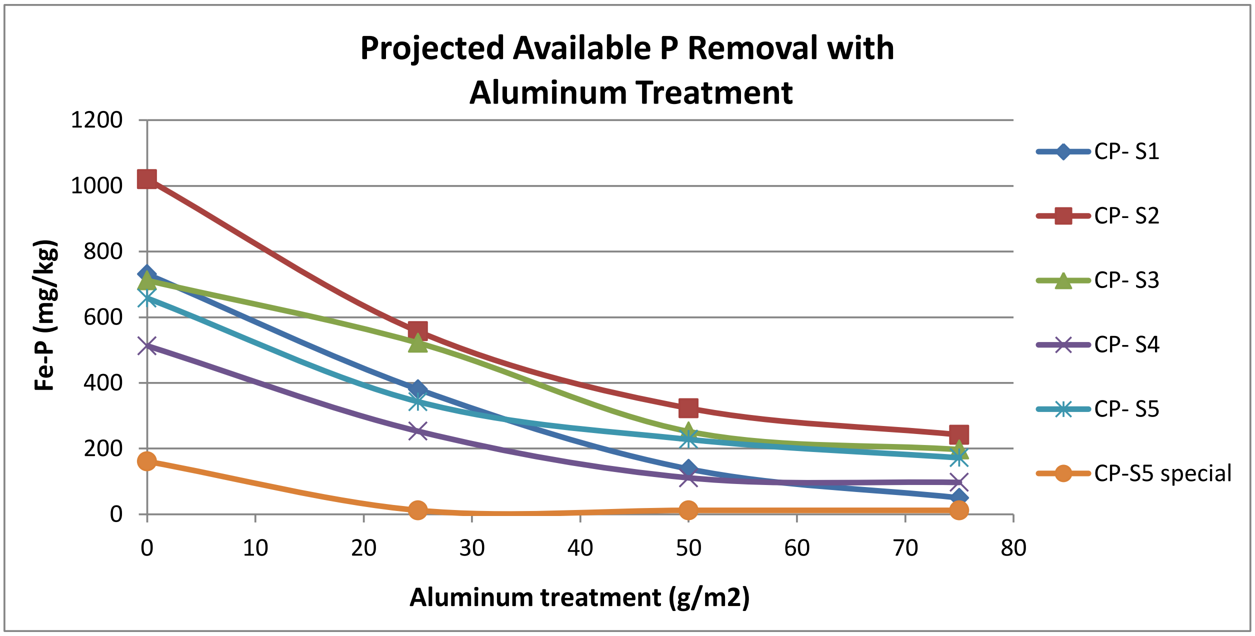


Figure 30. Decline in Fe-P with increasing aluminum dose

Plankton Analysis

Complete plankton data from 2013 are provided in Appendix A. Chlorophyll-a, a photosynthetic pigment common to all algae, was assessed on all plankton sampling dates, and revealed high values for August and October (Figure 31). Values in April through July were lower and generally acceptable, but there were visible algae blooms in April and early July. The April bloom was a filamentous chrysophyte, *Tribonema*, which has more chlorophyll-c, so the chlorophyll-a value is not truly indicative of algal biomass on that date. The water was quite discolored by the Tribonema, however (Figure 32, left). The late-June/early July bloom was *Anabaena lemmermanii*, a clumping form that rises from the bottom already in a pin-head sized tangled mass of filaments and can congeal into bigger particles with wind action. The wind moved this bloom to the northern and western shores, where it was quite visible (Figure 32, right), but it was not evident in the central station samples. Consequently, the July 1, 2013 chlorophyll-a measure is not representative of the whole lake. The elevated August and October chlorophyll-a values correspond to a persistent bloom of *Aphanizomenon*, which does not have a lot of chlorophyll per unit biomass, so this was a major bloom.

Phytoplankton composition and biomass (Figure 33) supplement the chlorophyll-a data. The dominance by golden algae in April and June samples is evident, with a high biomass in April and more moderate level in June. Three samples were collected on July 1st, given the observed variation over space with a wind-blown surface algae bloom. The central and boat launch cove samples exhibited moderate biomass and only a little cyanobacteria, while the boat concession area, on the west shore of the pond, had an elevated biomass of *Anabaena*. The highest clarity and lowest chlorophyll-a values were obtained in mid-July, and the corresponding algae sample had the lowest biomass and a mix of algae types that included a few common planktonic diatoms, a few small green algae, and some *Aphanizomenon*, the algae that would become dominant in August. The transition to a full *Aphanizomenon* blooms was evident in August, and conditions remained similar into October, with a high biomass of that one cyanobacterium and very little else. Although *Aphanizomenon* was detected in the early and mid-July samples at low levels, it is not clear that the population grew to bloom proportion in place; there may have been a mass hatch from resting stages in the sediment in response to high availability of phosphorus in that sediment. Nutrient levels in upper waters were not high, although *Aphanizomenon* may have been very efficient in its use of phosphorus. Aphanizomenon is a known toxin producing genus of cyanobacteria, although it has often been found not to produce toxins in natural pond situations; concern is warranted, but no assumption of toxicity should be made.

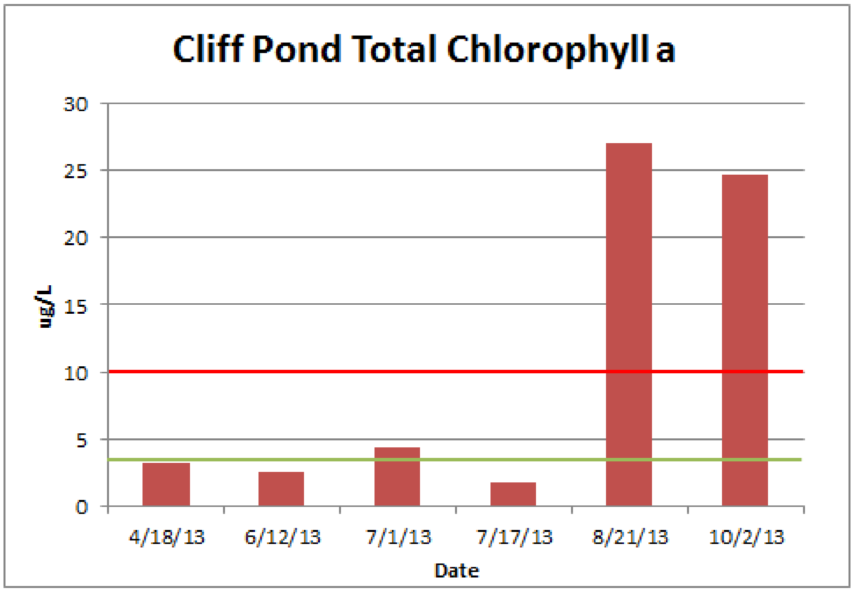


Figure 31. Total chlorophyll-a

Figure 32. Blooms of *Tribonema* (left) and *Anabaena* (right) in Cliff Pond

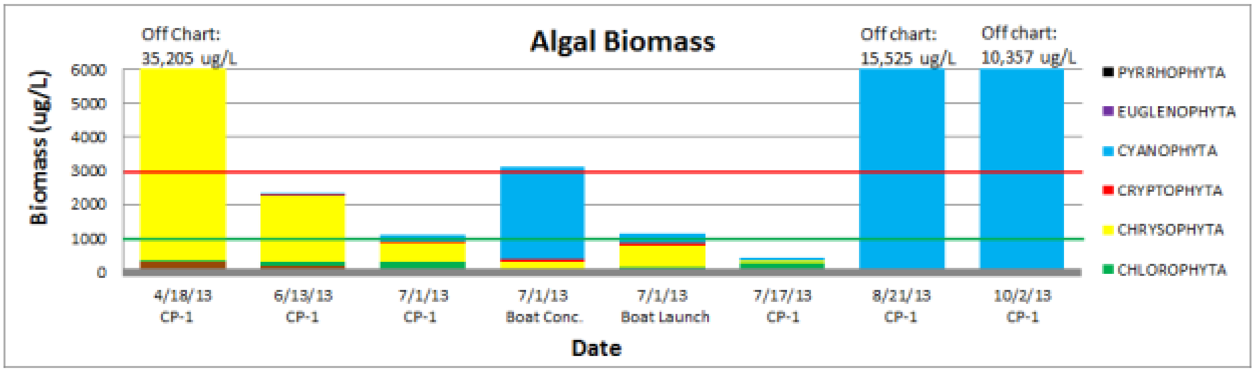


Figure 33. Algal biomass

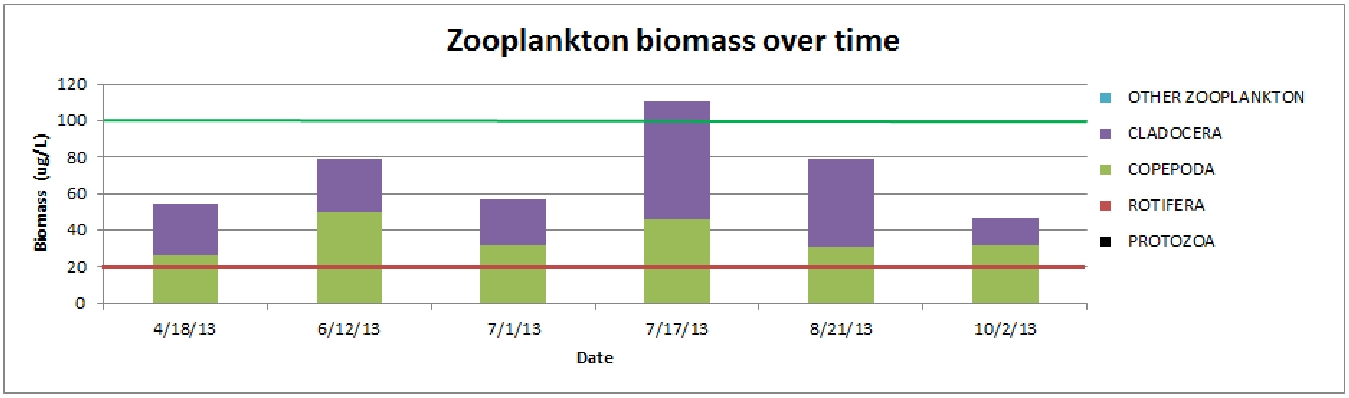


Figure 34. Zooplankton biomass

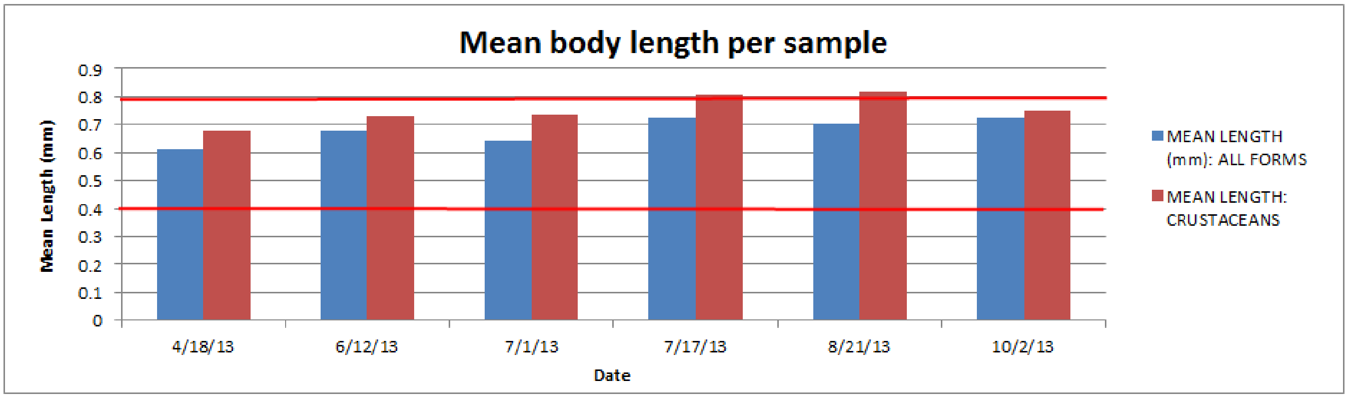


Figure 35. Zooplankton mean body length

Zooplankton were sampled at the same time as phytoplankton and assessed for species composition and biomass (Figure 34) and mean length (Figure 35). Zooplankton included mainly cladocerans and copepods at moderate densities, with a few rotifers observed. The largest biomass was obtained on July 17th, matching the lowest algal abundance and highest water clarity; large bodied, filtering cladocerans can clear the water of many algae, but calanoid copepods also eat mainly algae; both were moderately abundant on that date. Lower but not negligible biomasses of zooplankton were found on other dates, always a mix of copepods and cladocerans. *Daphnia*, among the most desirable forms of zooplankton for both consumption of algae and as food for small fish, were present until mid-July, but disappeared after that; these zooplankters are often reduced to minimal levels by mid-summer by fish predation, and return each year from resting eggs normally deposited in June. A substantial population of *Leptodora*, a predatory cladoceran, was also observed for most of the summer.

Average body length for zooplankton was quite favorable (Figure 35), neither too small (which would indicate intense predation and little algae grazing capacity) nor too large (which would suggest fish community problems with lack of small fish) (Mills et al. 1987). While a higher abundance of zooplankton would be desirable for both algae control and fish community support, the zooplankton community exhibited generally favorable characteristics and could be expected to respond to better conditions. In particular, the low oxygen in deeper waters restricts daytime migration into dark areas to reduce predation by fish; a larger oxygenated zone would be expected to foster a more robust zooplankton community.

Macrophyte and Mussel Analysis

Macrophyte and mussel assessment was not a focus of this investigation, but there are so few macrophytes in Cliff Pond that little effort was needed to characterize the plant community. Floating heart (*Nymphoides peltata*) and common naiad (*Najas flexilis*) were the only non-emergent plants observed, and then not commonly. Peripheral emergent growths including such species as hedge hyssop (Gratiola neglecta) and various sedges and rushes, but these were rarely dense in the sandy to cobbly peripheral substrate. Nearby ponds, such as Grassy Nook Pond, had abundant water lilies (*Nymphaea odorata*), but Cliff Pond had none. Cliff Pond is not a rooted plant dominated system, and fish depend largely on rocks and woody debris for habitat in shallow water. Open water fish species will do best in this pond, given limited cover, but the low oxygen will restrict habitat for those fish as well.

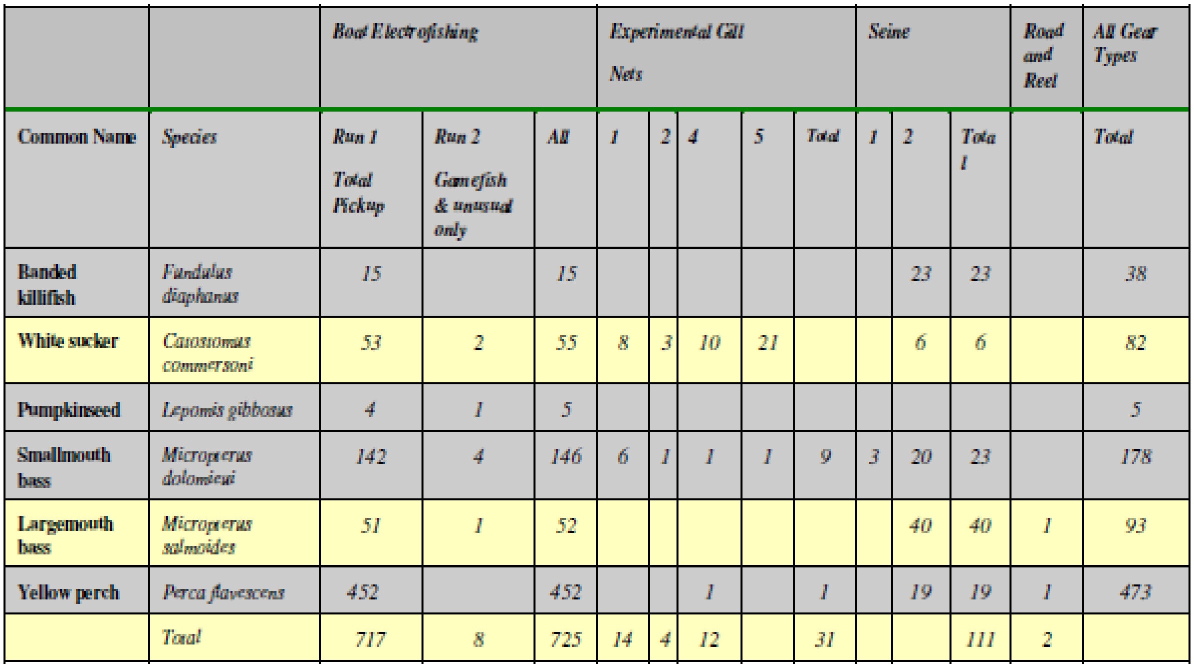
Freshwater mussels observed in Cliff Pond during the course of other surveys included the eastern elliptio (*Elliptio complanata*), the eastern lampmussel (*Lampilis radiata*), the eastern floater (*Pyganodon cataracta*) and the eastern pondmussel (*Ligumia nasuta*). None were especially abundant anywhere they were encountered.

Fishery Assessment

Cliff Pond has been assessed for fish populations multiple times over the last century, but had not been recently assessed, so a survey was conducted in August of 2013 by the Division of Fisheries and Wildlife with aid from WRS. The DFW provided tabular and graphic analysis of the results. Six warm water species were observed in shallow water during day and night collection activity (Table 5). Length ranges (Table 6) were substantial for both species of bass and suckers, but many more small fish were found than large ones. Reproduction certainly appears successful, but the survey was not extensive enough to provide a reliable overview of fish populations. Size distribution of largemouth and smallmouth bass (Figure 36) illustrates this situation well, with many small individuals indicating excellent reproduction, but many fewer large individuals scattered over a substantial range of size classes. Small fish were not even collected in the second electrofishing run, as there were so many observed in the first run. The warm water fishery is not intensely managed, but there certainly appears to be one, with potential for trophy bass based on the available forage base.

Cliff Pond is stocked with trout multiple times per year, including large salmonids, and is very popular as a put-and-take trout fishery. In past decades holdover populations were present, with growth into larger size categories possible, but there is so little habitable water in the summer now that holdover fish would be rare. What was at one time a 20 foot (6 m) thick layer of habitable water below the thermocline during summer stratification was reduced to just a few feet (<2 m) by 2000 and was effectively 0 in 2011-2013. Oxygen depletion is a major fishery problem in Cliff Pond.

Table 5. Fish captured by gear type in Cliff Pond, August 21, 2013



		Boat Electrofishing			*Experimental Gill Nets*					*Seine*			*Road and Reel*	*All Gear Types*
Common Name	*Species*	*Run 1 Total Pickup*	*Run 2 Gamefish & unusual only*	*All*	*1*	*2*	*4*	*5*	*Total*	*1*	*2*	*Total*		*Total*
Banded killifish	*Fundulus diaphanus*	15		15							23	23		38
White sucker	*Catostomus commersoni*	53	2	55	8	3	10	21			6	6		82
Pumpkinseed	*Lepomis gibbosus*	4	1	5										5
Smallmouth bass	*Micropterus dolomieui*	142	4	146	6	1	1	1	9	3	20	23		178
Largemouth bass	*Micropterus salmoides*	51	1	52							40	40	1	93
Yellow perch	*Perca flavescens*	452		452			1		1		19	19	1	473
	Total	717	8	725	14	4	12		31			111	2	

Table 6. Average and range of length for fish captured in Cliff Pond, August 21, 2013

		Length (mm)		Length (inches)	
Species	No.	Ave. (SD)	Range	Ave.	Range
Banded killifish	38	78.6 (7.12)	70-104	3.1	2.8-4.1
White sucker	82	192.3 (137.4)	65-434	7.6	2.6 – 17.1
Pumpkinseed	5	87.6 (10.67)	70-95	3.4	2.8 – 3.7
Smallmouth bass	141	92.6 (54.23)	61-370	3.7	2.4 – 14.6
Largemouth bass	93	103.4 (96.96)	50-453	4.1	2.0 – 17.8
Yellow perch	200	77.6 (21.10)	54-232	3.1	2.1 – 9.1

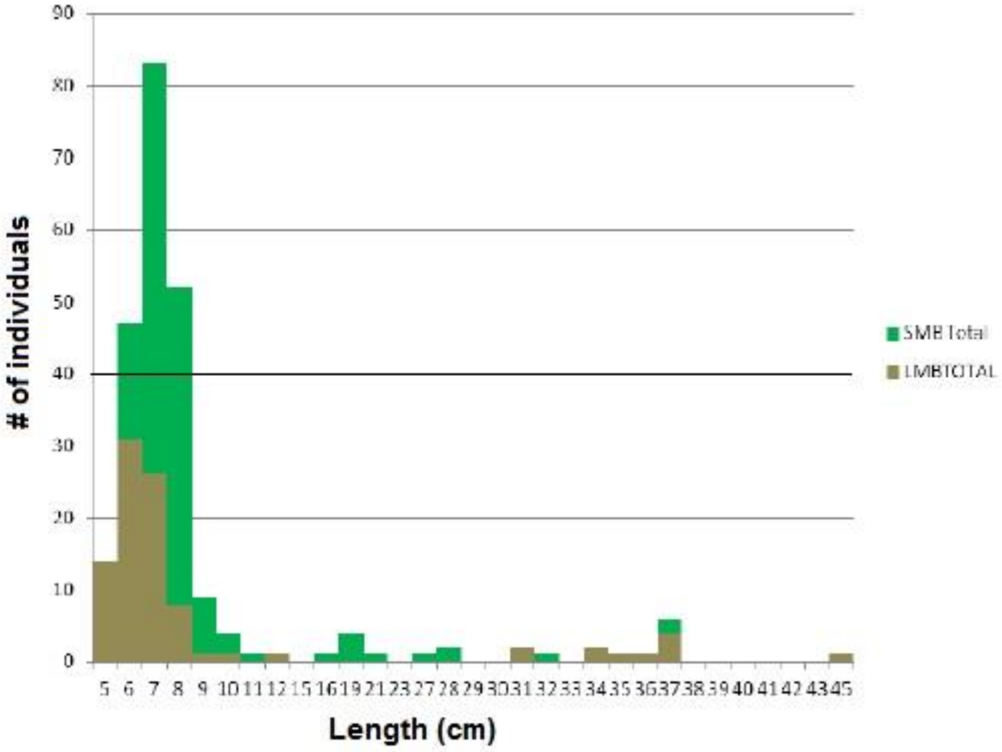


Figure 36. Size distribution of largemouth and smallmouth bass captured on August 21, 2013

Data Analysis and Interpretation

Oxygen Demand

Oxygen profile data can be used to assess oxygen demand from data, preferably where oxygen levels have not dropped to levels too low (<2 mg/L) to allow linear interpretation of loss over depth or time. Applying data from April through June of 2013 and using only data from water deeper than 33 feet (10 m), oxygen demand ranges from 0.52 to 2.76 $g/m^2/day$ (Table 7). The use of only the bottom waters avoids issues with stratification and greater temperature change later in spring. Leaving out any possible demand from surface waters may cause a slight underestimate, but the oxygen demand for the water deeper than 33 feet was over 82% of the total for the first two periods, the most reliable estimates derived. The temperature of the water affects oxygen content, but the change between each pair of assessed dates is low enough to ignore for the deep water. Because oxygen near the bottom was low and appears to have been disturbed by major storms in late June, the first two periods appear much more reliable as estimates. Further, the second period has a few values <2 mg/L, which will cause oxygen demand to be underestimated. Consequently, the best available estimate of oxygen demand is 2.76 $g/m^2/day$.

Ponds with oxygen demand levels in excess of about 0.55 $g/m^2/day$ will often experience some anoxia (Hutchinson 1957), and those with oxygen demand >1.0 $g/m^2/day$ are likely to experience substantial anoxia. Values as high as 4.0 $g/m^2/day$ have been recorded in Cape Cod ponds. So the Cliff Pond value is not unusual, but is high and does explain the observed anoxia.

As oxygen gets low near the sediment-water interface, oxygen is drawn from above and consumed, causing a gradual lowering of oxygen levels from the bottom toward the top. Once stratification occurs, oxygen movement across the thermocline is minimal, and oxygen can be depleted in the bottom water layer. This process is not rapid, and may take the whole summer. In some years (2005, for example), the bottom layer retained considerable oxygen, while in other years (2011-2013), oxygen has been depleted from the bottom to the thermocline by mid-August. This variation suggests that the weather plays a significant role, and that organic inputs from the previous year and the year of any investigation may be very important. It does not appear, either from the oxygen data or the sediment data, that there is a major build-up of decaying organic matter in the deep pond sediments yet. However, loss of oxygen and creation of additional oxygen demand by stimulation of algal blooms can become a self-sustaining cycle that must be broken if the pond is to be returned to an acceptable condition.

Countering anoxia by adding oxygen will require more oxygen than the demand would indicate. Adding oxygen as pure oxygen or air causes water movement across the sediment, increasing the oxygen demand by a factor between 1.25 and about 5.0. This rather wide range must be addressed in any design effort. Pure oxygen causes less induced oxygen demand than air. Bubble size, release rate, and other factors also influence the induced demand, and by extension, the cost of countering it.

Table 7. Oxygen demand in Cliff Pond

Start date	date	4/18/2013	5/3/2013	6/4/2013	6/13/2013
End date	date	5/3/2013	6/4/2013	6/13/2013	6/28/2013
Total O2 loss	grams	47.33	97.46	7.89	22.71
>10 m O2 loss	grams	41.38	80.08	4.64	18.22
Days between readings	days	15	32	9	15
Avg temperature change	^{o}C	1.2	0.2	-0.2	0.7
DO demand (>10 m)	g/m2/day	2.76	2.50	0.52	1.21

The depth at which low oxygen occurs is of paramount importance to the condition of Cliff Pond and may account for most of the variation among years with regard to water clarity and algal blooms. The relationship between the depth at which anoxia occurs and Secchi transparency is fairly strong over the range of 30 to 46 feet (9 to 14 m), with greater clarity observed in years where anoxia occurred deeper in the water column (Figure 37). Beyond 46 feet (14 m) of depth, the correlation declines and conditions do not get better, but if anoxia was held deeper than 46 feet the relationship suggests that Secchi transparency would be >16.5 feet (5 m).

Likewise, the relationship between the depth at which oxygen is less than 5 mg/L is also strongly correlated with Secchi transparency (Figure 38). This relationship is even stronger and covers a range of 16.5 to almost 60 feet (5 to 18 m). An oxygen level >5 mg/L at 43 feet (13 m) corresponds to a Secchi transparency of 16.5 feet (5 m). Oxygen provides many benefits in an aquatic system, including limting adverse sediment-water interactions and supporting biological processes that purify the water. The entire pond does not have to be maintained in an oxic condition; it is natural for deep ponds to lose oxygen, but extensive anoxia tends to promote algal blooms by multiple means.

The decrease in deep water oxygen in Cliff Pond is evident in the long term record, reducing summer trout water and expanding the bottom area exposed to low oxygen. This could become a self-sustaining summer condition if not counteracted, and appears to have moved in that direction over the last three years. Algal blooms over a decade ago may have been a harbinger of the eutrophication process, but variability in weather conditions and long detention time can mediate impacts and create variability that masks longer term trends. Restoring oxygen to deeper waters appears to deserve a very high priority in the management of Cliff Pond.

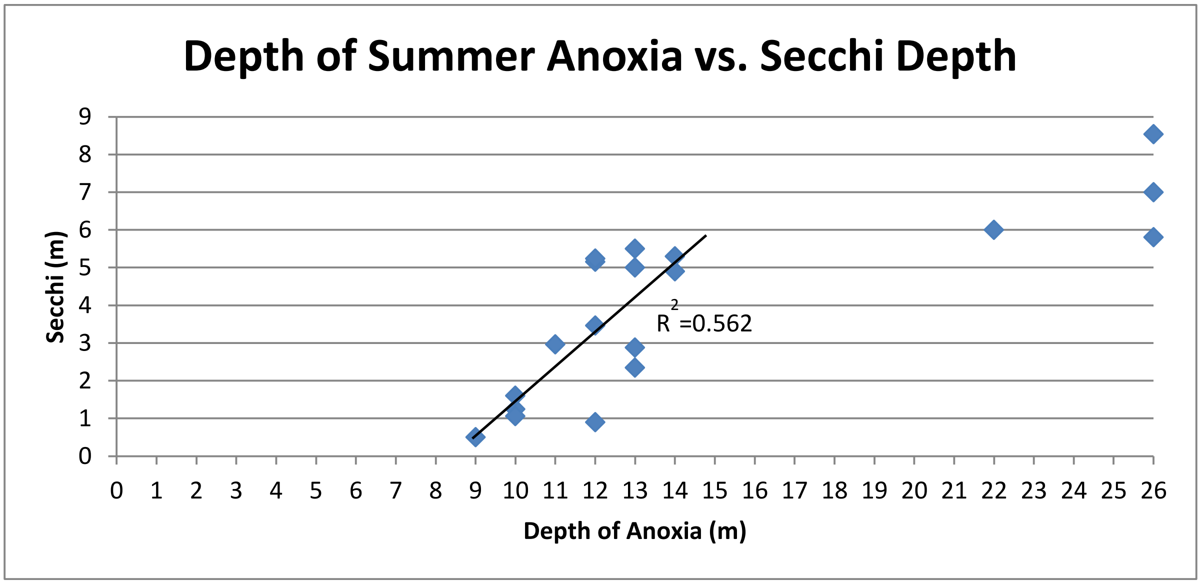


Figure 37. Relationship between depth of anoxia and Secchi depth in Cliff Pond

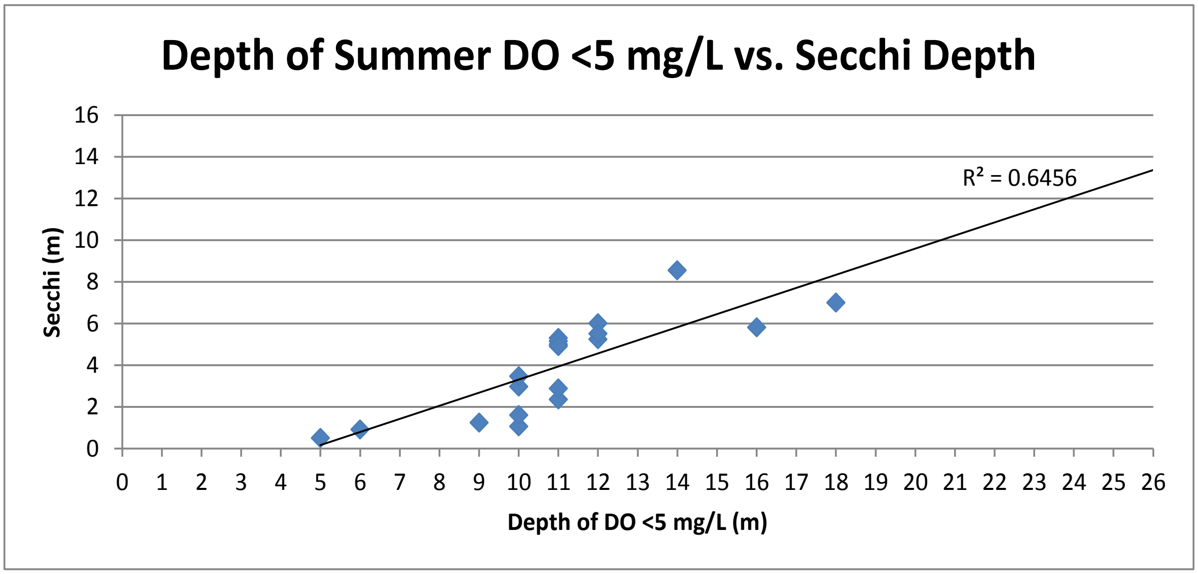


Figure 38. Relationship between depth of oxygen <5 mg/L and Secchi depth in Cliff Pond

Hydrologic Loading

In the simplest terms, water inputs include direct precipitation, runoff, ground water flow, and any natural or directed stream flow. For Cliff Pond in its current situation, there appear to be no direct overland flows other than a very small amount of runoff from a very small land area. Direct precipitation is easily calculated as annual precipitation falling on 207 acres (83 ha) of pond. At 46 inches (1.16 m) per year, direct precipitation would be about 34.5 million ft^3 (978,000 m^3). This value could be higher or lower by about 25% depending on the weather in any given year.

Ground water flow is more difficult to estimate. We have a direct empirical measurement for late spring/early summer in a wet period that suggests an annual ground water input of 11.2 million ft^3 (316,600 m^3), but this may underestimate actual inputs considerably due to high water levels at the time of measurement. Applying the simple formula of flow equals transmissivity times slope times area, with transmissivity at 400 feet per day (Guswa and LeBlanc 1985), slope at 0.00033 ft/ft (5 foot drop over 15,000 horizontal feet from Long Pond to Cliff Pond), and an interface area of about 200,000 ft^2 (5000 feet wide by 40 feet deep), an annual ground water flow of 9.73 million ft^3 (276,000 m^3), not all that different from the empirical measure of about 11.2 million ft^3 (316,600 m3) used in estimating nutrient loading from groundwater.

There are no tributaries or piped discharges, but we can assume some small amount of runoff from the direct watershed, which is only about 170 acres (68 ha). If we assumed that 25% of the rainfall become runoff, a generous allocation with such sandy soils, the total annual runoff input would be 7.1 million ft^3 (201,000 m^3). Actual runoff is probably less than this, possibly as little as 5% of precipitation, or 1.4 million ft^3 (40,200 m^3).

The resulting hydrologic load (Table 8) suggests a total inflow of about 34.5 million cubic feet (978,000 cubic meters) of water each year, although variability will be substantial as a function of precipitation differences among years. Less ground water enters the pond than precipitation, based on a single round of measurements and a general calculation, but the two approaches were in general agreement at around 11.2 million cubic feet (317,000 m^3) per year. Runoff is estimated at about 2.8 million cubic feet (80,400 m^3) per year. We observed no significant runoff in 2013, but erosion on steep slopes suggests that some occurs. The water in the pond is replaced about once every 5.3 years, or 0.19 flushings per year. This is a very rudimentary hydrologic load analysis, but the key point is that there is no major watershed load to the pond, limiting associated nutrient inputs.

Table 8. Hydrologic load to Cliff Pond

Source	Assumptions	Ft3/yr	m3/yr	%
Direct Precipitation	46 inches of precipitation falling on 206.7 acres	34,515,000	977,800	71.1%
Ground Water	Direct measurement one time	11,172,000	316,500	23.0%
Runoff	10% of precipitation becomes runoff over 170 acres	2,839,000	80,400	5.9%
Total		48,526,000	1,374,700	100.0%
Pond Volume		256,900,000	7,277,000	
Flusing Rate	Number of times water in pond is completely exchanged per year	0.19	per year	
Detention Time	Average residence time for water in pond in years	5.29	years	

Nutrient Loading

The nutrient loading sources (Table 9) are the same as for the hydrologic load, except that there is also an internal load (release from sediment) and a wildlife load (mostly from water-dependent birds). As with the hydrologic load, a number of assumptions are made, each outlined in the table. The lack of true tributaries or diversions eliminates those sources.

Precipitation and direct runoff inputs are straight calculations of estimated flow times an assumed concentration for each of nitrogen and phosphorus that are reasonable for this area but not based on any data specifically for Cliff Pond. Ground water inputs are from direct measurement, and are also not large. Although there is uncertainty associated with all estimates, these seem in line with results from other area ponds.

Wildlife loads are usually estimated based on the typical input from an animal pro-rated for the amount of time spent at the pond. So a group of 100 birds that spends only the months of May through October on the lake would equate to 50 bird-years (100 birds present for one half a year). We did not do detailed wildlife counts, but a significant population of birds (gulls, ducks, and herons) was noted on most visits. As a rough estimate, 100 bird-years were multiplied by literature values for inputs from larger birds, and the results are relatively small. As with the other itemized loads, there is considerable uncertainty associated with this estimate, but it is typical of other area ponds.

This leaves the internal load, which is mainly a function of releases of dissolved phosphorus and usually ammonium nitrogen from anoxic sediments. Oxic release is possible, but tends to be so much smaller as to be inconsequential where a substantial portion of the pond bottom is exposed to anoxic conditions each summer. Anoxic release rates for phosphorus range from about 2 to 20 mg/m^2/day, with an average around 12 mg/m^2/day. Nitrogen tends to be released at 3 to 7 times the phosphorus, a low ratio that favors cyanobacteria; ponds with a strong internal loading component tend to experience cyanobacteria blooms.

The average phosphorus level below a depth of 36 feet (11 m) increases over the period of stratification by 0.08 mg/L, which in a volume of 40 million ft^3 (1.3 million m^3) equates to a total of 104.4 kg of phosphorus. Evaluating the release of phosphorus from the anoxic area of the pond bottom as a function of changing area and number of days each area is subjected to anoxia, applying an anoxic release of 10 mg/m^2/day and an effective transfer rate of 10% (Appendix B) yields a phosphorus loading estimate of 106.4 kg, remarkably close to the measured accumulation rate. There is flux in and out of the bottom during the period of accumulation, so these estimates are still just approximations, but they are consistent with expectations.

For nitrogen, the average change below a depth of 36 feet (11 m) is about 0.6 mg/L, or about 783 kg kg of nitrogen. Release of nitrogen from bottom sediments at a rate of seven times the phosphorus release rate suggests a nitrogen load of 744 kg, slightly below the observed rate, which is therefore slightly higher than the typical range known from other area ponds. The measured accumulation rate was applied in this nutrient loading analysis.

The resulting estimated loads of phosphorus and nitrogen to Cliff Pond are 156.5 and 1301.8 kg/yr, respectively (Table 9). Considerable variation among years can be expected, based on observed variation in phosphorus and nitrogen concentrations in data from just the last decade, but this is the best available estimate of current loading, and seems to accurately reflect at least 2011-2013. The internal load represents 67% of the annual phosphorus input and 60% of the annual nitrogen load, by far the largest portion of each load.

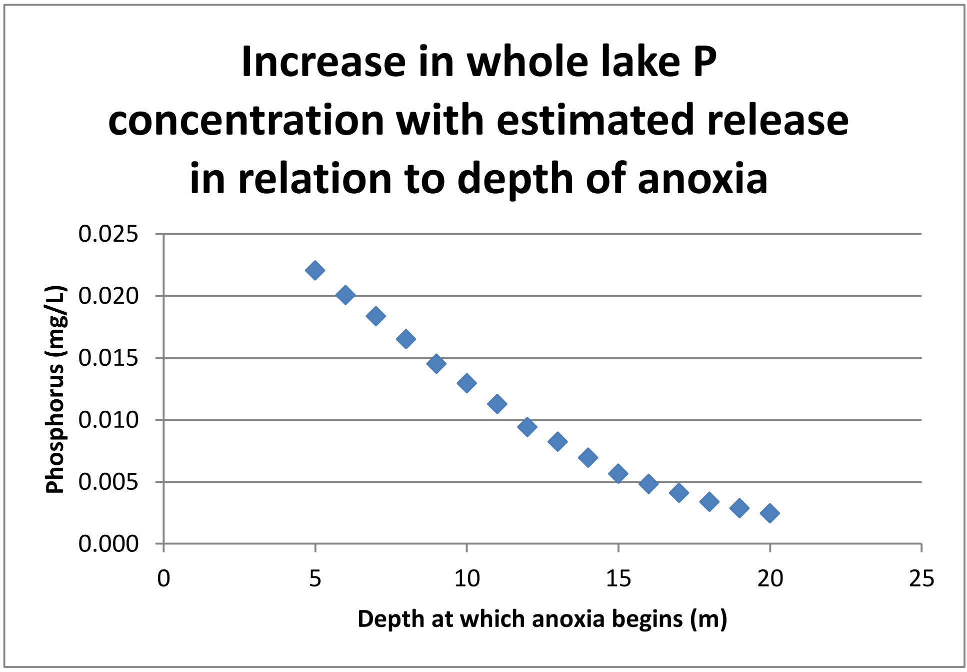
Table 9. Nutrient loads to Cliff Pond

Source	Assumptions	Water m3/yr	P (kg/yr)	% P Load	N (kg/yr)	% N Load
Direct Precipitation	P@0.015 mg/L; N@0.2 mg/L	977,800	14.7	9.4%	195.6	15.0%
Ground Water	From direct measurement	316,500	9.4	6.0%	142.8	11.0%
Runoff	P@0.10 mg/L; N@1.0 mg/L	80,400	8.0	5.1%	80.4	6.2%
Wildlife	100 bird-years with P@0.2 kg/bird-year and N@1.0 kg/bird-year	0	20.0	12.8%	100.0	7.7%
Internal Load	Direct measurement of accumulation in hypolimnion in 2013	0	104.4	66.7%	783.0	60.1%
Total		1,374,700	156.5	100.0%	1301.8	100.0%

Application of a series of five empirical models (Appendix B) often used for New England lakes suggests that a phosphorus load of 156.5 kg/yr should result in an in-lake concentration of 0.023 mg/L, which matches the grand average for pondwide phosphorus Cliff Pond in 2013. Phosphorus is not evenly distributed over depth in the pond, and this may be important to algal bloom development, but these general models do appear to adequately characterize average conditions in Cliff Pond. A set of three models for nitrogen suggest that a load of 1301.8 kg/yr should result in a concentration of 0.94 mg/L when the average in 2013 was 0.84 mg/L. The models suggest that the estimated load is close to the total necessary to produce the observed in-lake concentrations. Extensions of the models predict average chlorophyll-a in surface waters of 9.2 µg/L, while the average in 2013 was 10.6 µg/L. Predicted peak chlorophyll-a is 30 µg/L, while the peak in 2013 was 27 µg/L. Predicted Secchi transparency is 2.1 m, while the average for 2013 was 2.4 m. The models would appear to properly represent the situation in Cliff Pond.

Working from concentrations to load with the empirical models, achieving a desirable total chlorophyll-a level of about 4 µg/L requires a total phosphorus level of 0.012 mg/L. The average surface phosphorus level is close to that now, but this value is the whole water column average, which is currently about 0.023 mg/L. At a water column average of 0.012 mg/L the average Secchi reading would be 3.4 m and peak chlorophyll-a would be about 12.5 µg/L; blooms would be a rare occurrence. To reach a target water column average phosphorus level of 0.012 mg/L would require a phosphorus load of about 79.8 kg/yr, a 49% reduction from the currently estimated load. Reduction of nitrogen would be desirable as well, as long as a low N:P ratio is not fostered (which would continue to favor cyanobacteria); reduction of the pondwide nitrogen concentration to 0.5 mg/L would require a load of 686 kg/yr, a reduction of 47%.

Since the internal load is potentially so important, and oxygen appears to govern expression of that internal load, the relationship between expected increase in whole water column phosphorus level and depth of anoxia was explored. Using a release rate of 10 mg/m2/day and an exposure duration of 60 days, the change in phosphorus concentration can be graphed in response to depth of anoxia, translated through exposed area of pond bottom (Figure 39). This is just one calculated example for Cliff Pond, but it is realistic and suggests that if anoxia climbs higher in the water column than about 40 feet (12 m), a phosphorus increase of 0.010 mg/L is expected. Background phosphorus level is somewhere between 0.005 and 0.010 mg/L; the empirical models suggest that if internal load is removed, the average phosphorus concentration in Cliff Pond would be 0.008 mg/L. So a 0.010 mg/L increase would put Cliff Pond in very real danger of an algal bloom. Even the increase of 0.005 mg/L expected with anoxia at 50 feet (15 m) could be a problem if background phosphorus is not as low as possible.



Depth (m)	Bottom Area (m2)
5	534400
6	486800
7	445200
8	400400
9	352000
10	314000
11	273200
12	228000
13	199600
14	168400
15	137200
16	117200
17	99600
18	81600
19	69600
20	59200

Figure 39. Relationship between depth of anoxia and phosphorus concentration increase

Biological Status

Cliff Pond has been plagued by algal blooms for many years, particularly cyanobacteria, but the problem has not been continuous. The relation to elevated loads of nitrogen and phosphorus is not as clear as for many lakes, as surface concentrations of nutrients are not extreme. Algae may be growing at the sediment-water interface for some time, then floating to the surface, a common cyanobacteria strategy (Reynolds 2006). Changes in land use are not evident, and the erratic pattern of problems is indicative of internal loading that is impacted by weather conditions.

Of particular concern are the cyanobacteria blooms, which are triggered by very specific conditions in ponds. A low nitrogen to phosphorus ratio (<10:1) favors cyanobacteria, many of which can utilize dissolved gaseous nitrogen. Sediment releases of nitrogen and phosphorus almost invariably result in low N:P ratios. Further, there is recent evidence (Molot et al. 2014) that cyanobacteria need ferrous iron for maximum growth and especially nitrogen fixation; this is the form of iron released by exposure of iron-rich sediment to anoxia. The dissociation of iron and phosphorus under low oxygen may provide two nutrients that stimulate cyanobacteria at once.

The depth of anoxia determines the area of sediment exposed to that anoxia and therefore the amount of phosphorus, nitrogen, iron and possibly other substances released. A small enough area of anoxia may have its releases sufficiently diluted by the vast overlying water mass, but once the exposed area is large enough, dilution becomes insufficient. And cyanobacteria may grow right at the sediment-water interface, absorbing nutrients and growing substantially before forming gas vesicles and floating upward for more light with adequate nutrients to allow a bloom, even when nutrients in the overlying water are not abundant. Sediment features and oxygen status are most likely the key to preventing blooms in Cliff Pond.

The low light created by blooms and the coarse substrate in shallow areas has minimized submergent vascular plant biomass. The continued low summer oxygen in deep water has minimized habitat for stocked trout during summer, and restricts habitat for warm water species to more peripheral areas. The zooplankton assemblage was generally desirable in terms of types, size and biomass in 2013; more large zooplankton, especially Daphnia, would be preferred. A reduction in small fish and/or improved deep water oxygen would allow longer summer survival of larger zooplankton, particularly *Daphnia*, which consume algae and can both improve water clarity and reduce the oxygen demand of settling algae particles.

While greater biological balance is needed to optimize conditions in Cliff Pond, all the desirable components are present. Reduced phosphorus loading that leads to reduced cyanobacteria would be expected to increase water clarity and should reduce oxygen demand in deeper water.

Whatever management actions are taken, proponents should be advised that the entire area around and including Cliff Pond is listed as Priority Habitat 15 by the Massachusetts Natural Heritage and Endangered Species Program, based on available online mapping. Further interaction with NHESP will be necessary to ascertain what species is/are present and how any management action may affect any protected species. From the aquatic and terrestrial coverage of the map, multiple species are likely to be involved.

Diagnostic Conclusions

Returning to the list of goals from the project background and needs section, a response to the data needs can now be provided.

1. Assessment of current conditions in the pond, especially with regard to oxygen status and nutrient levels.

   Oxygen is depleted in deep water over the course of the summer. Stratification separates the lower water layer and movement of oxygen into that layer is very limited. At the same time, oxygen demand is variable but substantial, and water near the bottom loses oxygen to the point of depletion fairly early in summer. Depending on weather conditions and the settling of algae and other oxygen-demanding particles from the upper water column into the bottom water layer, some portion of the bottom layer becomes devoid of oxygen. In recent years, the entire lower water layer has become anoxic by late summer. The natural aging of a deep lake leads to this situation, although it can be greatly accelerated by human actions. There is no evidence, however, that any human actions are responsible for the current condition of Cliff Pond.

   Phosphorus and other compounds can be released from sediment when exposed to anoxia. When the exposed area is small, the released compounds are diluted in the overlying water and have relatively little impact. However, when the exposed area is large enough, which in this case corresponds to the sediment area at any water depth <46 feet (14 m), the release is large enough to alter overlying water quality and support algae blooms. Further, as the anoxic area extends into shallower water depths where even a little light penetrates, algal growth at the sediment-water interface is stimulated. Cyanobacteria can develop gas pockets and rise to the surface, causing blooms quickly, even when surface water quality seems acceptable.

   The change in oxygen status is the single most striking feature of Cliff Pond, and affects virtually all aspects of pond condition. Loss of oxygen impacts habitat for fish and invertebrates, facilitates nutrient availability that supports algal blooms, and sets up a self-sustaining cycle of worsening conditions. Virtually all negative aspects of Cliff Pond can be explained by the loss of oxygen, and the variability in that loss between years appears responsible for the observed range of conditions over the last two decades.

2. Quantification of external sources of phosphorus and nitrogen to the pond to the extent possible with existing data.

   External loading sources include direct precipitation, ground water inflow, and overland runoff. There are no tributaries or discharges associated with Cliff Pond. Direct precipitation is the largest source of water to the pond at 71%, but contributes only 9.4% of phosphorus and 15% of nitrogen. Ground water enters all around the pond by virtue of steep slopes, but the primary direction of ground water flow in this area is from the southwest. Ground water represents 23% of the water input, 6% of the phosphorus load, and 11% of the nitrogen input. Runoff is limited, and is estimated to provide 5.9% of the water, 5.1% of the phosphorus, and 6.2% of the nitrogen. Wildlife, mainly water-dependent birds, also contributes nutrients directly to the pond, and are estimated to contribute 12.8% of the phosphorus load and 7.7% of the nitrogen input to Cliff Pond.

All totaled, the above external sources account for about 52 kg/yr of phosphorus and 519 kg/yr of nitrogen entering Cliff Pond. These loads would be expected to result in pondwide, whole water column average concentrations of 0.008 mg/L for phosphorus and 0.38 mg/L for nitrogen, neither of which represents a major threat to water quality.

3. Quantification of the amount of phosphorus in the surficial sediments that could be released into the water column, and assessment of the build-up over the course of the summer.

   Sediment testing revealed high levels of iron-bound phosphorus in the fine sediments found in deeper water in Cliff Pond. Iron-bound phosphorus in sediments with even slightly higher sand content were much lower, and negligible amounts of iron-bound phosphorus would be expected in the very sandy substrate in water <33 feet (10 m) deep.

   The quantity of phosphorus potentially available when fine sediments are exposed to anoxia is more than enough to account for the difference in actual water column concentrations and those predicted in the absence of any internal load. The accumulation of phosphorus in the bottom water layer during stratification closely follows the area exposed to anoxia, and only 10% of that phosphorus has to reach the upper water layer to create the observed conditions. The internal load based on both actual measured accumulation of phosphorus in the bottom water layer and calculation based on a typical release rate times the area of sediment exposed to anoxia times the duration of that exposure was in excess of 100 kg/yr, and represents two thirds of the total phosphorus load to Cliff Pond.

   Nitrogen is an issue as well, and the internal load is largely as ammonium and is estimated at 783 kg/yr, 60% of the total nitrogen load to Cliff Pond. Water clarity is actually more closely correlated to nitrogen levels than phosphorus, although both nutrients co-vary and are strongly linked to internal loading. In addition to phosphorus and nitrogen, the release of ferrous iron may be a stimulant to cyanobacteria, which appear to prefer this form of iron and need it to fix nitrogen from gaseous sources in the pond. Some portion of the nitrogen load is from nitrogen fixation by cyanobacteria, and is counted as part of the internal load.

4. Assessment of the area of the pond subject to anoxia and potentially contributing to the internal phosphorus load.

   The shallowest depth at which anoxia or oxygen lower than 5 mg/L occurs exhibits a strong correlation with water clarity, linked through exposure of sediment to anoxia and release of nutrients that support algal blooms. The depth of the thermocline varies somewhat among years, but does not seem to be a major factor in anoxia or algal blooms in Cliff Pond, other than setting the minimum depth at which anoxia may occur. If oxygen depletion is severe in the bottom water layer, oxygen may be lost above the depth of the thermocline, but at depths <33 feet (10 m) there is little fine sediment that harbors nutrient reserves for release. So the functional range of concern is low oxygen between 33 and about 66 feet (10-20 m). The potentially exposed area at greater depths is not large enough to make much difference to water quality, while the shallower depths are not associated with fine sediments that may release significant quantities of nutrients.

To maintain clear water and low algae density through oxygen management, anoxia must be held at a depth >40 feet (12 m) and preferably >46 feet (14 m). Oxygen at deeper levels will provide a margin of safety and greater habitat for fish. The alternative is to remove the nutrient-rich sediment or inactivate the phosphorus within it. Inactivation of phosphorus will not solve all the problems associated with low oxygen, but would limit algal growth and resultant blooms.

5. Documentation of the algae in the pond that are impairing water clarity.

   The results of algae monitoring have been historically limited. We know that cyanobacteria blooms have occurred since the late 1990s, possibly earlier, but that summer blooms have been more frequent and probably more severe in recent years. Monitoring in 2013 detected a bloom of the filamentous chrysophyte *Tribonema* in April, a known but not common occurrence in nutrient rich lakes. Chlorophyll-a content was not high, but the water was highly colored and algal biomass was substantial. A June bloom of *Anabaena lemmermannii* was observed; this cyanobacterium forms colonies on nutrient-rich sediment and then develops gas pockets that cause it to float upward. Further growth at the surface and particle merging from wind-induced collisions result in large, visible algal “chunks” near the surface, and windblown accumulations were substantial in some areas, while other parts of the pond appeared relatively clear.

   These sporadic blooms gave way to a sustained bloom of the cyanobacterium *Aphanizomenon flos-aquae* by mid-August, and that alga remained dominant into October. This alga can form visible ‘flakes” in the water, but was mostly single filaments in Cliff Pond in 2013, and discolored the water an off green color. Water clarity was greatly reduced, but there were very few algae below a depth of 30 feet (9 m); all the algae were in the upper water layer. The observed *Anabaena* and *Aphanizomenon* are known to be able to produce toxins, but their presence does not guarantee toxin production. Surveys of toxin distribution (Lindon and Heiskary 2009, Graham and Jones 2009, Bigham et al. 2009) have demonstrated the erratic occurrence of toxins, and direct testing is advised. However, as Cliff Pond has apparently experienced toxic blooms in the past, this is a serious concern.

6. Inventory of biological components of the pond that may have bearing on which alternative actions can be implemented under current regulatory limits and that could affect the outcome of any action under consideration.

   There are few submergent plants in Cliff Pond. There are at least four mussel species, but they do not appear to be abundant. Warm water fish are abundant, and the pond is stocked with multiple trout species, although holdover habitat in summer is negligible at this time. There is one or more species listed under the Massachusetts Endangered Species Act, administered by the Natural Heritage and Endangered Species Program, as the entire pond is covered by priority habitat mapping. Consultation with NHESP will be necessary in the permitting phase of any project, but as attention will be focused on either the volume of Cliff Pond that has low oxygen or the bottom of the pond under areas of anoxia, there should be little negative influence on any animal or plant species that may be listed.

7. Assessment of water quality that might affect choice of management alternatives or constrain implementation.

   Alkalinity is low in Cliff Pond, as is the case for most other Cape Cod ponds. Any addition of aluminum will have to be buffered to minimize pH fluctuation that could harm biota. No other water quality features loom as impediments to possible management actions. Any action that increased oxygen levels below a depth of 33 feet (10 m) would represent an improvement in pond condition.

Management Options

Overview

Low oxygen and blooms of algae are the identified problems facing Cliff Pond. These problems are linked, and other problems are largely a function of low oxygen and algae. There are many potential options for preventing and managing algal blooms. There are fewer options for enhancing oxygen at the bottom of a pond, but these overlap with algal control options. A tabular review of all options for the control of algae (Table 10) allows dismissal of inapplicable options, and narrows the field to the following applicable approaches:

- Watershed management
- Dredging
- Algaecides
- Sonication
- Bacterial additives
- Sediment oxidation
- Circulation
- Oxygenation
- Phosphorus Inactivation
- Biomanipulation

Watershed management is nearly always applicable, and should be part of almost all lake management plans, but in this case there is very little to do in the watershed. Repair and maintenance of erosion scars on the steep slopes by the pond would be appropriate. Maintenance of wastewater disposal facilities is desirable. But there are no permitted discharges or intense urban or agricultural uses to be managed. Although the problems of the pond are ultimately caused by the watershed, these have been a long time developing and there is no evidence of any major watershed influence on Cliff Pond at this time.

Dredging is an ideal way to set a pond back in time; it is true lake restoration. Removal of accumulated soft sediment eliminates nutrient sources, oxygen demand and algae resting stages. Where external loads are nominal, the results should be spectacular. However, the cost and environmental constraints placed on dredging limits application of this technique. A substantial study would be needed to assess the feasibility of dredging Cliff Pond, emphasizing quantification of sediment quantity and quality. If we assumed that 1 foot (0.3 m) of sediment would have to be removed from acres 68 acres (27.3 ha) of the pond (the area deeper than 36ft or 11 m), that would equate to over 110,000 cubic yards of material. At a low end cost of $30 per cubic yard, the cost would approach $3.3 million. Finding more sediment or any quality issues with that sediment that affected disposal options would increase the cost, possibly by a factor of four. Further, dredging at depths of over 33 feet (10 m) is virtually unheard of in freshwater lakes on technical grounds (hydraulic dredging would be needed, and the elevation differential creates major challenges). As attractive as dredging is as a restoration approach, it is not feasible in many cases, and is not really practical for Cliff Pond.

Table 10. Algae management options review

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
WATERSHED CONTROLS				
1) Management for nutrient input reduction	♦ Includes wide range of watershed and lake edge activities intended to eliminate nutrient sources or reduce delivery to lake ♦ Essential component of algal control strategy where internal recycling is not the dominant nutrient source, and desired even where internal recycling is important	♦ Acts against the original source of algal nutrition ♦ Creates sustainable limitation on algal growth ♦ May control delivery of other unwanted pollutants to lake ♦ Facilitates ecosystem management approach which considers more than just algal control	♦ May involve considerable lag time before improvement observed ♦ May not be sufficient to achieve goals without some form of in-lake management ♦ Reduction of overall system fertility may impact fisheries ♦ May cause shift in nutrient ratios which favor less desirable algae	♦ While always applicable at some level, the watershed of Cliff Pond does not appear to be a major source of nutrients now
1a) Point source controls	♦ More stringent discharge requirements ♦ May involve diversion ♦ May involve technological or operational adjustments ♦ May involve pollution prevention plans	♦ Often provides major input reduction ♦ Highly efficient approach in most cases ♦ Success easily monitored	♦ May be very expensive in terms of capital and operational costs ♦ May transfer problems to another watershed ♦ Variability in results may be high in some cases	♦ Inapplicable; no current point source inputs

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
1b) Non-point source controls	♦ Reduction of sources of nutrients ♦ May involve elimination of land uses or activities that release nutrients ♦ May involve alternative product use, as with no phosphate fertilizer	♦ Removes source ♦ Limited ongoing costs	♦ May require purchase of land or activity ♦ May be viewed as limitation of "quality of life" ♦ Usually requires education and gradual implementation	♦ Minimally applicable; very few options. ♦ Repair and manage erosion on adjacent steep slopes
1c) Non-point source pollutant trapping	♦ Capture of pollutants between source and lake ♦ May involve drainage system alteration ♦ Often involves wetland treatments (det./infiltration) ♦ May involve storm water collection and treatment as with point sources	♦ Minimizes interference with land uses and activities ♦ Allows diffuse and phased implementation throughout watershed ♦ Highly flexible approach ♦ Tends to address wide range of pollutant loads	♦ Does not address actual sources ♦ May be expensive on necessary scale ♦ May require substantial maintenance	♦ Minimally applicable; encourage park administration and watershed property owners to manage properties well

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
IN-LAKE PHYSICAL CONTROLS				
2) Circulation and destratification	♦ Use of water or air to keep water in motion ♦ Intended to prevent or break stratification ♦ Generally driven by mechanical or pneumatic force	♦ Reduces surface build-up of algal scums ♦ May disrupt growth of blue-green algae ♦ Counteraction of anoxia improves habitat for fish/invertebrates ♦ Can eliminate localized problems without obvious impact on whole lake	♦ May spread localized impacts ♦ May lower oxygen levels in shallow water ♦ May promote downstream impacts	♦ Applicable, in theory, but would disrupt cold water habitat. That habitat is not useable now, but compromising it to make it habitable is not logical
3) Dilution and flushing	♦ Addition of water of better quality can dilute nutrients ♦ Addition of water of similar or poorer quality flushes system to minimize algal build-up ♦ May have continuous or periodic additions	♦ Dilution reduces nutrient concentrations without altering load ♦ Flushing minimizes detention; response to pollutants may be reduced	♦ Diverts water from other uses ♦ Flushing may wash desirable zooplankton from lake ♦ Use of poorer quality water increases loads ♦ Possible downstream impacts	♦ Inapplicable; no source of water

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
4) Drawdown	♦ Lowering of water over autumn period allows oxidation, desiccation and compaction of sediments ♦ Duration of exposure and degree of dewatering of exposed areas are important ♦ Algae are affected mainly by reduction in available nutrients.	♦ May reduce available nutrients or nutrient ratios, affecting algal biomass and composition ♦ Opportunity for shoreline clean-up/structure repair ♦ Flood control utility ♦ May provide rooted plant control as well	♦ Possible impacts on non-target resources ♦ Possible impairment of water supply ♦ Alteration of downstream flows and winter water level ♦ May result in greater nutrient availability if flushing inadequate	♦ Inapplicable; no outlet control
5) Dredging	♦ Sediment is physically removed by wet or dry excavation, with deposition in a containment area for dewatering ♦ Dredging can be applied on a limited basis, but is most often a major restructuring of a severely impacted system ♦ Nutrient reserves are removed and algal growth can be limited by nutrient availability	♦ Can control algae if internal recycling is main nutrient source ♦ Increases water depth ♦ Can reduce pollutant reserves ♦ Can reduce sediment oxygen demand ♦ Can improve spawning habitat for many fish species ♦ Allows complete renovation of aquatic ecosystem	♦ Temporarily removes benthic invertebrates ♦ May create turbidity ♦ May eliminate fish community (complete dry dredging only) ♦ Possible impacts from containment area discharge ♦ Possible impacts from dredged material disposal ♦ Interference with uses during dredging	♦ Applicable but very expensive ♦ Would need major study of sediment quality and quantity to move forward ♦ Impractical for Cliff Pond at great depth

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
5a) “Dry” excavation	♦ Lake drained or lowered to maximum extent practical ♦ Target material dried to maximum extent possible ♦ Conventional excavation equipment used to remove sediments	♦ Tends to facilitate a very thorough effort ♦ May allow drying of sediments prior to removal ♦ Allows use of less specialized equipment	♦ Eliminates most aquatic biota unless a portion left undrained ♦ Eliminates lake use during dredging	♦ Inapplicable; no way to drain pond
5b) “Wet” excavation	♦ Lake level may be lowered, but sediments not substantially exposed ♦ Draglines, bucket dredges, or long-reach backhoes used to remove sediment	♦ Requires least preparation time or effort, tends to be least cost dredging approach ♦ May allow use of easily acquired equipment ♦ May preserve aquatic biota	♦ Usually creates extreme turbidity ♦ Normally requires intermediate containment area to dry sediments prior to hauling ♦ May disrupt ecological function ♦ Use disruption	♦ Inapplicable; cannot reach shore with available equipment and shoreline impacts would be major
5c) Hydraulic removal	♦ Lake level not reduced ♦ Suction or cutterhead dredges create slurry which is hydraulically pumped to containment area ♦ Slurry is dewatered; sediment retained, water discharged	♦ Creates minimal turbidity and impact on biota ♦ Can allow some lake uses during dredging ♦ Allows removal with limited access or shoreline disturbance	♦ Often leaves some sediment behind ♦ Cannot handle coarse or debris-laden materials ♦ Requires sophisticated and more expensive containment area	♦ Applicable but expensive ♦ Challenge of great depth may be difficult to overcome

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
6) Light-limiting dyes and surface covers	♦ Creates light limitation	♦ Creates light limit on algal growth without high turbidity or great depth ♦ May achieve some control of rooted plants as well	♦ May cause thermal stratification in shallow ponds ♦ May facilitate anoxia at sediment interface with water	♦ Inapplicable; would interfere with uses and ecology of the pond
6.a) Dyes	♦ Water-soluble dye is mixed with lake water, thereby limiting light penetration and inhibiting algal growth ♦ Dyes remain in solution until washed out of system.	♦ Produces appealing color ♦ Creates illusion of greater depth	♦ May not control surface bloom-forming species ♦ May not control growth of shallow water algal mats ♦ Altered thermal regime	♦ Inapplicable
6.b) Surface covers	♦ Opaque sheet material applied to water surface	♦ Minimizes atmospheric and wildlife pollutant inputs	♦ Minimizes atmospheric gas exchange ♦ Limits recreation	♦ Inapplicable
7) Mechanical removal	♦ Filtering of pumped water for water supply purposes ♦ Collection of floating scums or mats with booms, nets, or other devices ♦ Continuous or multiple applications per year usually needed	♦ Algae and associated nutrients can be removed from system ♦ Surface collection can be applied as needed ♦ May remove floating debris ♦ Collected algae dry to minimal volume	♦ Filtration requires high backwash and sludge handling capability ♦ Labor and/or capital intensive ♦ Variable collection efficiency ♦ Possible impacts on non-target aquatic life	♦ Inapplicable; microalgae not amenable to practical physical removal

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
8) Selective withdrawal	♦ Discharge of bottom water which may contain (or be susceptible to) low oxygen and higher nutrient levels ♦ May be pumped or utilize passive head differential	♦ Removes targeted water from lake efficiently ♦ May prevent anoxia and phosphorus build up in bottom water ♦ May remove initial phase of algal blooms which start in deep water ♦ May create coldwater conditions downstream	♦ Possible downstream impacts of poor water quality ♦ May promote mixing of remaining poor quality bottom water with surface waters ♦ May cause unintended drawdown if inflows do not match withdrawal	♦ Inapplicable; no structure available and gradient is too slight to create substantial flow
9) Sonication	♦ Sound waves disrupt algal cells	♦ Supposedly affects only algae (new technique) ♦ Applicable in localized areas	♦ Unknown effects on non-target organisms ♦ May release cellular toxins or other undesirable contents into water column	♦ Applicable in theory but not completely consistent with uses of pond ♦ Not certain that all problem species would be affected
IN-LAKE CHEMICAL CONTROLS				
10) Hypolimnetic aeration or oxygenation	♦ Addition of air or oxygen provides oxic conditions ♦ Maintains stratification ♦ Can also withdraw water, oxygenate, then replace	♦ Oxic conditions reduce P availability ♦ Oxygen improves habitat ♦ Oxygen reduces build-up of reduced cpds	♦ May disrupt thermal layers important to fish community ♦ Theoretically promotes supersaturation with gases harmful to fish	♦ Applicable ♦ Would greatly enhance habitat, but would carry ongoing costs

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
11) Algaecides	♦ Liquid or pelletized algaecides applied to target area ♦ Algae killed by direct toxicity or metabolic interference ♦ Typically requires application at least once/yr, often more frequently	♦ Rapid elimination of algae from water column , normally with increased water clarity ♦ May result in net movement of nutrients to bottom of lake	♦ Possible toxicity to non-target species ♦ Restrictions on water use for varying time after treatment ♦ Increased oxygen demand and possible toxicity ♦ Possible recycling of nutrients	♦ Applicable, but treats the symptoms when problem resolution appears available
11a) Forms of copper	♦ Cellular toxicant, disruption of membrane transport ♦ Applied as wide variety of liquid or granular formulations	♦ Effective and rapid control of many algae species ♦ Approved for use in most water supplies	♦ Possible toxicity to aquatic fauna ♦ Accumulation of copper in system ♦ Resistence by certain green and blue-green nuisance species ♦ Lysing of cells releases nutrients and toxins	♦ Applicable, but should limit repetitive treatment in any year
11b) Peroxides	♦ Disrupts most cellular functions, tends to attack membranes ♦ Applied as a liquid or solid. ♦ Typically requires application at least once/yr, often more frequently	♦ Rapid action ♦ Oxidizes cell contents, may limit oxygen demand and toxicity	♦ Much more expensive than copper ♦ Limited track record ♦ Possible recycling of nutrients	♦ Applicable and more appropriate for cyanobacteria problems

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
11c) Synthetic organic algaecides	♦ Absorbed or membrane-active chemicals which disrupt metabolism ♦ Causes structural deterioration	♦ Used where copper is ineffective ♦ Limited toxicity to fish at recommended dosages ♦ Rapid action	♦ Non-selective in treated area ♦ Toxic to aquatic fauna (varying degrees by formulation) ♦ Time delays on water use	♦ Inapplicable; used more for mat forming algae
12) Phosphorus inactivation	♦ Typically salts of aluminum, iron or calcium are added to the lake, as liquid or powder ♦ Lanthanum in more recent use ♦ Phosphorus in the treated water column is complexed and settled to the bottom of the lake ♦ Phosphorus in upper sediment layer is complexed, reducing release from sediment ♦ Permanence of binding varies by binder in relation to redox potential and pH	♦ Can provide rapid, major decrease in phosphorus concentration in water column ♦ Can minimize release of phosphorus from sediment ♦ May remove other nutrients and contaminants as well as phosphorus ♦ Flexible with regard to depth of application and speed of improvement	♦ Possible toxicity to fish and invertebrates, especially by aluminum at low pH ♦ Possible release of phosphorus under anoxia or extreme pH ♦ May cause fluctuations in water chemistry, especially pH, during treatment ♦ Possible resuspension of floc in shallow areas ♦ Adds to bottom sediment, but typically an insignificant amount	♦ Applicable; would attack internal load, the primary source of phosphorus at this time ♦ Should reduce but not eliminate oxygen demand in deeper water

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
13) Sediment oxidation	♦ Addition of oxidants, binders and pH adjustors to oxidize sediment ♦ Binding of phosphorus is enhanced ♦ Denitrification is stimulated	♦ Can reduce phosphorus supply to algae ♦ Can alter N:P ratios in water column ♦ May decrease sediment oxygen demand	♦ Possible impacts on benthic biota ♦ Longevity of effects not well known ♦ Possible source of nitrogen for blue-green algae	♦ Applicable in theory; could reduce oxygen demand ♦ Not extensive practiced in USA, no track record in region
14) Settling agents	♦ Closely aligned with phosphorus inactivation, but can be used to reduce algae directly too ♦ Lime, alum or polymers applied, usually as a liquid or slurry ♦ Creates a floc with algae and other suspended particles ♦ Floc settles to bottom of lake ♦ Re-application typically necessary at least once/yr	♦ Removes algae and increases water clarity without lysing most cells ♦ Reduces nutrient recycling if floc sufficient ♦ Removes non-algal particles as well as algae ♦ May reduce dissolved phosphorus levels at the same time	♦ Possible impacts on aquatic fauna ♦ Possible fluctuations in water chemistry during treatment ♦ Resuspension of floc possible in shallow, well-mixed waters ♦ Promotes increased sediment accumulation	♦ Inapplicable; would add to oxygen demand and not reduce internal recycling

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
15) Selective nutrient addition	♦ Ratio of nutrients changed by additions of selected nutrients ♦ Addition of non-limiting nutrients can change composition of algal community ♦ Processes such as settling and grazing can then reduce algal biomass	♦ Can reduce algal levels where control of limiting nutrient not feasible ♦ Can promote non-nuisance forms of algae ♦ Can improve productivity of system without increased standing crop of algae	♦ May result in greater algal abundance through uncertain biological response ♦ May require frequent application to maintain desired ratios ♦ Possible downstream effects	♦ Inapplicable; may get shift away from cyanobacteria, but will still have algae blooms
IN-LAKE BIOLOGICAL CONTROLS				
16) Enhanced grazing	♦ Manipulation of biological components of system to achieve grazing control over algae ♦ Typically involves alteration of fish community to promote growth of grazing zooplankton	♦ May increase water clarity by changes in algal biomass or cell size without reduction of nutrient levels ♦ Can convert algae into fish ♦ Harnesses natural processes	♦ May involve introduction of exotic species ♦ Effects may not be controllable or lasting ♦ May foster shifts in algal composition to even less desirable forms	♦ Applicable, but unlikely to maintain consistent control
16.a) Herbivorous fish	♦ Stocking of fish that eat algae	♦ Converts algae directly into potentially harvestable fish ♦ Grazing pressure can be adjusted through stocking	♦ Typically requires introduction of non-native species ♦ Difficult to control over long term ♦ Smaller algal forms may be benefited	♦ Inapplicable; types of algae causing problems not consumable by fish

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
16.b) Herbivorous zooplankton	♦ Reduction in planktivorous fish to promote grazing pressure by zooplankton ♦ May involve stocking piscivores or removing planktivores ♦ May also involve stocking zooplankton or establishing refugia	♦ Converts algae indirectly into harvestable fish ♦ Zooplankton response to increasing algae can be rapid ♦ May be accomplished without introduction of non-native species ♦ Generally compatible with most fishery management goals	♦ Highly variable response expected; temporal and spatial variability may be high ♦ Requires careful monitoring and management action on 1-5 yr basis ♦ Larger or toxic algal forms may be benefitted and bloom	♦ Applicable; need to adjust fish community and oxygen levels in deep water to foster survival of *Daphnia*
17) Bottom-feeding fish removal	♦ Removes fish that browse among bottom deposits, releasing nutrients to the water column by physical agitation and excretion	♦ Reduces turbidity and nutrient additions from this source ♦ May restructure fish community in more desirable manner	♦ Targeted fish species are difficult to control ♦ Reduction in fish populations valued by some lake users (human/non-human)	♦ Inapplicable; bottom feeding fish not the source of current problems
18) Microbial competition	♦ Addition of microbes, often with oxygenation, can tie up nutrients and limit algal growth ♦ Tends to control N more than P	♦ Shifts nutrient use to organisms that do not form scums or impair uses to same extent as algae ♦ Harnesses natural processes ♦ May decrease sediment	♦ Minimal scientific evaluation ♦ N control may still favor cyanobacteria ♦ May need aeration system to get acceptable results	♦ Potentially applicable; may be able to reduce muck sediment, but need oxygenation system, and no peer reviewed literature supports this approach

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
19) Pathogens	♦ Addition of inoculum to initiate attack on algal cells ♦ May involve fungi, bacteria or viruses	♦ May create lakewide “epidemic” and reduction of algal biomass ♦ May provide sustained control through cycles ♦ Can be highly specific to algal group or genera	♦ Largely experimental approach at this time ♦ May promote resistant nuisance forms ♦ May cause high oxygen demand or release of toxins by lysed algal cells ♦ Effects on non-target organisms uncertain	♦ Inapplicable; no commercially available products
20) Competition and allelopathy by plants	♦ Plants may tie up sufficient nutrients to limit algal growth ♦ Plants may create a light limitation on algal growth ♦ Chemical inhibition of algae may occur through substances released by other organisms	♦ Harnesses power of natural biological interactions ♦ May provide responsive and prolonged control	♦ Some algal forms appear resistant ♦ Use of plants may lead to problems with vascular plants ♦ Use of plant material may cause depression of oxygen levels	♦ Inapplicable; few submergent plants present and unlikely to cover enough of the pond to make a difference without compromising uses

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO CLIFF POND
20a) Plantings for nutrient control	♦ Plant growths of sufficient density may limit algal access to nutrients ♦ Plants can exude allelopathic substances which inhibit algal growth ♦ Portable plant “pods” , floating islands, or other structures can be installed	♦ Productivity and associated habitat value can remain high without algal blooms ♦ Can be managed to limit interference with recreation and provide habitat ♦ Wetland cells in or adjacent to the lake can minimize nutrient inputs	♦ Vascular plants may achieve nuisance densities ♦ Vascular plant senescence may release nutrients and cause algal blooms ♦ The switch from algae to vascular plant domination of a lake may cause unexpected or undesirable changes	♦ Inapplicable
20b) Plantings for light control	♦ Plant species with floating leaves can shade out many algal growths at elevated densities	♦ Vascular plants can be more easily harvested than most algae ♦ Many floating species provide waterfowl food	♦ Floating plants can be a recreational nuisance ♦ Low surface mixing and atmospheric contact promote anoxia	♦ Inapplicable
20c) Addition of barley straw	♦ Input of barley straw can set off a series of chemical reactions which limit algal growth ♦ Release of allelopathic chemicals can kill algae ♦ Release of humic substances can bind phosphorus	♦ Materials and application are relatively inexpensive ♦ Decline in algal abundance is more gradual than with algaecides, limiting oxygen demand and the release of cell contents	♦ Success appears linked to uncertain and potentially uncontrollable water chemistry factors ♦ Depression of oxygen levels may result ♦ Water chemistry may be altered in other ways unsuitable for non-target organisms	♦ Marginally applicable, as it tends to impact cyanobacteria, but this is basically an unregistered herbicide and cannot be officially permitted or performed by a licensed applicator in Massachusetts

Algaecides represent a maintenance approach to reducing algal blooms. While not philosophically very satisfying (they do not address the source of the problem), algaecides can be practical and do not have to cause major environmental damage as is commonly assumed or claimed. Copper and peroxide based algaecides are by far the most common, and would both be applicable to Cliff Pond. Peroxides present less risk of impact to non-target organisms, but are more expensive. Proper use of algaecides involves close tracking of the algae community and reaction before a bloom is formed. The cost of the monitoring program is likely to be more than the cost of the actual treatment.

Repetitive treatments tend to signify that the problem is more severe and that consideration should be given to nutrient controls. We believe this to be the case for Cliff Pond even without having conducted any algaecide treatments; the potential for nutrient levels to support algae blooms is just too high in this pond. Use of algaecides may be appropriate on a very intermittent basis in the future, but does not appear to represent a solution to the current problem. Additionally, killing algae adds to oxygen demand and the nutrient reserves in the bottom of the pond, neither of which is desirable. We will therefore not further consider algaecides for Cliff Pond.

Sonication can prevent algae blooms if continually applied at complete coverage, if the algae are susceptible. It is not clear that all problem algae in Cliff Pond are susceptible, but most are, and a reduction in blooms would be expected. However, getting continual and complete coverage would require many units at substantial cost, and killing algae as they develop would add oxygen demand and increase nutrient reserves at the pond bottom. Units may interfere with fishing and would require power lines in the pond. As with algaecides, this technique might be useful as a supplement to other approaches in some localized area, but it is not well suited to be the mainstay of algae control in Cliff Pond.

Bacterial additives are difficult area for professional lake managers to assess. Contents are universally proprietary, the focus appears to be on nitrogen control, and engineered organisms, undescribed enzymes, and unquantified nutrients may be involved. No two formulations are the same, but they all have one thing in common; in order to digest sediment and inactivate nutrients, they require oxygen. As the bottom of Cliff Pond is very short on oxygen for the summer, this approach has minimal potential unless oxygen levels are raised. As a supplement to oxygenation or circulation, this approach might have merit, but there is no reason to recommend it until oxygen enhancing techniques are in place and assessed for effectiveness on their own.

Sediment oxidation is actually an old technique that has fallen out of favor as oxygenation systems have improved. The addition of an oxidizing substance such as calcium nitrate fosters reactions in the sediment that reduce oxygen demand and limit release of phosphorus. Nitrates are preferentially metabolized by bacteria before sulfate metabolism and other more objectionable reactions take place, and a single treatment can lower oxygen demand for some time. Side effects were reported, however, and this approach was not generally recommended for lakes not in very poor condition. While Cliff Pond is not what it should be, it could get far worse and less intrusive techniques are more appropriate at this point.

Biomanipulation in this case would involve altering the fish community to maximize large herbivorous zooplankton (mainly *Daphnia*), which would convert algae into a resource useable by fish. *Daphnia* are present in the pond already, but disappeared under what appears to be intense predation by early July. Biomanipulation would best be accomplished by stocking more gamefish that could reduce the panfish population, but the focus of current stocking is on trout and salmon that are less effective predators of the fish in question. Additionally, biomanipulation tends not to be very effective if phosphorus levels remain high, and levels in Cliff Pond in at least the deep water are very high at times. As salmonid fishing is a goal for Cliff Pond, it makes more sense to alter the physical and chemical conditions to support that goal, as these would also favor a desirable zooplankton community.

Artificial circulation involves moving water within a water body to minimize stagnation. Done in just the upper layer, it creates a strong separation from the lower layer that has sometimes yielded water quality benefits, but has provided inconsistent results and would not improve oxygen in the deep water of Cliff Pond, an important goal in this case. Whole lake circulation, or destratification, would likely be needed to make a difference in Cliff Pond. This would homogenize the water body, or at least most of it, and may be counter to the desire to host a major trout fishery. The water temperature may be too warm in the mixed portion, and any deeper unmixed portion would still have no oxygen by late summer. This alone may be grounds for dismissing this option.

Additionally, review of many other circulation systems (Wagner 2014) has revealed that most systems are able to shift the types of algae blooming, but not prevent blooms from occurring. Enough algae are tolerant of mixing, or even favored by it. Reducing actual algae quantity is more a matter of reducing available nutrients, which the circulation system should do, but not as effectively as might be desired. Finally, that same review has revealed that nearly all air driven circulation (and oxygenation) systems experience compressor problems; ongoing and rapid maintenance is essential to maximizing system performance, and is often not high on the priority of town or state agencies.

It should also be noted that circulation can be accomplished by updraft or downdraft pumping instead of compressed air. Downdraft pumping would involve one floating unit in the middle of the pond, but a deflector plant would be needed to minimize resupension of sediment. Such a system could work to effectively mix Cliff Pond, should increase deep water oxygen and minimize cyanobacteria, but may not eliminate algal blooms and would raise the temperature in deeper water. It would also have an ongoing power and maintenance cost.

Updraft pumping is the final mixing option, and involves smaller, often solar powered units that pull water up from a selected depth. Many cases have involved just circulating surface water, and this has sometimes reduced cyanobacteria blooms, but will not improve deep water oxygen or depress internal loading of phosphorus. Use of updraft pumps to completely mix the pond is possible, but studies (reviewed by Wagner 2014) have revealed that commercially available units have been unable to overcome the heat input during hot, sunny summer periods, reducing the effective mixing zone to as little as an acre and rarely more than 5 acres. A large number of units would be necessary on Cliff Pond, creating surface obstacles for boating and altering the viewscape.

No power is required for solar-powered units, but maintenance contracts would carry an annual operational cost.

A circulation system to mix enough of Cliff Pond to alter oxygen dynamics and reduce internal loading does not seem practical or consistent with pond use goals. Given the ability to add oxygen without destratifying the pond, this option will not be considered further.

Reduction of the internal load and increase in deep water oxygen are necessary to achieve the desired conditions. It is often difficult for people focused on source control and watershed management to grasp the significance of the internal load, but this has been documented as a major force in many lakes, one that cannot be reversed quickly by watershed management. Yet internal load, when dominant, can be controlled with extended benefits (Mattson et al. 2004, Cooke et al. 2005, NYSFOLA 2009). We have discussed and dismissed potentially applicable rehabilitation means that were either impractical or somehow inconsistent with other use goals for Cliff Pond. We are left with just three options for controlling the internal load and reducing oxygen depletion.

There are three well documented ways to reduce internal loading of phosphorus: remove the sediment which harbors the available phosphorus, inactivate the phosphorus in place, or provide enough oxygen to prevent phosphorus from being released to surface waters. Removing the phosphorus involves dredging, which is a truly restorative technique, but extremely expensive and difficult to permit in Massachusetts. It has already been discussed and considered infeasible for Cliff Pond. This leaves inactivation and enhanced oxygen levels as logical approaches to the management of Cliff Pond.

Inactivation could be accomplished with addition of oxygen if natural phosphorus binders are present in adequate supply. The most common phosphorus binder by far for Cape Cod ponds is iron. Phosphorus not bound to iron is largely in organic forms, some of which may decay and release that phosphorus, but very slowly. However, under anoxic conditions iron and phosphorus tend to resolubilize and increase in the overlying water column. By keeping oxygen levels high, the phosphorus stays bound to iron in insoluble compounds. Phosphorus released from organic compounds is likely to be bound by iron fairly quickly where oxygen is adequate. Even if oxygenation is not extended to the sediment-water interface, presence of enough oxygen below the boundary between lower and upper water layers during stratification can cause the iron and phosphorus to recombine and settle downward again. Creation of an oxygenated boundary layer can be achieved anywhere between the sediment-water interface and the bottom of the upper water layer, based on controlling water temperature to create a stable density gradient. The entire pond can also be kept in a mixed condition, circulating oxygen rich water from top to bottom.

Oxygenating all or part of the deeper water layer requires adequate input of oxygen from at least May through September every year, and success is often variable over space and time. The additional benefits of more oxygen in deeper water include better habitat for fish and invertebrates and reduced concentrations of ammonium, sulfides, iron and manganese. The ongoing expense and load control uncertainty associated with deep water oxygenation are cause for hesitation, and this approach is less often used for internal load control, but it is becoming extremely popular in the drinking water and power industry for overall water quality improvement and fish habitat enhancement. There are multiple ways to add the needed oxygen, and systems are flexible enough to add oxygen when needed and cut back when not necessary. Oxygen can be targeted to specific layers, even within the generally defined upper and lower layers, the epilimnion and hypolimnion, based on find density differences. Oxygen can be placed near the bottom or in a layer just under the thermocline for maximum advantage. The evolution of oxygenation technology over the last two decades is impressive. The primary downside is ongoing cost; while oxygen demand will often decrease over time with treatment, it will not be eliminated.

Inactivation by a binder other than iron has been practiced in water and waste water treatment for many decades, with calcium and aluminum most often applied, and does not require oxygen to be effective. Calcium only precipitates at higher pH than experienced in a healthy Cape Cod pond, so aluminum would be the binder of choice. Aluminum combines with phosphorus to form an insoluble floc between pH 6.0 and 8.0, settles to the bottom, and interacts with the sediment phosphorus in the upper few inches of sediment, preventing later release. Aluminum comes in several reactive forms, some causing the pH to decline and others causing it to rise, and a balanced addition of two aluminum compounds with opposite pH tendencies can maintain the pH at a desired level. Keeping the pH between 6.0 and 8.0, and preferably between 6.5 and 7.5, maximizes reaction efficiency and minimizes possible toxicity impacts of reactive aluminum (Mattson et al. 2004, Cooke et al. 2005).

Once reacted, there is no significant threat of aluminum toxicity, but during the reaction process there is a risk to aquatic organisms. The treatment of Hamblin Pond in 1995 did not have a balanced mix of aluminum compounds, and while available sediment phosphorus was greatly reduced, there was substantial fish mortality during the treatment. A similar situation occurred in a Connecticut lake in 2000, prompting research into causative agents, and avoiding mortality is now easily achieved. No deaths of fish or mussels have been documented in 7 aluminum treatments in Cape Cod ponds over the last decade.

By inactivating the phosphorus in surficial sediment, internal loading is lowered and algal growth can be limited. This approach has worked well in multiple Cape Cod lakes since 1995, despite early non-target impacts. Hamblin Pond in Marstons Mills experienced its first algae bloom in 19 year in September 2013, a brief *Anabaena* bloom that may be a fluke or may signal the need for another treatment. Nearby Mystic Lake was treated in 2010 and has been improving ever since. Long Pond in Brewster and Harwich was treated in 2007; cyanobacteria blooms have been eliminated and water clarity doubled after treatment through 2013. Oxygen levels in deeper water may or may not be improved, depending on the importance of ongoing inputs. Hamblin Pond experienced improved oxygen below the thermocline, to the extent that trout can now be supported year round, but there is still anoxia in the deepest waters. The oxygen status of Long Pond has not changed appreciably, but measured oxygen demand has decreased in the deepest basin of that pond, and oxygen depletion does not approach the thermocline, so there is adequate trout water all summer.

More recently inactivation has been performed using lanthanum, an element that binds with phosphorus in the water column better than does aluminum and binds with phosphorus in the sediment to an acceptable degree based on limited data to date. Lanthanum is delivered in association with a bentonite clay slurry that also forms a sealing layer on the sediment and may further serve to limit release of phosphorus to the overlying water. This technique is too new to be able to cite longer term results, but it is a promising competitor for aluminum treatments. There is some indication from anecdotal accounts of treatments with lanthanum that it strips phosphorus from the water column better than aluminum, but is not a coagulant, so algae and other solids may not be settled as well as with aluminum. Ability to inactivate surficial sediment phosphorus, the primary reason for such treatments, has not yet been sufficiently documented to assess long-term effectiveness.

Currently applicable, feasible and appropriate options for Cliff Pond include only oxygenation and phosphorus inactivation. Either of these could be effective, and an approach for each is provided. Both could be applied; they are not mutually exclusive. If surficial sediment phosphorus inactivation yielded less oxygen improvement in deeper water than desired, recalculation of the necessary oxygen input could allow a less expensive oxygenation system to be designed. If oxygenation did not lower phosphorus levels sufficiently to minimize algae abundance, contributing areas of sediment could be treated to augment the benefits of oxygenation. As each represents and expensive investment in the pond, however, it is unlikely that both would be applied simultaneously.

Oxygenation

Circulation is a form of oxygenation, but has been eliminated from consideration for Cliff Pond. Yet it is also possible aerate water in a chamber and distribute that water to areas of low oxygen, or to put pure oxygen into those low oxygen waters. These oxygenation strategies include three air-based approaches and three oxygen-base methods:

1. Full lift aeration – Air is input at the bottom of a chamber that extends from the target zone to the surface of the water body. Oxygen exchange is fostered both from bubbles and at the surface. Water is returned to the target zone with much more oxygen than it had originally and is distributed laterally to improve oxygen levels in deeper waters without disrupting stratification.
2. Partial lift aeration – Much like full lift aeration, but the chamber does not extend to the surface of the water body and all oxygen transfer is from air bubbles. Efficiency is low, usually <3% transfer per vertical movement, with most systems transferring no more than 30% of the oxygen in the input air.
3. Layer aeration – Air input move water and transfers oxygen, but water from a warmer zone is mixed with water from a colder zone to make a stable, mid-temperature layer that is well oxygenated and minimizes transport of undesirable materials from deep water to shallow water.
4. Diffused oxygenation – Pure oxygen is released as tiny bubbles and absorbed in the target zone without disrupting stratification. These systems can have minimal moving parts and require no power, with liquid oxygen being turned into gas and moving through diffusion hoses under its own pressure. The cost of oxygen can offset the cost of power to run pumps or compressors, making this an attractive option in many cases.

5. Speece cone oxygenation – Water is pumped into a sealed cone from the top while pure oxygen is released from the bottom, and with proper balancing of the two flows, all oxygen is dissolved in the pumped water, which is then distributed within the target zone.
6. Sidestream supersaturation oxygenation – Water is pumped to a pressurized container where pure oxygen is added to achieve supersaturation of oxygen. The water is then pumped to the target zone to supply oxygen to that volume by lateral mixing and diffusion.

Each of these options is to some degree applicable to Cliff Pond, and each carries considerable capital and operational cost. Results with diffused pure oxygen have been very favorable (Wagner 2014), and such a system would be recommended as the way to directly oxygenate Cliff Pond. Other options require power, have multiple moving parts, have been less reliable in actual cases, or have less of a track record, although all can be successful if properly designed, installed, and operated. Diffused oxygen also appears to be the least expensive system in terms of capital and operating costs. For the conditions and features of Cliff Pond and its management by the Department of Conservation and Recreation, the relative cost, limited maintenance and excellent results offered by diffused oxygen are most attractive.

The main elements of a diffused oxygen system include an oxygen tank, a vaporizer (to convert liquid oxygen to gas), and a tubing system to deliver the oxygen to the water body (Figures 40 and 41). It is a relatively simple system, with power required only for instrumentation. Liquid oxygen from the storage tank moved through a pipe to the vaporizer by gravity, converts to gas, and moves through the delivery lines under its own pressure. The valve controlling the flow of liquid oxygen from the tank controls oxygen delivery.

Figure 40. Oxygen tank and vaporizer for a diffused oxygen system

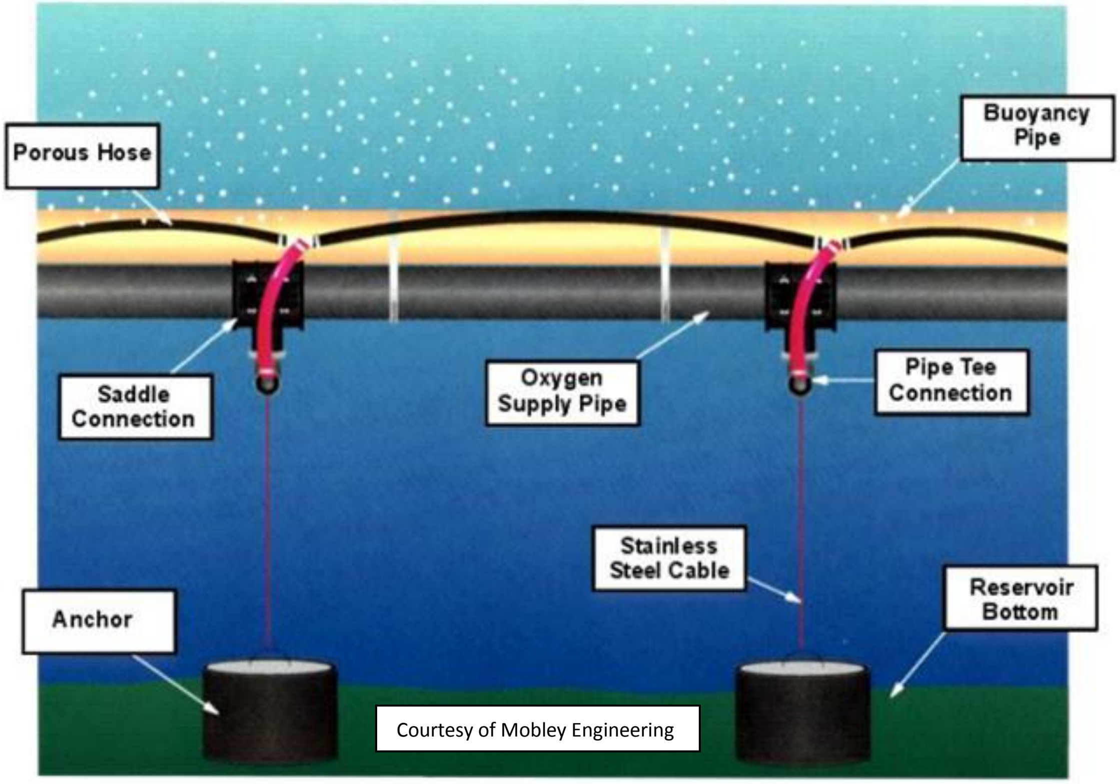


Figure 41. Oxygen delivery system for diffused oxygen system

The piping in the lake would consist of several lines covering the target area. Small oxygen bubbles are released through what is basically soaker hose and are absorbed by water low on oxygen. The amount of oxygen put into the waterbody should balance the oxygen demand, and if done properly, no bubbles rise to the surface and the mixing force applied is not sufficient to destratify the water body. In many projects over the last decade, this system has worked well.

The system has great flexibility to address varying oxygen demand. If monitoring indicates less need for oxygen, the system can be throttled back. If demand increases, the oxygen input can be increased. This can be done manually or by a feedback loop created by an in-situ monitoring system for oxygen and controls that allow automatic adjustment or remote control by an operator.

Based on recent review (Wagner 2014), a diffused oxygen system has an average capital cost of $2000/acre, and this approach offers the fewest moving parts, the least use of power, and generally lowest maintenance costs. The maximum area of Cliff Pond that would be addressed is the area under 33 feet (10 m), or 78.5 acres (31.4 ha), suggesting a capital cost of $157,000. There is no feature of Cliff Pond that suggests higher than average capital cost for installation, but a 20% contingency cost would be recommended based on the cost variation of projects from which the average is generated. This yields an expected capital cost of about $190,000. An additional $50,000 might be assumed for modeling and design, raising the maximum expected cost to put a system in place of $240,000.

Most of the oxygenation approaches have similar operational costs, but with different contributory factors. The cost of a diffused oxygen system is mostly related to oxygen cost, and costs from actual cases have varied from about $100 to $1000 per acre with an average of $350 per acre per year. For 78.5 acres of Cliff Pond, a diffused oxygen system would cost $27,500 per year based on the average value. This includes oxygen, part replacement and system maintenance; oxygen represents the largest portion of operational cost, but replacement of hoses is expected at least once per decade.

Calculation of operational cost for a specific installation relies mostly on determining the amount of oxygen needed. The oxygen demand measured for a water body before oxygenation system installation will be lower than what will be encountered with the system running. Movement of water due to gas input will cause greater expression of oxygen demand, with a range of about 1.25 to 5 times the pre-treatment level empirically found for a variety of oxygenation approaches. Use of pure oxygen creates less movement than air, and the values are mostly less than twice the pre-treatment demand. Most diffused oxygen systems are now designed to deliver twice the oxygen projected to be needed before system installation, and can be throttled back if less oxygen is needed.

For Cliff Pond with a best estimate of 2.76 g/m^2/day, the need to plan for up to about 5.52 g/m2/day is indicated. For a maximum target area of 78.5 acres (31.4 ha), a maximum oxygen delivery of 3812 lbs/day (1733 kg/day) would be needed. An average oxygen cost of $100 per ton suggests a maximum daily cost of just under $200. If the maximum oxygen amount was needed for 100 days per summer, the total oxygen cost would be $20,000, leaving $7500 for other maintenance in the annual operation budget estimated from the average cost of other diffused oxygen projects. It is entirely possible that the Cliff Pond system would operate at lower cost, but an annual operating budget of at least $20,000 should be assumed. An appropriate automated monitoring system would cost an additional $30,000, with an annual operational cost of $5000.

Put on a 20 year basis, an initial capital cost of up to $240,000 and an annual operational budget of $20,000 would lead to a cost of $640,000. Adding monitoring costs over the 20 year period of $130,000, the total cost could be as high as $770,000. The actual cost might be considerably lower, as the maximum area and maximum oxygen delivery are not essential, but for planning purposes at this stage, the costs provided here are appropriate. The design stage would allow adjustment for lower areas or volumes of the pond to be treated, based on a goal of less than complete oxygenation. For example, if only the layer between 33 and 46 feet (10 and 14 m) was oxygenated, this would be adequate to provide acceptable water clarity and considerably increased trout habitat, based on the relationship between water clarity and depth of anoxia (Figure 37). This would cut the affected bottom area and total volume of water improved by roughly half, and should reduce the capital and operational costs similarly. A balance of cost and achievement of goals is possible with this approach.

Phosphorus Inactivation

The inactivation of phosphorus in Cape Cod ponds has been accomplished with aluminum in all cases to date. Lanthanum in bentonite clay (tradename PhosLock) may represent a viable alternative, but other than the problem at Hamblin Pond in 1995 due to unbalanced application of two aluminum chemicals that raised the pH, there has been no documented mortality of any aquatic animal of concern. Aluminum treatments, while not commonplace, have become relatively routine and have produced success in every case on Cape Cod. The results are not irreversible, with Hamblin Pond finally showing signs of a return to undesirable conditions after 19 years, but the return on the investment is quite high. If Cliff Pond can follow the path of Hamblin Pond, the stocked trout might have a chance to survive the summer and biological balance might be restored to Cliff Pond with limited additional effort.

The data collected as part of this investigation indicate high accumulation of iron-bound phosphorus in Cliff Pond, similar to that found in Mystic Lake in Marston's Mills but more than found in Long Pond in Brewster and Harwich. Aluminum doses can be estimated by calculation, but are best determined by lab assay. Even then, the lab is not the field, and some interpretation and professional judgment is needed. It is important not to underdose the pond sediment, while with proper precautions for pH control and the amount of aluminum put into an area at once, there is no downside other than increased cost to overdosing.

The data for Cliff Pond suggest that the minimum dose would be 75 g/m^2, the highest dose tested in lab assays as part of this investigation. A higher dose may be needed to get a more complete internal load reduction, but a dose of 75 g/m2 would reduce the current load by about 75%. Such a reduction would lower the total phosphorus load by 50% to 78.2 kg/yr. Based on the empirical models applied in nutrient budget derivation, whole water column average phosphorus would decline from 0.023 to 0.012 mg/L, average chlorophyll-a would be lowered from 9.2 to 3.7 µg/L, and average Secchi transparency would increase from 6.9 to 11.6 feet (2.1 to 3.5 m). Chlorophyll-a values >10 µg/L would be expected less than 2% of the time, compared with over 33% now.

Review of aluminum treatments over the last decade suggests an average cost of $150 per gram of aluminum placed on each square meter of a hectare (2.5 acres) of pond sediment. At the recommended dose of 75 g/m^2 and a maximum treatment area of 78.5 acres (31.4 ha), the anticipated cost would be $353,250. The dose could be increased to as much as 100 g/m^2 after additional aluminum assays, in which case the anticipated cost would be $471,000. Monitoring during the treatment to guide the process and after the treatment for at least a year to document the results would cost about $60,000. Ongoing monitoring would be recommended, but is not essential to an inactivation treatment, which requires no operational support after the application is complete. Follow up testing to more accurately determine the dose and environmental constraints (e.g., maximum application at one time, buffer ratio) would cost about $25,000. The cost of an appropriate phosphorus inactivation project for Cliff Pond would therefore be estimated at between $440,000 and $560,000.

If conducted in the spring, results from the treatment should be apparent in the following summer. If conducted in the fall, results should also be apparent in the following summer, but may not reach a peak for several years. While this phenomenon is not well understood, it appears to relate to limited ability of aluminum to strip phosphorus from the water column at low to moderate concentrations. With most phosphorus still in the sediment in spring, the treatment maximizes phosphorus binding. With considerable phosphorus in the water column in fall, but with those concentrations still low relative to sediment levels, the aluminum prevents most further release from the sediment but the existing water column phosphorus has to work its way through the system by uptake, settling, flushing with some recycling, and this may take several times the detention time of the pond (which is years in many cases).

It is difficult to predict how much oxygen benefit will be achieved by a phosphorus inactivation treatment, as the results have been inconsistent among treated lakes and ponds. Some benefit is expected, but continued anoxia near the sediment-water interface is expected during stratification, based on current oxygen demand. It may lessen over a period of years, but is not likely to be eliminated. The situation in Cliff Pond appears similar to that at Long Pond, which was treated in 2007. Oxygen demand before treatment was about 2 g/m^2/day and anoxia occurred at 33 feet (10 m). Oxygen demand has declined gradually since treatment to about 1.3 g/m^2/day in 2013, with anoxia occurring between 40 and 46 feet (12 and 14 m). This would represent an improvement in Cliff Pond that should increase water clarity and enhance fish habitat, but not to the extent that an oxygenation project can guarantee.

The duration of benefits from a one-time phosphorus inactivation are also not easy to predict, but the same variables as at Hamblin Pond are at work, with lesser watershed impact at Cliff Pond. Hamblin Pond is still in much better condition than prior to treatment, but did experience its first algae bloom in September of 2013, over 19 years after treatment. With continued limited watershed inputs, at least 20 years of much improved conditions could be expected, after which a gradual decline may occur as slow phosphorus deposition allows increased internal recycling.

Conclusions and Recommendations

With the substantial data available from past monitoring and this investigation, it is clear that internal recycling of phosphorus and nitrogen is facilitating algal blooms, and that those releases are mediated by loss of oxygen in the bottom water layer as a consequence of elevated oxygen demand. How the oxygen demand got so high and how the phosphorus reserves in the fine sediment in deep water became so substantial is not known, but there is no evidence of any current watershed problem. Rehabilitation of Cliff Pond would be most beneficially achieved by increasing the oxygen in the bottom layer of the lake during summer stratification. Prevention of anoxia would limit releases of nutrients from the sediment and oxygen >5 mg/L would provide expanded trout habitat.

Increased oxygen can be achieved with a direct addition, diffused oxygen system that requires minimal moving parts or power. There are other oxygenation systems that are applicable, but a diffused oxygen system would be most appropriate and least expensive among the oxygenation alternatives. Diffused oxygen could be used to oxygenate the entire bottom layer of the pond, or to oxygenate just a layer between the thermocline and a depth that provides adequate nutrient reduction and sufficient trout habitat. The key depth for minimizing phosphorus release and maximizing water clarity is about 46 feet (14 m), and would require only about half the oxygen required for full bottom layer oxygenation.

The cost of designing and installing a diffused oxygenation system is estimated at $240,000. Operational costs will vary with oxygen needs and goals, but are estimated at $20,000 per year for full bottom layer oxygenation and $10,000 for the minimum application recommended. A monitoring system to guide oxygenation system operation would cost about $30,000 to install and another $5000 per year to run, independent of how much oxygen is added. If the operational costs of such an oxygenation system can be supported, this is the approach that would provide the most benefit to Cliff Pond. The cost over a 20 year period of operation would be between $570,000 and $770,000.

A phosphorus inactivation project could be conducted in Cliff Pond with a high probability of success, based on the experience of the last 20 years on the Cape and elsewhere. The maximum dose applied in lab assays as part of this investigation was not enough to lower the available phosphorus in sediment samples to the desired level of <50 mg/kg, but the projected internal load reduction at the 75 g/m^2 dose (the maximum tested) was 75%, adequate to meet most use goals and likely to provide at least some trout water during summer.

If operational costs for an oxygenation system cannot be afforded, phosphorus inactivation using aluminum is recommended. Some additional testing to determine the most appropriate dose and any application constraints is needed at a cost of about $25,000; the 75 g/m^2 dose is the recommended minimum, but a dose as high as 100 g/m^2 may be preferable. If the 75 g/m^2 dose is sufficient, the expected cost would be about $353,000. At 100 g/m^2, the cost would be about $471,000. In both cases, a monitoring program during and following treatment for two years would cost about $60,000, but there would be no operational costs after application. Rounding up, the total cost to move from this recommendation to a completed phosphorus inactivation project is between about $440,000 and $560,000. The duration of benefits is expected to be at least 20 years.

The benefits provided by the oxygenation system are perceived as greater than those from the phosphorus inactivation project, but goals for Cliff Pond could be achieved by either means. The capital cost of the oxygenation system is less than that of the phosphorus inactivation, but operational costs for oxygenation are substantial, while there are no operational costs for the phosphorus inactivation. Over a 20 year period, the oxygenation system would cost $130,000 to $210,000 more than the phosphorus inactivation treatment, or about $6500 to $10,500 per year.

Both oxygenation and phosphorus inactivation could be applied; they are not mutually exclusive and benefits would be compounded. It would seem most logical to inactivate first, then determine how much oxygen was still needed to provide the desired amount deep water fish habitat. If oxygenation is applied first, and clarity is not sufficiently improved, investigation of where to apply phosphorus in activators would be needed to achieve best results.

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APPENDIX A. Monitoring Data for Cliff Pond

Water Quality Data

Temperature °C																											
Depth	8/16/48	8/7/74	812/76	7/29/80	9/16/87	8/30/00	6/8/02	6/23/02	7/6/02	7/21/02	8/5/02	8/19/02	9/9/02	11/13/02	5/10/03	5/27/03	6/12/03	6/25/03	7/13/03	7/28/03	8/13/03	8/22/03	8/28/03	9/26/03	10/14/03	10/26/03	11/18/03
meters																											
0.5	23.9	25	24	26.5	21.5	24	18.6	21.9	26.5	25.1	27.4	27.7	23.0	11.7	13.3	14.5	18.7	21.6	24.9	25.3	26.3	26.8	25.1	21.7	17.8	13.4	9.6
1							18.2	21.9	26.4	24.8	27.4	27.5	23.0	11.7	13.2	14.5	18.7	21.6	24.8	25.2	26.3		25.1	21.6	17.8	13.4	9.5
2							18.1	21.9	26.2	24.4	27.4	27.2	22.7	11.6	13.2	14.5	18.6	21.5	24.8	25.1	26.3		25.1	21.5	17.8	13.4	9.5
3							18.0	21.9	26.1	24.3	27.3	27.1	22.7	11.6	13.1	14.5	18.3	19.6	24.7	25.0	26.2		25.1	21.5	17.8	13.4	9.5
4							18.0	20.7	25.9	24.3	26.1	26.8	22.5	11.6	13.0	14.4	18.2	19.2	24.6	24.9	26.2		25.1	21.5	17.8	13.4	9.5
5							17.9	19.5	24.7	24.2	24.5	26.0	22.2	11.4	12.9	14.4	18.0	18.8	24.4	24.8	25.9		25.1	21.5	17.7	13.4	9.5
6							17.7	18.3	20.4	24.1	23.8	24.8	22.1	11.2	12.1	14.3	16.8	18.4	20.8	24.7	25.6		25.1	21.4	17.7	13.4	9.5
7							17.4	17.8	18.8	22.3	22.9	23.2	21.8	11.2	11.6	14.1	15.8	17.8	19.2	23.5	24.4		24.9	21.4	17.7	13.4	9.5
8							14.5	17.2	17.6	18.2	19.5	19.6	21.4	11.1	11.5	14.0	15.1	16.7	16.9	17.9	20.4		22.6	21.3	17.6	13.4	9.5
9							13.9	15.6	15.9	16.2	16.7	16.6	19.0	11.0	10.4	12.4	14.2	14.3	15.2	15.5	16.2		17.3	20.9	17.6	13.4	9.5
10							13.5	14.0	14.4	14.8	15.1	15.2	15.6	10.8	10.0	10.2	13.0	12.2	13.3	13.8	14.0		14.9	18.5	17.6	13.4	9.5
11							13.0	13.0	13.3	13.4	13.8	13.9	14.2	10.7	9.6	9.5	11.2	11.1	11.7	12.0	12.3		12.7	14.3	17.4	13.4	9.5
12							12.5	12.7	12.8	12.7	13.1	13.0	13.5	10.6	9.3	9.1	9.8	10.2	10.4	10.7	11.3		11.8	12.8	15.6	13.4	9.5
13							12.2	12.2	12.4	12.2	12.3	12.2	13.1	10.4	8.9	8.9	9.3	9.5	9.7	10.0	10.8		10.8	11.9	13.1	13.3	9.4
14							11.7	11.8	11.8	11.7	11.7	11.7	12.0	10.3	8.8	8.7	9.0	9.2	9.3	9.7	10.4		10.1	11.0	11.0	13.1	9.4
15							11.3	11.2	11.1	11.1	11.3	11.1	11.4	10.2	8.4	8.5	8.8	9.0	9.0	9.3	9.5		9.6		10.1	13.0	9.4
16							10.7	10.8	10.8	10.6	10.8	10.5	10.8	10.2	8.2		8.7	8.8	8.8	9.0			9.4		9.6	12.7	9.4
17							10.2	10.3	10.4	10.2	10.3	10.2	10.4	10.2	8.1		8.5	8.6	8.7	8.8			9.1		9.0	9.7	9.3
18							9.6	9.7	10.0	9.9	10.0	10.0	10.1	10.2	8.1		8.5	8.5	8.6	8.8			8.9		8.8	8.9	9.3
19							9.3	9.5	9.7	9.7	9.9	9.9	10.0	10.2	8.1		8.4	8.5	8.5	8.6			8.8		8.7	8.7	9.3
20							9.3	9.4	9.6	9.6	9.7	9.8	9.9	10.2	8.0		8.4	8.5	8.5				8.7		8.7	8.7	
21							9.2	9.4	9.5	9.5	9.7	9.8	9.8	10.2	8.0		8.4	8.5	8.5				8.7		8.6	8.6	
22							9.2	9.4	9.5	9.5	9.7	9.8	9.8	10.1	7.9		8.4	8.5	8.5				8.6		8.6	8.6	
23							9.2	9.3	9.5	9.5	9.7	9.8	9.8	10.1	7.9		8.4	8.5	8.5				8.6		8.6	8.6	
24							9.2	9.3	9.5	9.5	9.7		9.8	10.1	7.9		8.4	8.5	8.5				8.6		8.7	8.7	
24.5																	8.5	8.5									
25																			8.4				8.6		8.7	8.7	
26																											

Temperature °C																														
Depth	5/14/04	5/31/04	6/13/04	6/29/04	7/15/04	8/2/04	8/17/04	8/30/04	9/13/04	10/13/04	10/31/04	11/17/04	5/2/05	5/20/05	6/6/05	6/15/05	7/1/05	7/15/05	8/4/05	8/18/05	9/7/05	5/18/06	6/16/06	7/15/06	8/17/06	9/5/06	9/27/06	5/3/07
meters																												
0.5	16.8	17.1	19.7	22.3	22.9	25.2	23.9	24.8	23.2	16.6	13.1	9.2	12.3	14.1	20.1	21.3	23.2	24.0	25.8	25.9	24.8	10.4	19.9	25.0	24.8	21.4	20.2	12.4
1	16.7	17.1	19.7	22.3	22.9	25.2	23.8	24.7	23.1	16.5	13.0	9.2	12.2	14.1	20.1	21.3	23.2	23.9	25.8	25.9	24.6	10.4	19.8	25.0	24.7		20.2	12.4
2	16.6	16.9	19.7	22.3	22.8	25.1	23.7	24.7	23.1	16.5	13.0	9.2	12.2	14.1	20.0	21.2	23.2	23.7	25.7	2.6	24.5	10.4	19.6	24.9	24.7		20.0	12.3
3	16.4	16.7	19.5	22.3	22.7	25.0	23.6	24.6	23.1	16.4	13.0	9.2	12.1	14.1	18.5	21.0	23.1	23.6	25.5	25.9	24.4	10.4	19.4	24.8	24.6		19.9	12.3
4	15.8	16.6	19.2	22.1	22.7	24.9	23.5	24.5	23.0	16.3	12.9	9.1	11.9	14.1	15.6	20.6	23.1	23.2	25.3	25.9	24.3	10.3	19.2	24.5	24.5		19.8	12.3
5	15.1	16.4	18.3	21.9	22.6	24.6	23.5	24.3	23.0	16.2	12.9	9.1	11.8	13.8	13.9	10.7	21.7	23.0	25.0	25.7	24.3	10.4	18.1	24.3	24.4		19.8	12.2
6	14.6	16.3	17.7	21.7	22.5	24.1	23.5	23.8	22.9	16.2	12.9	9.1	11.8	13.0	12.9	13.8	17.9	21.4	24.5	25.5	24.1	10.3	17.6	23.9	24.2		19.7	12.1
7	13.9	16.0	17.2	20.2	22.3	23.4	23.4	23.4	22.9	16.2	12.8	9.0	11.8	12.5	12.5	13.1	14.4	18.3	21.1	22.7	23.9	10.3	16.9	19.8	24.0		19.7	9.5
8	12.7	15.3	16.2	17.6	19.7	21.7	22.9	22.6	22.5	16.2	12.8	9.0	11.7	11.9	12.2	12.6	13.3	14.5	16.7	17.7	19.6	10.3	15.9	17.1	21.8		19.6	9.0
9	11.8	12.8	13.9	15.0	16.0	17.2	18.6	20.2	20.1	16.2	12.7	9.0	11.6	11.3	11.9	11.9	12.7	13.2	14.7	15.0	15.6	10.3	14.3	15.5	16.6		19.5	8.3
10	10.5	11.3	11.6	12.4	13.3	13.6	14.4	14.9	15.7	16.2	12.7	9.0	11.1	11.0	11.8	11.9	0.1	12.5	13.5	13.4	13.6	10.2	13.2	13.8	14.4		18.9	7.6
11	10.1	10.3	10.4	10.8	11.8	11.9	12.2	12.6	13.0	16.1	12.7	9.0	10.7	10.9	11.7	11.6	0.8	11.9	12.3	12.5	12.6	10.0	12.2	12.7	12.8		14.1	7.4
12	9.6	9.4	9.7	9.7	10.4	10.8	11.4	11.6	11.7	15.6	12.7	9.0	8.5	10.8	11.6	11.4	0.5	11.4	11.8	11.9	11.9	9.7	10.8	11.6	11.6		12.3	7.3
13	9.1	8.9	9.2	9.2	9.5	10.1	10.4	10.7	10.8	14.6	12.7	9.0	7.7	10.5	11.3	11.1	0.1	11.0	11.4	11.3	11.3	9.1	9.6	10.3	10.7		11.3	7.2
14	8.6	8.6	8.6	8.7	8.9	9.2	9.6	9.9	10.0	12.6	12.6	9.0	7.2	10.3	10.9	10.6	10.5	10.4	10.6	10.7	11.0	9.1	8.9	9.4	10.0		10.3	7.2
15	7.8	8.1	8.3	8.5	8.5	8.8	9.0	9.1	9.1	9.5	12.5	9.0	7.0	8.8	10.3	9.9	9.8	10.0	10.1	10.2	10.4	9.1	8.3	8.8	9.4		9.6	7.2
16	7.4	7.8	8.1	8.3	8.2	8.4	8.6	8.7	8.8	9.0	12.4	9.0	6.7	8.0	9.3	9.2	9.2	9.3	9.2	9.5		8.9	8.1	8.5	8.9		9.2	7.2
17	7.3	7.4	7.7	7.9	8.0	8.2	8.4	8.5	8.6	8.6	9.1	9.0	6.7	7.2	7.6	8.0	8.5	8.3	8.8	9.0		9.0	8.0	8.1	8.8		8.6	7.2
18	7.1	7.3	7.6	7.8	7.8	8.0	8.2	8.2	8.3	8.4	8.4	9.0	6.7	7.0	7.2	7.5	7.8	7.9	7.9	8.5		8.8	7.7	7.8	8.3		8.3	7.1
19	7.1	7.3	7.6	7.7	7.8	7.9	8.1	8.1	8.2	8.2	8.2	9.0	6.7	6.9	7.0	7.2	7.3	7.7	7.7	7.8		8.8	7.6	7.7	8.2		8.3	7.0
20	7.1	7.3	7.6	7.7	7.8	7.9	8.0	8.1	8.2	8.2	8.1	9.0	6.6	6.8	6.9	7.1	7.2	7.4	7.6	7.7		8.7	7.6	7.7	8.1		8.1	7.0
21	7.0	7.3	7.6	7.7	7.8	7.9	8.0	8.0	8.1	8.1	8.1	9.0	6.5	6.7	6.8	7.1	7.2	7.3	7.5	7.6		8.7	7.5	7.6	8.1		8.1	7.0
22	7.0	7.3	7.6	7.7	7.8	7.9		8.0	8.1	8.1	8.1	8.9	6.5	6.7	6.8	7.1	7.1	7.2	7.5	7.6		8.6	7.5	7.6	8.0		8.1	7.0
23	7.0	7.3	7.6	7.7	7.8	7.9		8.0	8.1	8.1	8.1	8.9	6.5	6.6	6.8	7.0	7.1	7.2	7.4	7.5		8.3	7.5	7.6	8.0		8.1	7.0
24	7.0	7.3	7.6		7.8	8.0		8.0		8.1	8.1	8.9	6.5	6.6	6.8	7.0	7.1	7.2	7.4	7.5		8.3	7.5	7.6	8.0		8.1	7.0
24.5																												
25	7.0	7.3	7.6		7.8	8.0		8.0				8.9	6.5	6.5	6.8	7.1	7.0	7.2	7.4	7.5		8.1	7.5	7.6	8.1		8.1	7.0
26															6.8	7.1	7.0	7.2	7.4			7.9	7.5	7.7	8.2		8.2	7.0

Temperature °C																					
Depth	9/13/07	9/26/07	8/20/08	9/8/08	9/8/09	9/21/09	8/18/10	9/1/10	9/1/11	9/21/11	4/25/12	8/20/12	9/20/12	4/18/13	6/12/13	7/1/13	7/17/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters																			Central	Southeast	West	North
0.5	22.5	21.0	24.5	23.5	23.0	20.3	26.0	24.7	23.9	21.1	14.5	26.0	21.2	10.0	20.4	23.7	28.2	26.2	19.6	19.8	19.4	19.5
1		21.0		23.6	23.0	20.1	26.0	24.5	23.9	20.7	14.3	26.0	21.2	10.0								
2		21.0		23.5	23.0	20.0	26.0	24.3	23.8	20.3	14.3	26.0	21.1	10.0				24.7				
3		21.0		23.5	23.0	19.9	26.0	23.9	23.7	20.3	14.2	26.0	21.1	9.9	20.4	23.6	27.6		18.8			
4		20.9		23.4	23.0	19.9	26.0	23.5	23.4	20.3	14.1	25.8	21.0	9.9				24.1				
5		20.9		23.4	23.0	19.9	26.0	23.2	23.3	20.2	14.0	24.5	21.0	9.9				23.6				
6		20.9		23.3	23.0	19.9	26.0	23.0	23.2	20.2	13.9	22.0	20.8	9.7	20.3	21.9	23.5	20.3	18.7			
7		20.8		23.2	23.0	19.8	26.0	22.6	23.1	20.2	13.3	20.0	20.8	9.6								
8		20.6		22.9	22.8	19.8	25.8	22.4	21.9	20.1	12.1	16.5	19.2	9.6					18.6			
9		20.4		22.3	22.3	19.8	22.0	21.9	16.9	19.9	9.8	14.3	14.5	9.6	12.9	14.6	14.7	15.7	18.5			
10		17.8		18.8	18.8	19.7	17.5	20.7	12.9	14.9	9.3	12.5	12.7	8.8				13.4	14.3			
11		12.8		13.7	16.0	18.5	15.0	16.2	11.4	12.0	8.9	11.5	11.2	8.4					11.3			
12		10.2		11.3	13.8	13.8	12.3	12.6	10.5	10.7	8.6	10.3	10.2	7.4	9.2	9.4	9.8	10.0	10.5			
13		9.3		9.9	12.0	11.4	11.3	11.1	9.8	10.1	8.7	10.0	9.7	7.1					9.7			
14		8.9		9.0	11.0	11.4	10.3	10.4	9.5	9.7	8.0	9.5	9.3	7.0				9.1	9.3			
15		8.1		8.2	10.0	9.6	10.0	9.6	9.1	9.4	7.9	9.3	9.1	7.0	8.3	8.6	8.7		9.0	9.0	8.9	9.6
16		8.0		7.9	9.8	9.1	9.3	9.0	8.9	9.2	7.8	9.0	8.8	7.0				8.6				
17		7.8		7.7	9.8	8.9	9.0	8.5	8.8	9.2	7.7	9.0	8.7	7.0								
18		7.6		7.5	9.0	8.7	8.8	8.3	8.7	9.2	7.7	9.0	8.6	7.0	8.0	8.1	8.2	8.4	8.5			
19		7.6		7.4	9.0	8.7	8.5	8.2	8.6	9.2	7.7	9.0	8.6	7.0								
20		7.6		7.3	9.0	8.6	8.5		8.6	9.2	7.7	9.0	8.6	6.9				8.3				
21		7.6		7.2	9.0	8.5	8.5	8.2	8.6		7.7	9.0	8.6	6.9	7.8	8.0	8.1		8.4			
22		7.5		7.2	9.0	8.5	8.5	8.2	8.6		7.7	9.0	8.5	6.9				8.2				
23		7.5		7.2	9.0	8.5	8.5	8.1	8.6		7.7	9.0	8.5	6.9								
24		7.5		7.2	9.0	8.5	8.5	8.1	8.6		7.6	9.0	8.5	7.0	7.8	8.0	8.1	8.2	8.4			
24.5					9.0		8.5				7.6	9.0										
25		7.5		7.2	9.0	8.5	8.5	8.1	8.5			9.0	8.5									
26					9.0	8.5		8.0	8.5		7.6	9.0										

DO mg/L																											
Depth	8/16/48	8/7/74	812/76	7/29/80	9/16/87	8/30/00	6/8/02	6/23/02	7/6/02	7/21/02	8/5/02	8/19/02	9/9/02	11/13/02	5/10/03	5/27/03	6/12/03	6/25/03	7/13/03	7/28/03	8/13/03	8/22/03	8/28/03	9/26/03	10/14/03	10/26/03	11/18/03
meters																											
0.5							9.9	9.9	8.3	8.5	8.1	8.7	15.1	7.7	11.7	10.0	10.2	10.2	8.6	8.6	8.3		8.2	9.1	8.9	9.3	10.1
1							9.9	9.9	8.3	8.6	8.1	8.8	15.5	7.8	11.8	10.0	10.2	10.2	8.7	8.6	8.3		8.3	9.1	8.9	9.3	10.2
2							9.9	9.9	8.4	8.6	8.1	8.7	15.3	7.9	11.7	10.0	10.2	10.2	8.7	8.6	8.3		8.3	9.1	8.9	9.3	10.1
3							9.9	9.9	8.5	8.6	8.1	8.7	15.4	8.0	11.7	10.0	10.2	10.6	8.7	8.6	8.3		8.3	9.1	8.9	9.3	10.1
4							9.9	10.2	8.4	8.6	8.5	8.6	15.0	8.1	11.7	10.0	10.2	10.7	8.6	8.6	8.3		8.3	9.1	8.9	9.2	10.1
5							9.9	10.6	9.2	8.5	8.8	8.5	15.0	8.1	11.7	10.0	10.2	10.7	8.6	8.6	8.3		8.3	9.1	8.9	9.2	10.1
6							9.9	10.6	10.1	8.3	8.5	7.7	14.8	8.1	11.7	10.0	10.5	10.6	10.6	8.6	8.1		8.3	9.0	8.9	9.2	10.1
7							9.8	10.4	10.2	8.9	8.3	6.8	12.1	8.1	11.9	9.9	10.4	10.8	10.8	8.9	7.9		8.2	9.0	8.9	9.2	10.1
8							10.6	10.3	10.0	9.7	7.9	6.0	10.1	8.2	11.9	9.9	10.1	10.8	10.9	10.6	9.5		8.9	8.9	8.9	9.2	10.1
9						<5	10.3	9.3	9.5	8.2	5.7	4.1	5.2	8.2	11.7	9.6	9.6	9.3	10.2	9.8	8.6		9.3	8.8	8.9	9.2	10.1
10						<1	9.1	7.6	7.1	5.0	3.1	2.6	1.1	8.2	11.4	9.4	8.9	7.0	7.9	8.6	6.0	<5	7.1	7.1	8.9	9.2	10.1
11						<1	7.6	5.2	5.0	2.4	1.7	0.8	0.4	8.2	11.1	8.2	7.7	6.4	5.2	5.1	3.9	<5	3.9	1.7	8.8	9.2	10.1
12					<5	<1	6.2	4.7	3.4	1.6	0.5	0.2	0.3	8.3	10.8	8.0	7.2	6.2	3.5	2.5	2.6	<5	2.1	0.8	4.3	9.2	10.0
13					<1	<1	6.1	3.8	2.0	0.9	0.3	0.2	0.3	8.3	10.5	7.7	6.9	5.4	3.4	1.8	2.1	<5	0.6	0.2	0.1	8.9	10.0
14		<5			<1	<1	6.0	3.7	1.9	0.9	0.2	0.2	0.3	8.3	10.5	7.5	6.7	5.4	3.1	1.6	1.2	<1	0.1	0.1	0.0	8.2	10.0
15		<5		<5	<1	<1	5.8	3.5	2.0	0.8	0.2	0.2	0.3	8.3	10.3	7.5	6.6	5.4	3.1	1.4	0.3	<1	0.0		0.0	8.0	10.0
16		<5	<5	<5	<1	<1	5.6	3.5	2.0	0.8	0.2	0.2	0.3	8.3	10.2		6.7	5.4	2.7	1.5		<1	0.0		0.0	6.7	10.0
17		<5	<5	<5	<1	<1	5.1	3.2	1.7	0.6	0.2	0.2	0.3	8.6	10.3		6.2	5.1	2.7	1.3		<1	0.0		0.0	0.0	10.0
18	<5	<5	<5	<5	<1	<1	4.5	2.6	1.4	0.3	0.2	0.2	0.3	8.6	10.3		6.1	4.9	2.6	1.2		<1	0.0		0.0	0.0	10.0
19	<5	<5	<5	<5	<1	<1	4.1	2.1	1.2	0.3	0.2	0.2	0.3	8.6	10.3		6.0	4.7	2.4	0.9		<1	0.0		0.0	0.0	10.0
20	<5	<5	<5	<5	<1	<1	3.9	2.0	0.8	0.2	0.2	0.2	0.3	8.5	10.2		5.7	4.5	2.2			<1	0.0		0.0	0.0	
21	<5	<5	<5	<5	<1	<1	3.6	1.8	0.5	0.2	0.1	0.2	0.2	8.4	10.1		5.7	4.3	2.0			<1	0.0		0.0	0.0	
22	<5	<5	<5	<5	<1	<1	3.6	1.7	0.4	0.2	0.1	0.2	0.2	8.3	9.8		5.7	4.2	1.9			<1	0.0		0.0	0.0	
23	<5	<5	<5	<5	<1	<1	3.5	1.3	0.3	0.2	0.1	0.2	0.2	8.3	9.8		5.6	4.0	1.8			<1	0.0		0.0	0.0	
24	<5	<5	<5	<5	<1	<1	3.3	1.1	0.3	0.2	0.1		0.3	8.3	9.6		5.6	3.8	1.7			<1	0.0		0.0	0.0	
24.5	<5	<5	<5	<5	<1	<1											5.6	3.4				<1					
25	<5	<5	<5	<5	<1	<1													1.3			<1	0.0		0.0	0.1	
26	<1	<1	<1	<1	<1	<1																<1					

DO mg/L																												
Depth	5/14/04	5/31/04	6/13/04	6/29/04	7/15/04	8/2/04	8/17/04	8/30/04	9/13/04	10/13/04	10/31/04	11/17/04	5/2/05	5/20/05	6/6/05	6/15/05	7/1/05	7/15/05	8/4/05	8/18/05	9/7/05	5/18/06	6/16/06	7/15/06	8/17/06	9/5/06	9/27/06	5/3/07
meters																												
0.5	10.4	10.3	10.7	9.3	8.9	8.5	9.2	8.8	8.5	9.4	10.1	11.3	10.6	11.3	9.1	8.7	10.1	11.7	6.4	8.7	8.8	13.7	8.9	7.5	8.3		8.8	10.1
1	10.4	10.3	10.8	9.3	8.9	8.5	9.3	8.8	8.5	9.4	10.1	11.2	10.7	11.3	9.0	8.6	10.1	11.4	6.2	8.7	8.9	13.6	9.0	7.6	8.4		8.8	10.1
2	10.4	10.3	10.8	9.3	8.9	8.6	9.3	8.9	8.5	9.4	10.2	11.2	10.7	11.3	9.2	8.4	9.7	10.2	5.9	8.7	8.8	13.6	9.0	7.6	8.4		8.9	10.1
3	10.5	10.3	10.8	9.3	9.0	8.6	9.3	8.8	8.5	9.4	10.2	11.2	10.8	11.3	9.8	8.7	9.6	9.5	5.8	8.7	8.7	13.5	9.0	7.6	8.4		8.9	10.1
4	10.7	10.3	10.8	9.3	9.0	8.6	9.2	8.8	8.4	9.4	10.1	11.2	10.8	11.3	10.9	8.5	9.4	9.0	5.7	8.7	8.7	13.4	9.0	7.5	8.4		8.9	10.1
5	10.7	10.3	11.5	9.3	9.0	8.6	9.2	8.7	8.4	9.5	10.1	11.2	10.8	11.3	11.7	10.7	10.0	8.3	5.5	8.5	8.7	13.2	9.5	7.6	8.4		8.9	11.1
6	10.6	10.4	11.6	9.4	9.0	8.7	9.0	8.8	8.4	9.5	10.1	11.2	10.7	11.2	12.0	11.8	12.1	9.3	5.5	8.5	8.4	13.1	9.6	7.5	8.2		8.9	10.1
7	10.4	10.4	11.6	10.1	9.0	9.0	9.0	8.5	8.3	9.4	10.0	11.1	10.7	11.0	11.9	11.8	13.3	9.9	6.6	9.4	7.8	12.8	9.5	9.2	8.1		8.6	10.9
8	10.4	10.2	11.4	11.0	10.8	10.1	8.9	7.2	8.0	9.4	9.9	11.1	10.6	10.6	11.6	11.7	12.6	10.9	7.4	10.8	8.3	12.7	9.5	9.5	8.8		8.5	10.9
9	10.4	10.1	10.6	10.7	11.2	11.4	10.4	5.4	3.8	9.2	9.8	11.1	10.6	10.3	11.1	10.9	11.9	10.8	8.7	11.1	8.5	12.6	8.9	9.4	9.4		8.3	10.8
10	10.2	8.9	8.5	8.0	9.6	8.6	8.0	5.2	2.7	9.3	9.7	11.1	10.5	9.9	10.8	10.4	10.1	10.0	9.4	9.2	7.3	12.1	8.4	8.2	7.8		7.4	9.6
11	9.6	7.9	6.7	5.2	6.4	5.1	3.5	2.3	1.0	9.2	9.7	11.1	10.5	9.7	10.5	9.7	9.7	8.3	8.6	6.2	3.0	11.6	7.7	6.7	4.6	<5	3.1	10.0
12	9.4	7.2	5.9	4.4	2.9	2.5	1.6	1.2	0.3	8.0	9.6	11.1	10.3	9.6	10.1	8.9	8.2	7.3	7.5	4.1	1.3	10.5	6.8	4.9	2.4	<5	2.0	9.7
13	9.2	6.9	5.6	3.2	1.8	1.4	0.9	0.3	0.1	5.2	9.6	11.1	10.2	9.2	9.9	8.3	7.1	7.1	7.4	3.3	0.8	9.3	6.6	3.2	1.4	<1	1.9	9.5
14	9.2	7.3	5.8	3.3	1.7	0.5	0.1	0.2	0.1	0.9	9.5	11.1	10.0	8.8	9.7	8.6	7.0	7.4	6.6	3.2	0.9	8.2	6.6	2.7	1.0	<1	2.0	9.5
15	9.4	7.4	5.8	3.6	1.8	0.5	0.1	0.2	0.1	0.1	9.1	11.1	10.0	8.8	9.1	8.3	7.1	7.1	6.5	2.9	0.9	7.7	6.6	2.6	0.7	<1	2.1	9.6
16	9.4	7.4	6.1	3.4	1.6	0.4	0.1	0.2	0.1	0.1	8.6	11.1	10.1	8.8	8.6	8.1	6.8	7.0	6.6	3.0		7.5	6.7	2.5	0.1	<1	2.1	9.6
17	9.2	7.6	5.9	3.3	1.5	0.3	0.1	0.2	0.2	0.1	0.1	11.1	10.1	8.8	7.9	7.6	6.4	6.6	6.6	3.0		7.3	6.7	2.5	0.1	<1	2.2	9.5
18	9.2	7.3	5.9	3.4	1.3	0.2	0.1	0.2	0.2	0.2	0.1	11.0	10.1	8.9	7.8	7.5	5.9	6.5	6.6	3.1		7.3	6.4	2.1	0.1	<1	2.2	9.5
19	9.2	7.2	5.9	3.3	1.2	0.1	0.1	0.2	0.2	0.2	0.2	11.0	10.0	8.9	7.5	7.1	5.3	6.4	7.0	3.2		7.2	6.3	1.8	0.1	<1	2.2	9.5
20	9.2	7.0	5.9	3.1	1.2	0.1	0.2	0.2	0.2	0.2	0.2	10.9	10.0	8.7	7.1	7.0	5.0	6.0	6.9	3.2		7.2	6.3	1.8	0.1	<1	2.3	9.6
21	9.1	7.0	5.9	3.0	1.1	0.1	0.2	0.3	0.2	0.2	0.2	10.9	10.0	8.5	6.7	6.9	4.9	5.7	6.8	3.2		7.2	6.1	1.7	0.1	<1	2.3	9.5
22	9.0	6.9	5.8	3.0	1.0	0.2		0.3	0.2	0.2	0.2	10.9	10.0	8.3	6.6	6.9	4.7	5.3	6.2	3.2		7.2	6.0	1.6	0.1	<1	2.5	9.5
23	9.0	6.9	5.7	2.6	0.9	0.2		0.3	0.2	0.2	0.2	11.0	10.0	7.8	6.2	6.6	4.6	5.2	6.2	3.1		7.2	5.9	1.6	0.1	<1	2.4	9.4
24	9.0	6.8	5.6	2.4	0.3	0.2		0.3		0.2	0.3	11.0	9.8	7.6	6.0	6.6	4.2	5.1	6.2	3.1		7.2	5.7	1.5	0.1	<1	2.4	9.4
24.5													9.6	7.7	5.8	6.6	3.9	4.9	6.2	3.1						<1		
25	8.8	6.7	5.6	2.4	0.2	0.3		0.3				11.0			5.7	6.6	3.7	4.9	6.1			7.2	5.6	1.5	0.2	<1	2.1	9.4
26																						7.2	5.6	1.4	0.2	<1	2.6	9.2

DO mg/L																						
Depth	9/13/07	9/26/07	8/20/08	9/8/08	9/8/09	9/21/09	8/18/10	9/1/10	9/1/11	9/21/11	4/25/12	8/20/12	9/20/12	4/18/13	6/12/13	7/1/13	7/17/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters																			Central	Southeast	West	North
0.5		8.5		8.6	10.3	8.6	9.4	8.6	9.5	8.2	12.1	9.2	8.8	12.8	9.8	9.4	8.7	10.0	9.9	9.9	10.1	10.0
1		8.5		8.5	10.3	8.7	9.5	8.7	9.5	8.6	12.0	9.6	8.8	12.8								
2		8.5		8.6	10.3	8.7	9.6	8.7	9.6	8.2	12.0	9.6	8.8	12.9				10.3				
3		8.5		8.6	10.3	8.7	9.6	8.8	9.2	7.8	11.9	9.0	8.7	12.8	9.8	9.3	9.5		10.4			
4		8.5		8.6	10.3	8.7	9.6	8.8	8.4	7.7	11.7	8.0	8.7	12.8				8.6				
5		8.6		8.5	10.3	8.7	9.6	8.8	8.5	7.3	11.7	4.4	8.6	12.9				6.1				
6		8.5		8.5	10.1	8.7	9.6	8.9	7.7	7.3	11.7	3.4	8.3	12.9	9.8	9.2	10.0	4.3	9.8			
7		8.5		8.5	10.1	8.7	9.6	8.8	6.9	7.0	11.5	3.4	8.2	12.9								
8		8.2		8.5	10.0	8.6	9.4	8.8	6.4	7.0	11.6	1.8	3.1	12.9					8.3			
9		7.7		8.5	10.2	8.6	10.2	8.5	4.8	6.1	11.5	0.2	1.3	12.9	10.3	9.4	9.2	4.6	7.2			
10	<5	4.4		7.3	11.3	8.5	10.8	8.0	0.3	0.8	10.7	0.1	1.3	13.1				3.9	0.0			
11	<5	1.7	<5	3.7	3.9	6.8	8.2	6.1	0.2	0.6	10.2	0.1	1.4	12.9					0.0			
12	<1	0.8	<5	0.1	0.2	0.3	2.7	1.5	0.2	0.5	9.2	0.1	1.4	12.3	4.2	3.7	2.0	0.2	0.0			
13	<1	0.8	<5	0.1	0.1	0.2	1.3	0.2	0.2	0.5	8.6	0.1	1.4	12.2					0.0			
14	<1	0.8	<1	0.1	0.1	0.2	0.7	0.1	0.2	0.5	8.7	0.3	1.4	12.2				0.0	0.0			
15	<1	0.8	<1	0.1	0.1	0.2	0.6	0.1	0.1	0.5	8.6	0.3	1.3	12.2	2.8	1.1	0.2		0.0	0.2	0.0	0.0
16	<1	0.8	<1	0.1	0.1	0.2	0.4	0.1	0.1	0.5	8.4	0.3	1.3	12.2				0.0				
17	<1	0.8	<1	0.1	0.1	0.2	0.4	0.1	0.1	0.5	8.4	0.1	1.2	12.2								
18	<1	0.9	<1	0.1	0.1	0.2	0.3	0.1	0.1	0.5	8.2	0.5	1.2	12.3	2.4	0.5	0.0	0.0	0.0			
19	<1	0.9	<1	0.1	0.1	0.1	0.3	0.1	0.1	0.5	8.0	0.3	1.2	12.4								
20	<1	0.9	<1	0.1	0.1	0.1	0.3		0.1	0.5	7.8	0.3	1.1	12.4				0.0				
21	<1	0.9	<1	0.1	0.1	0.1	0.3	0.1	0.1		7.8	0.3	1.1	12.3	2.2	0.0	0.0		0.0			
22	<1	0.9	<1	0.1	0.1	0.1	0.3	0.1	0.1		7.6	0.3	1.1	12.3				0.0				
23	<1	0.9	<1	0.1	0.1	0.1	0.3	0.1	0.1		7.6	0.3	1.1	12.3								
24	<1	0.9	<1	0.1	0.1	0.1	0.2	0.1	0.1		7.3	0.3	1.1	12.3	2.1	0.0	0.0	0.0	0.0			
24.5	<1		<1		0.1		0.2				6.9	0.3										
25	<1	0.9	<1	0.1	0.1	0.1	0.2	0.1	0.1			0.3	1.1									
26	<1		<1		0.1		0.2	0.1	0.1		6.4	0.3										

DO % Sat									
Depth	4/18/13	6/12/13	7/1/13	7/17/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters						Central	Southeast	West	North
0.5	114.4	109.6	112.1	113.4	125.8	109.9	110.1	111.7	109.9
1	114.9								
2	115.2				125.8				
3	114.9	110.0	111.2	122.7		113.5			
4	114.7				103.5				
5	115.1				73.0				
6	115.0	110.0	105.9	119.5	48.4	106.2			
7	114.9								
8	115.1					90.0			
9	114.7	99.2	93.6	92.0	47.0	77.4			
10	114.2				37.7	0.0			
11	111.5					0.0			
12	103.3	37.0	32.4	17.6	1.4	0.0			
13	102.4					0.0			
14	102.1				0.0	0.0			
15	101.8	24.4	9.5	2.0		0.4	1.9	0.3	0.0
16	101.8				0.0				
17	101.9								
18	102.6	20.7	4.1	0.0	0.0	0.0			
19	103.4								
20	103.2				0.0				
21	102.4	18.4	0.0	0.0		0.0			
22	102.2				0.0				
23	102.8								
24	102.5	17.7	0.0	0.0	0.0	0.0			
24.5									
25									
26									

Turbidity NTU									
Depth	4/18/13	6/12/13	7/1/13	7/17/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters						Central	Southeast	West	North
0.5	2.6	0.3	2.3	0.6	2.6	9.8	9.0	10.1	10.3
1	2.6								
2	2.7				3.0				
3	2.8	0.3	1.6	0.6		10.5			
4	2.8				2.7				
5	2.6				0.6				
6	2.6	0.3	0.4	1.0	0.4	10.4			
7	2.8								
8	2.8					9.2			
9	2.9	0.5	0.1	1.1	0.4	8.5			
10	3.0				0.4	1.3			
11	3.6					0.5			
12	3.1	0.3	0.3	0.7	0.5	0.4			
13	3.0					0.4			
14	3.0				0.5	0.2			
15	2.9	0.7	1.2	1.6		0.0	0.1	0.5	1.0
16	2.8				0.5				
17	2.7								
18	2.6	0.6	1.0	2.3	0.5	0.1			
19	2.5								
20	2.6				0.6				
21	2.9	1.8	1.5	2.5		0.2			
22	3.0				0.6				
23	2.8								
24	2.9	1.3	1.9	2.8	0.7	0.3			
24.5									
25									
26									

Specific Conductivity µS/cm											
Depth	8/18/10	4/18/13	6/12/13	7/1/13	7/17/13	8/20/12	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters								Central	Southeast	West	North
0.5	70	50	43	44	45	76	86	79	79	79	78
1		49									
2		49					86				
3		49	43	43	45			78			
4		49					78				
5		49					79				
6		49	43	43	44		78	78			
7		49									
8		49						78			
9		49	44	44	44		78	79			
10		50					79	82			
11		49						87			
12		50	45	46	46		85	89			
13		50						93			
14		50					89	94			
15		50	46	46	47			96	96	96	94
16		50					92				
17		50									
18		50	46	47	49		94	99			
19		50									
20		50					96				
21		50	47	47	50			100			
22		50					95				
23		50									
24		50	47	48	51		96	101			
24.5											
25											
26											

pH Units																								
Depth	9/11/01	9/9/02	8/28/03	8/30/04	9/7/05	8/17/06	9/26/07	9/8/08	9/21/09	8/18/10	9/1/10	9/1/11	9/21/11	4/25/12	4/18/13	6/12/13	9/20/12	7/1/13	7/17/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters																					Central	Southeast	West	North
0.5	6.2	6.4	6.3	6.7	6.7	6.5	6.2	6.4	6.3	7.3	6.7	6.6	6.5	6.6	7.7	6.9	7.1	8.6	7.7	9.6	7.2	6.8	7.2	6.9
1															7.7									
2															7.8					9.6				
3	6.3	6.5	6.3	6.5	6.6	6.4	6.2	6.3	5.8		6.0	6.7	6.5	6.9	7.8	6.8	6.9	8.1	8.7		7.4			
4															7.8					8.6				
5															7.8					7.8				
6															7.8	6.5		7.6	8.6	7.2	7.4			
7															7.8									
8															7.8						6.2			
9	5.8	5.8	5.3	6.1	6.2	6.1	6.1	6.1	5.8		6.5	6.2	6.3	6.4	7.8	6.2	6.1	7.0	7.4	6.6	6.2			
10															7.8					6.3	6.1			
11															7.7						6.1			
12															7.2	5.8		6.5	6.2	5.5	5.9			
13															7.1						6.1			
14															7.1					5.3	6.1			
15															7.0	5.8		6.2	5.6		5.5	6.0	6.2	6.4
16															7.0					5.1				
17															7.0									
18															6.9	5.8		6.1	5.2	4.9	5.6			
19															6.9									
20	6.3												6.4		6.9					4.9				
21															6.9	5.8		6.0	5.0		5.7			
22															6.9					4.9				
23															6.9									
24		6.4													6.9	5.8		5.8	5.0	4.9	5.8			
24.5																								
25			5.9	5.9										6.4			6.5							
26					6.3	5.7	6.1	6.3	6.3		6.7	6.0												
26																								

Alkalinity mg/L																			
Depth	9/11/01	9/9/02	8/28/03	8/30/04	9/7/05	8/17/06	9/26/07	9/8/08	9/21/09	9/1/10	9/1/11	9/21/11	4/25/12	9/20/12	4/18/13	6/12/13	7/1/13	7/17/13	8/21/13
meters																			
0.5	2.0	2.0	0.2	4.0	5.0	4.6	2.5	3.0	3.3	3.3	4.0	3.9	3.8	6.0	14.0		5.6		3.2
1																			
2																			
3	2.1	2.0	0.2	3.6	5.0	4.8	2.4	2.9	3.2	3.0	4.0	3.9	4.0	5.3					
4		2.4	0.2	4.0	5.2	4.8	2.4												
5		12.8	0.4	9.7	25.0	7.1	14.5												
6		23.5	25.2	25.0	26.0	26.0	25.5												
7																			
8																			
9	2.6	2.4	0.2	4.0	5.2	4.8	2.4	3.0	3.4	2.9	4.6	3.9	3.7	6.6					
10																			
11		23.5		25.0	26.0	26.0	25.5												
12																			
13																			
14																			
15																			
16																			
17																			
18																			
19																			
20	14.2											14.8							
21																			
22																			
23																			
24		12.8													20.0		5.3		8.7
24.5																			
25			0.4	9.7									4.5	17.7					
26					25.0	7.1	14.5	14.8	20.1	15.4	7.2								

Secchi meters																								
Date	8/16/48	8/7/74	8/12/76	8/27/92	9/11/01	6/8/02	6/23/02	7/6/02	7/21/02	8/5/02	8/19/02	9/9/02	11/13/02	5/10/03	5/27/03	6/12/03	6/25/03	7/13/03	7/28/03	8/13/03	8/28/03	9/26/03	10/14/03	
Depth	7.0	8.5	5.8	6.0	7.3	4.1	4.3	3.8	3.6	1.9	1.3	3.0	2.5	4.3	3.3	4.3	4.3	5.6	4.0	2.7	5.0	4.8	3.6	
Date	10/26/03	5/14/04	5/31/04	6/13/04	6/29/04	7/15/04	8/2/04	8/17/04	8/30/04	9/13/04	10/13/04	10/31/04	11/17/04	5/2/05	5/20/05	6/6/05	6/15/05	7/1/05	7/15/05	8/4/05	8/18/05	9/7/05	5/18/06	
Depth	3.3	5.4	4.6	5.8	5.9	5.2	5.6	3.4	2.3	2.3	2.9	3.0	2.7	3.6	4.8	5.3	4.7	6.2	6.9	5.7	2.5	2.9	3.8	
																					Central	Southeast	West	North
Date	6/16/06	7/15/06	8/17/06	9/27/06	5/3/07	9/26/07	9/8/08	9/8/09	9/21/09	8/18/10	9/1/10	9/1/11	9/21/11	4/25/12	8/20/12	4/18/13	6/12/13	7/1/13	7/17/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
Depth	4.4	4.5	5.3	2.7	4.2	3.5	5.2	4.6	5.2	6.2	5.5	1.2	1.1	1.6	0.5	2.2	4.3	2.6	4.9	0.9	1.6	1.5	1.6	1.6

Dissolved Phosphorus mg/L									
Depth	4/18/13	6/12/13	7/1/13	7/17/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters						Central	Southeast	West	North
0.5			0.012				0.009	0.008	0.008
1	0.015		0.014		0.012	0.012			
2									
3	0.015		0.015		0.013				
4									
5					0.013				
6	0.015		0.014						
7									
8									
9	0.015		0.010		<.005				
10						0.014			
11									
12	0.018		0.012		0.009				
13									
14									
15	0.017		0.017		0.015		0.075	0.100	0.074
16									
17									
18	0.015		0.015		0.010				
19									
20									
21	0.018		0.019		0.014				
22									
23									
24	0.015		0.022		0.017	0.100			
24.5									
25									
26									

ORP					
Depth	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters		Central	Southeast	West	North
0.5	172	79	88	63	-18
1					
2	170				
3		78			
4	185				
5	203				
6	216	80			
7					
8		41			
9	228	24			
10	236	-2			
11		-8			
12	239	79			
13		-10			
14	222	-7			
15		56	64	17	-44
16	211				
17					
18	207	43			
19					
20	209				
21		37			
22	212				
23					
24	214	24			
24.5					
25					
26					

Total Phosphorus mg/L																										
Depth	9/11/01	6/8/02	7/6/02	7/21/02	8/5/02	8/19/02	9/9/02	8/28/03	8/30/04	9/7/05	8/17/06	9/26/07	9/8/08	9/21/09	9/1/10	9/1/11	9/21/11	4/25/12	9/20/12	4/18/13	7/1/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters																							Central	Southeast	West	North
0.5		0.004	0.003	0.013	0.007	0.009	0.009	0.016	0.031	0.008	0.009	0.011	0.005	0.013	0.015	0.008	0.035	0.024	0.023		0.014			0.010	0.012	0.010
1																				0.016	0.017	0.013	0.014			
2																										
3	0.014	0.038	0.002	0.011	0.008	0.008	0.005	0.016	0.016	0.013	0.009	0.013	0.010	0.014	0.009	0.013	0.035	0.027	0.029	0.015	0.017	0.014				
4																										
5																						0.014				
6																				0.016	0.015					
7																										
8																										
9	0.014	0.008	0.010	0.009	0.008	0.008	0.015	0.012	0.028	0.023	0.012	0.013	0.012	0.021	0.011	0.012	0.041	0.029	0.031	0.015	0.013	0.005				
10																							0.014			
11																										
12																				0.019	0.014	0.010				
13																										
14																										
15																				0.017	0.017	0.018		0.076	0.110	0.077
16																										
17																										
18																				0.016	0.016	0.014				
19																										
20	0.178																0.188									
21																				0.020	0.022	0.016				
22																										
23						0.107																				
24		0.011	0.003	0.035	0.067		0.145													0.017	0.024	0.020	0.110			
24.5																										
25								0.099	0.102									0.170	0.032							
26										0.121	0.078	0.146	0.131	0.232	0.015	0.121										

Total Nitrogen mg/L																										
Depth	9/11/01	6/8/02	7/6/02	7/21/02	8/5/02	8/19/02	9/9/02	8/28/03	8/30/04	9/7/05	8/17/06	9/26/07	9/8/08	9/21/09	9/1/10	9/1/11	9/21/11	4/25/12	9/20/12	4/18/13	7/1/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters																							Central	Southeast	West	North
0.5	0.42	0.51	0.16	0.16	0.21	0.23	0.38	0.25	0.46	0.33	0.63	0.34	0.27	0.32	0.65	0.65	0.70	0.52	0.95		0.69			0.67	0.81	0.69
1																				0.47	0.87	0.80	0.66			
2																										
3	0.45	0.56	0.13	0.14	0.21	0.23	0.48	0.27	0.25	0.33	0.51	0.35	0.29	0.30	0.48	0.54	0.66	0.44	0.88	0.52	0.64	0.69				
4																										
5																						0.59				
6																				0.65	0.10					
7																										
8																										
9	0.43	0.56	0.25	0.20	0.21	0.21	0.62	0.33	0.25	0.39	0.56	0.35	0.31	0.30	0.38	0.51	0.63	0.32	0.47	0.58	0.66	0.72				
10																							0.80			
11																										
12																				0.67	0.88	0.70				
13																										
14																										
15																				0.68	0.96	1.08		1.49	1.79	1.49
16																										
17																										
18																				0.62	1.06	0.79				
19																										
20	0.88																0.75									
21																				0.66	1.12	1.38				
22																										
23						0.82																				
24		0.66	0.66	0.79	0.70		1.21	0.00	0.00	0.00	0.00	0.00								0.62	1.17	1.40	1.69			
24.5																										
25								0.87	0.48	0.00	0.00	0.00						0.68	1.02							
26										1.04	0.98	0.83	0.92	1.42	1.07	0.71	0.00									

Nitrate-N mg/L									
Depth	4/18/13	6/12/13	7/1/13	7/17/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters						Central	Southeast	West	North
0.5			0.08				0.07	0.07	0.07
1	0.21		0.17		0.08	0.08			
2									
3	0.19		0.08		0.08				
4									
5					<.01				
6	0.20		0.10						
7									
8									
9	0.19		0.16		0.16				
10						0.14			
11									
12	0.19		0.16		0.12				
13									
14									
15	0.18		0.15		0.08		0.09	0.09	0.09
16									
17									
18	0.18		0.14		0.09				
19									
20									
21	0.18		0.14		0.08				
22									
23									
24	0.18		0.12		0.10	0.09			

Ammonia-N mg/L									
Depth	4/18/13	6/12/13	7/1/13	7/17/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters						Central	Southeast	West	North
0.5			0.03				0.07	0.07	0.04
1	0.10		0.34		0.04	0.03	0.81		0.86
2									
3	0.10		0.08		0.25				
4									
5					0.08				
6	0.13		0.06						
7									
8									
9	0.12		0.10		0.12				
10						0.20			
11									
12	0.15		0.32		0.32				
13									
14									
15	0.17		0.41		0.57		0.81	0.87	0.86
16									
17									
18	0.16		0.58		0.23				
19									
20									
21	0.17		0.63		0.86				
22									
23									
24	0.20		0.58		0.87	1.10			

Total Kjeldahl Nitrogen mg/L									
Depth	4/18/13	6/12/13	7/1/13	7/17/13	8/21/13	10/2/13	10/2/13	10/2/13	10/2/13
meters						Central	Southeast	West	North
0.5			0.61				0.60	0.74	0.62
1	0.26		0.70		0.72	0.58			
2									
3	0.33		0.56		0.61				
4									
5					0.59				
6	0.45		<.2						
7									
8									
9	0.39		0.50		0.56				
10						0.66			
11									
12	0.48		0.72		0.58				
13									
14									
15	0.50		0.81		1.00		1.40	1.70	1.40
16									
17									
18	0.44		0.92		0.70				
19									
20									
21	0.48		0.98		1.30				
22									
23									
24	0.44		1.05		1.30	1.60			

Seepage Measurements:

Date	Map Waypoint	Depth (ft)	Distance from Shore (ft)	Time In	Time Out	Total Time (hr)	Volume (ml)	Volume (L)	L/m2/day	Average of adjecent seepage cell	L/m2/day/2	Seepage cell area	Seepage L/day
7/1/13	S13	2.0	20	2:04 PM	4:08 PM	2.06	250	0.25	11.65		5.8	18750	109223
7/1/13	S14	2.5	25	2:13 PM	4:15 PM	2.03	90	0.09	4.26		2.1	33000	70227
7/1/13	S15	2.5	45	2:22 PM	4:21 PM	1.98	145	0.145	7.03		3.5	33375	117318
7/1/13	S16	3.0	50	2:31 PM	4:27 PM	1.93	115	0.115	5.72	3.95	2.0	15375	30373
7/1/13	S17	3.0	50	2:30 PM	4:29 PM	1.98	45	0.045	2.18		0.0		0
7/2/13	S26	2.0	24	10:31 AM	3:30 PM	5.01	80	0.08	1.53		0.8	40125	30754
7/2/13	S25	2.0	25	10:27 AM	3:27 PM	5.00	130	0.13	2.50		1.2	27000	33696
7/2/13	S24	2.5	25	10:23 AM	3:23 PM	5.00	135	0.135	2.59		1.3	30000	38880
7/2/13	S23	2.5	30	10:17 AM	3:19 PM	5.03	30	0.03	0.57		0.3	33750	9662
7/2/13	S18	2.0	35	9:46 AM	3:01 PM	5.21	70	0.07	1.29		0.6	30375	19589
7/2/13	S19	2.0	40	9:52 AM	3:05 PM	5.05	50	0.05	0.95		0.5	30750	14614
7/2/13	S20	2.5	40	9:56 AM	3:08 PM	5.06	160	0.16	3.04		1.5	28500	43257
7/2/13	S21	2.0	20	10:03 AM	3:11 PM	5.13	70	0.07	1.31		0.7	23250	15228
7/2/13	S22	2.5	30	10:10 AM	3:15 PM	5.08	60	0.06	1.13		0.6	30000	17008
7/2/13	S27	2.0	20	10:35 AM	3:34 PM	4.98	170	0.17	3.28	5.74	2.9	17250	49526
6/11/13	S1	2.0	20	3:08 PM	5:04 PM	1.93	165	0.165	8.21		0.0		0
7/2/13	S28	2.5	28	10:41 AM	3:37 PM	4.93	130	0.13	2.53	4.53	2.3	18375	41650
6/11/13	S2	1.5	15	3:16 PM	5:08 PM	2.13	145	0.145	6.54		0.0		0
7/2/13	S29	2.5	25	10:45 AM	3:40 PM	4.92	210	0.21	4.10	5.59	2.8	9750	27250
6/11/13	S3	2.5	27	3:25 PM	5:15 PM	1.83	135	0.135	7.08		0.0		0
6/11/13	S4	1.5	20	3:30 PM	5:19 PM	1.81	225	0.225	11.93		6.0	8250	49227
6/11/13	S5	3.0	35	5:28 PM	9:45 AM	16.28	135	0.135	0.80		0.4	10500	4179
6/12/13	S6	2.0	30	10:00 AM	2:12 PM	4.20	50	0.05	1.14		0.6	53250	30429
6/12/13	S7	2.5	30	10:07 AM	2:18 PM	4.18	145	0.145	3.33		1.7	36375	60567
6/12/13	S8	2.5	22	10:13 AM	2:23 PM	4.16	155	0.155	3.58		1.8	20625	36887
6/12/13	S9	2.0	30	10:22 AM	2:27 PM	4.08	145	0.145	3.41		1.7	16500	28147
6/12/13	S10	3.0	40	10:53 AM	2:41 PM	4.20	40	0.04	0.91		0.5	31125	14229
6/12/13	S11	2.5	23	11:00 AM	2:46 PM	3.76	40	0.04	1.02		0.5	19875	10149
6/12/13	S12	2.0	35	11:16 AM	3:03 PM	3.78	105	0.105	2.67		1.3	21750	29000

Plankton Raw Data:

	PHYTOPLANKTON BIOMASS (UG/L)							
	Cliff	Cliff	Cliff	Boat Conc.	Boat launch	Cliff	Cliff	Cliff
	CP-1	CP-1	CP-1	CP-1	CP-1	CP-1	CP-1	CP-1
TAXON	**04/18/13**	**06/13/13**	**07/01/13**	**07/01/13**	**07/01/13**	**07/17/13**	**08/21/13**	**10/02/13**
BACILLARIOPHYTA								
Centric Diatoms								
Aulacoseira	0.0	140.9	0.0	0.0	0.0	0.0	0.0	0.0
Cyclotella	0.0	0.0	0.0	0.0	0.0	3.4	0.0	0.0
Araphid Pennate Diatoms								
Asterionella	7.2	13.9	0.0	0.0	0.0	0.0	0.0	0.0
Synedra	14.4	13.9	67.2	0.0	16.5	13.7	0.0	0.0
Tabellaria	280.8	27.8	0.0	0.0	0.0	0.0	0.0	0.0
Monoraphid Pennate Diatoms								
Biraphid Pennate Diatoms								
Nitzschia	0.0	0.0	0.0	0.0	16.5	0.0	0.0	0.0
CHLOROPHYTA								
Flagellated Chlorophytes								
Chlamydomonas	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0
Coccoid/Colonial Chlorophytes								
Ankistrodesmus	0.0	0.0	12.6	0.0	4.1	0.0	0.0	0.0
Closteriopsis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coelastrum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Golenkinia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kirchneriella	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oocystis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Paulschulzia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pediastrum	0.0	0.0	0.0	0.0	57.7	0.0	0.0	0.0
Scenedesmus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Schroederia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sphaerocystis	0.0	83.5	134.4	92.8	49.4	246.2	0.0	0.0
Filamentous Chlorophytes								
Desmids								
Closterium	0.0	0.0	84.0	0.0	0.0	0.0	0.0	0.0
Cosmarium	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Staurastrum	14.4	13.9	0.0	0.0	0.0	0.0	0.0	12.5
Staurodesmus	16.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CHRYSOPHYTA								
Flagellated Classic Chrysophytes								
Chrysococcus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dinobryon	54.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mallomonas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Synura	57.6	27.8	16.8	0.0	0.0	0.0	0.0	0.0
Non-Motile Classic Chrysophytes								
Haptophytes								
Tribophytes/Eustigmatophytes								
Centritractus	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tribonema	34758.0	1921.0	531.3	200.1	615.9	78.7	0.0	0.0
Raphidophytes								
Gonyostomum and related taxa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

CRYPTOPHYTA								
Cryptomonas	0.0	48.7	42.0	92.8	111.2	3.4	3.8	0.0
CYANOPHYTA								
Unicellular and Colonial Forms								
Aphanocapsa	0.0	0.0	0.0	58.0	0.0	0.0	0.0	0.0
Gomphosphaeria	0.0	0.0	0.0	0.0	33.0	0.0	0.0	0.0
Microcystis	0.0	26.1	0.0	0.0	0.0	0.0	0.0	0.0
Filamentous Nitrogen Fixers								
Anabaena	0.0	0.0	126.0	0.0	0.0	0.0	0.0	0.0
Aphanizomenon	0.0	0.0	0.0	75.4	53.6	88.9	15519.4	10324.5
Other Filamentous Bluegreens (L)	0.0	0.0	63.0	2610.0	164.8	0.0	0.0	0.0
Filamentous Non-Nitrogen Fixers								
Planktolyngbya	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pseudanabaena	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.7
EUGLENOPHYTA								
Trachelomonas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.6
PYRRHOPHYTA								
Peridinium	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BIOMASS (UG/L) SUMMARY								
BACILLARIOPHYTA	**302.4**	**196.6**	**67.2**	**0.0**	**33.0**	**17.1**	**0.0**	**0.0**
Centric Diatoms	0.0	140.9	0.0	0.0	0.0	3.4	0.0	0.0
Araphid Pennate Diatoms	302.4	55.7	67.2	0.0	16.5	13.7	0.0	0.0
Monoraphid Pennate Diatoms	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Biraphid Pennate Diatoms	0.0	0.0	0.0	0.0	16.5	0.0	0.0	0.0
CHLOROPHYTA	**30.6**	**97.4**	**231.0**	**92.8**	**111.2**	**246.2**	**1.9**	**12.5**
Flagellated Chlorophytes	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0
Coccoid/Colonial Chlorophytes	0.0	83.5	147.0	92.8	111.2	246.2	0.0	0.0
Filamentous Chlorophytes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Desmids	30.6	13.9	84.0	0.0	0.0	0.0	0.0	12.5
CHRYSOPHYTA	**34872.3**	**1948.8**	**548.1**	**200.1**	**615.9**	**78.7**	**0.0**	**0.0**
Flagellated Classic Chrysophy	111.6	27.8	16.8	0.0	0.0	0.0	0.0	0.0
Non-Motile Classic Chrysophyt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Haptophytes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tribophytes/Eustigmatophytes	34760.7	1921.0	531.3	200.1	615.9	78.7	0.0	0.0
Raphidophytes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CRYPTOPHYTA	**0.0**	**48.7**	**42.0**	**92.8**	**111.2**	**3.4**	**3.8**	**0.0**
CYANOPHYTA	**0.0**	**26.1**	**189.0**	**2743.4**	**251.3**	**88.9**	**15519.4**	**10329.2**
Unicellular and Colonial Forms	0.0	26.1	0.0	58.0	33.0	0.0	0.0	0.0
Filamentous Nitrogen Fixers	0.0	0.0	189.0	2685.4	218.4	88.9	15519.4	324.5
Filamentous Non-Nitrogen Fixe	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.7
EUGLENOPHYTA	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**15.6**
PYRRHOPHYTA	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
TOTAL	**35205.3**	**2317.7**	**1077.3**	**3129.1**	**1122.7**	**434.3**	**15525.0**	**10357.2**
BIOMASS DIVERSITY	**0.04**	**0.34**	**0.71**	**0.30**	**0.66**	**0.50**	**0.00**	**0.17**
BIOMASS EVENNESS	**0.04**	**0.34**	**0.75**	**0.39**	**0.66**	**0.64**	**0.00**	**0.29**
	04/18/13	**06/13/13**	**07/01/13**	**07/01/13**	**07/01/13**	**07/17/13**	**08/21/13**	**10/02/13**
BIOMASS (UG/L) SUMMARY								
BACILLARIOPHYTA	302	197	67	0	33	17	0	0
CHLOROPHYTA	31	97	231	93	111	246	2	12
CHRYSOPHYTA	34872	1949	548	200	616	79	0	0
CRYPTOPHYTA	0	49	42	93	111	3	4	0
CYANOPHYTA	0	26	189	2743	251	89	15519	329
EUGLENOPHYTA	0	0	0	0	0	0	0	16
PYRRHOPHYTA	0	0	0	0	0	0	0	0

	ZOOPLANKTON BIOMASS (UG/L)						
	Cliff	**Cliff**	**Cliff**	**Cliff**	**Cliff**	**Cliff**	
TAXON	**4/18/13**	**6/12/13**	**7/1/13**	**7/17/13**	**8/21/13**	**10/2/13**	
PROTOZOA							
Ciliophora	0.0	0.0	0.0	0.0	0.0	0.0	
ROTIFERA							
Asplanchna	0.4	0.0	0.0	0.0	0.0	0.0	
Conochilus	0.1	0.0	0.0	0.0	0.0	0.0	
Kellicottia	0.0	0.0	0.1	0.1	0.1	0.0	
Keratella	0.0	0.0	0.0	0.0	0.0	0.0	
COPEPODA							
Copepoda-Cyclopoida							
Cyclops	0.0	0.0	2.6	0.0	0.0	0.5	
Mesocyclops	2.1	2.2	1.8	2.6	11.7	7.0	
Copepoda-Calanoida							
Diaptomus	14.0	36.3	19.3	32.4	14.6	10.8	
Copepoda-Harpacticoida	0.0	0.0	0.0	0.0	0.0	0.0	
Other Copepoda-Adults	0.0	0.0	0.0	0.0	0.0	0.0	
Other Copepoda-Copepodites	0.0	0.0	0.0	0.0	0.0	0.0	
Other Copepoda-Nauplii	10.0	11.3	7.8	11.0	4.7	13.6	
CLADOCERA							
Bosmina	0.0	0.5	0.2	0.0	0.0	0.0	
Daphnia ambigua	4.1	7.5	2.4	0.2	0.0	0.0	
Daphnia pulex	23.8	0.5	0.5	0.6	9.1	0.0	
Diaphanosoma	0.0	0.0	5.0	41.6	12.0	15.0	
Leptodora	0.0	21.0	17.6	21.8	26.8	0.0	
OTHER ZOOPLANKTON							
Bryozoa	0.0	0.0	0.0	0.0	0.0	0.0	
Chaoboridae	0.0	0.0	0.0	0.0	0.0	0.0	
Chironomidae	0.0	0.0	0.0	0.0	0.0	0.0	
Coelentarata	0.0	0.0	0.0	0.0	0.0	0.0	
Culicidae	0.0	0.0	0.0	0.0	0.0	0.0	
Eubranchiopoda	0.0	0.0	0.0	0.0	0.0	0.0	
Gastrotrichia	0.0	0.0	0.0	0.0	0.0	0.0	
Hydracarina	0.0	0.0	0.0	0.0	0.0	0.0	
Mysidacea	0.0	0.0	0.0	0.0	0.0	0.0	
Nematoda	0.0	0.0	0.0	0.0	0.0	0.0	
Ostracoda	0.0	0.0	0.0	0.0	0.0	0.0	
Other Zooplankton #1	0.0	0.0	0.0	0.0	0.0	0.0	
Other Zooplankton #2	0.0	0.0	0.0	0.0	0.0	0.0	
Other Zooplankton #3	0.0	0.0	0.0	0.0	0.0	0.0	
SUMMARY STATISTICS							
BIOMASS	**4/18/13**	**6/12/13**	**7/1/13**	**7/17/13**	**8/21/13**	**10/2/13**	
PROTOZOA	0.0	0.0	0.0	0.0	0.0	0.0	
ROTIFERA	0.5	0.0	0.1	0.1	0.1	0.0	
COPEPODA	26.2	49.7	31.5	46.0	30.9	31.9	
CLADOCERA	27.9	29.5	25.7	64.2	47.9	15.0	
OTHER ZOOPLANKTON	0.0	0.0	0.0	0.0	0.0	0.0	
TOTAL ZOOPLANKTON	54.6	79.2	57.3	110.4	78.9	46.9	
MEAN LENGTH (mm): ALL FORMS	0.61	0.68	0.64	0.73	0.70	0.73	
MEAN LENGTH: CRUSTACEANS	0.68	0.73	0.73	0.81	0.82	0.75	

Chlorophyll a, Phaeo a and Total Chlorophyll a Data:

Depth	Chlorophyll a ugL													
meters	9/11/01	9/9/02	8/28/03	8/30/04	9/7/05	8/17/06	9/26/07	9/8/08	9/21/09	9/1/10	9/1/11	9/21/11	4/25/12	9/20/12
0.5	5.8	11.0	1.5	7.7	10.5	2.4	5.5	3.8	2.0	5.4	41.7	16.9	19.7	31.4
1														
2														
3	7.1	10.4	1.4	12.0	12.2	3.2	5.4	4.7	2.5	1.0	45.9	18.7	23.3	27.0
4														
5														
6														
7														
8			4.6											
9	2.8	2.5		28.1	14.1	3.8	6.2	17.5	9.2		0.6	14.2	14.7	0.9
10														
11														
12														
13														
14														
15														
16														
17														
18														
19														
20	1.0											1.0		
21														
22														
23		1.8												
24														
24.5														
25			1.6	1.6									8.8	0.4
26					3.1	1.7	6.2	1.0	<0.05	2.0	1.7			

Depth	**Phaeo (ug/L)**													
meters		9/9/02	8/28/03	8/30/04	9/7/05	8/17/06	9/26/07	9/8/08	9/21/09	9/1/10	9/1/11	9/21/11	4/25/12	9/20/12
0.5		0.1	0.0	1.5	0.6	0.5	1.0	0.3	0.6	<0.05	3.5	2.4	<0.05	3.0
1														
2														
3		0.1	0.0	0.0	0.4	0.0	1.2	<0.05	1.3	<0.05	2.3	1.6	3.0	12.2
4														
5														
6														
7														
8			0.8	0.0										
9		2.2		6.5	1.0	0.6	1.8	1.8	0.9		1.4	1.2	4.6	3.6
10														
11														
12														
13														
14														
15														
16														
17														
18														
19														
20												2.6		
21														
22														
23		3.4												
24														
24.5														
25			4.0										3.6	3.9
26					7.2	3.3	6.5	8.8	14.1	9.1	3.1			

Total Chlorophyll a ug/L (chl-a + phaeo)

Depth	9/9/02	8/28/03	8/30/04	9/7/05	8/17/06	9/26/07	9/8/08	9/21/09	9/1/10	9/1/11	9/21/11	4/25/12	9/20/12
meters													
0.5	11.1	1.5	9.2	11.0	2.8	6.5	4.1	2.6	5.4	45.1	19.2	19.7	34.4
1													
2													
3	10.5	1.4		12.6	3.2	6.6	4.8	3.8	1.0	48.1	20.3	26.3	39.2
4													
5													
6													
7													
8		5.4											
9	4.6		34.6	15.2	4.4	8.1	19.3	10.1		2.0	15.4	19.2	4.5
10													
11													
12													
13													
14													
15													
16													
17													
18													
19													
20											3.7		
21													
22													
23	5.2												
24													
24.5													
25		5.6	1.6									12.4	4.4
26				10.3	5.1	12.7	9.9	14.2	11.1	4.7			

APPENDIX B: Calculations and Analyses

Oxygen Demand Calculation

	4/18/2013	5/3/2013	6/4/2013	6/13/2013	6/28/2013
Depth	DO	D.O.	D.O.	DO	D.O.
meters	mg/l	mg/L	mg/L	mg/l	mg/L
1	12.8	11.99	9.25	9.8	9.27
2	12.9	11.87	9.23	9.8	9.18
3	12.8	11.79	9.48	9.8	9.01
4	12.8	11.75	9.51	9.8	9.38
5	12.9	12.84	9.51	9.8	9.27
6	12.9	12.71	10.63	9.8	9.78
7	12.9	12.48	10.84	10.0	9.30
8	12.9	12.29	11.66	10.2	9.84
9	12.9	12.1	12.33	10.3	9.67
10	13.1	11.56	9.33	8.3	8.84
11	12.9	11.11	7.06	6.2	6.56
12	12.3	10.29	6.58	4.2	3.89
13	12.2	9.83	5.18	3.8	2.17
14	12.2	9.84	5.09	3.3	1.59
15	12.2	9.8	4.62	2.8	1.31
16	12.2	9.8	4.21	2.7	1.19
17	12.2	10.08	4.07	2.6	1.08
18	12.3	9.98	3.49	2.4	0.53
19	12.4	9.95	0.28	2.3	0.44
20	12.4	9.76	0.60	2.3	0.39
21	12.3	9.82	0.50	2.2	0.44
22	12.3	9.76	0.43	2.2	0.28
23	12.3	0.34	0.40	2.1	0.27

	4/18/2013	5/3/2013	6/4/2013	6/13/2013	
	5/3/2013	6/4/2013	6/13/2013	6/28/2013	
	DO diff	DO diff	DO diff	DO diff	
	mg/L	mg/L	mg/L	mg/L	
	0.82	2.74	-0.51	0.49	
	0.98	2.64	-0.53	0.58	
	1.03	2.31	-0.31	0.78	
	1.05	2.24	-0.28	0.41	
	0.02	3.33	-0.28	0.52	
	0.18	2.08	0.82	0.03	
	0.44	1.64	0.84	0.70	
	0.63	0.63	1.51	0.31	
	0.80	-0.23	1.99	0.67	
	1.53	2.23	1.03	-0.54	
	1.80	4.05	0.86	-0.36	
	2.01	3.71	2.38	0.31	
	2.39	4.65	1.38	1.63	
	2.37	4.75	1.79	1.71	
	2.40	5.18	1.79	1.52	
	2.40	5.59	1.56	1.46	
	2.14	6.01	1.52	1.47	
	2.32	6.49	1.07	1.89	
	2.45	9.67	-2.02	1.86	
	2.62	9.16	-1.65	1.86	
	2.46	9.32	-1.66	1.72	
	2.50	9.33	-1.72	1.87	
	11.99	-0.06	-1.69	1.82	
Total O2 loss	47.33	97.46	7.89	22.71	mg/L
>10 m O2 loss	41.38	80.08	4.64	18.22	mg/L
Days between	15	32	9	15	days
DO demand (>10 m)	2.76	2.50	0.52	1.21	g/m2/d

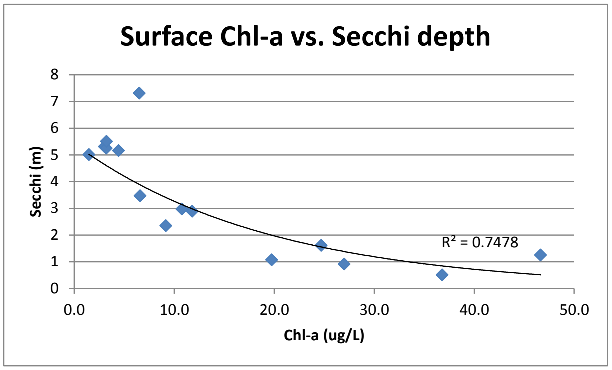
	4/18/2013	5/3/2013	6/4/2013	6/13/2013	6/28/2013
Depth	Temp	Temp	Temp	Temp	Temp
meters	°C	°C	°C	°C	°C
1	10.0	14.8	21.1	20.4	24.7
2	10.0	14.8	21.0	20.4	24.7
3	9.9	14.8	21.0	20.4	24.6
4	9.9	14.7	20.9	20.4	24.2
5	9.9	12.7	20.9	20.4	23.6
6	9.7	11.7	18.5	20.3	21.8
7	9.6	11.3	17.6	17.8	20.0
8	9.6	11.1	15.3	15.4	18.3
9	9.6	10.8	12.6	12.9	15.9
10	8.8	10.6	10.6	11.6	12.7
11	8.4	10.3	9.8	10.4	11.4
12	7.3	10	9.6	9.2	10.6
13	7.1	9.6	9.2	8.9	9.8
14	7.0	9	8.8	8.6	9.4
15	7.0	8.7	8.6	8.3	9.1
16	7.0	8.4	8.2	8.2	8.9
17	7.0	8	8.1	8.1	8.8
18	7.0	7.7	8.1	8.0	8.7
19	7.0	7.7	8.1	8.0	8.6
20	6.9	7.7	8.1	7.9	8.5
21	6.9	7.6	8.1	7.8	8.5
22	6.9	7.6	8.1	7.8	8.5
23	6.9	7.6	8.1	7.8	8.5

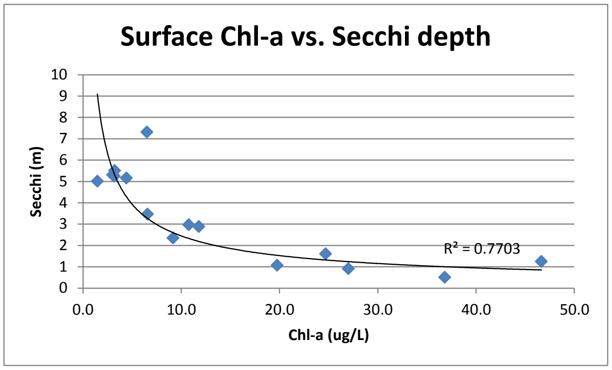
Empirical Models for Current Conditions

THE TERMS				
SYMBOL	**PARAMETER**	**UNITS**	**DERIVATION**	**VALUE**
TP	Lake Total Phosphorus Conc.	ppb	From data or model	23
L	Phosphorus Load to Lake	g P/m2/yr	From data or model	0.189
TPin	Influent (Inflow) Total Phosphorus	ppb	From data	24.6
TPout	Effluent (Outlet) Total Phosphorus	ppb	From data	13
I	Inflow	m3/yr	From data	1374700
A	Lake Area	m2	From data	827000
V	Lake Volume	m3	From data	7300000
Z	Mean Depth	m	Volume/area	8.827086
F	Flushing Rate	flushings/yr	Inflow/volume	0.188315
S	Suspended Fraction	no units	Effluent TP/Influent TP	0.528455
Qs	Areal Water Load	m/yr	Z(F)	1.662273
Vs	Settling Velocity	m	Z(S)	4.66472
R	Retention Coefficient (from TP)	no units	(TPin-TPout)/TPin	0.471545
Rp	Retention Coefficient (settling rate)	no units	((Vs+13.2)/2)/(((Vs+13.2)/2)+Qs)	0.843102
Rlm	Retention Coefficient (flushing rate)	no units	1/(1+F^0.5)	0.697373
	ADDENDUM FOR NITROGEN			
TN	Lake Total Nitrogen Conc.	ppb	From data or model	839
L	Nitrogen Load to Lake	g N/m2/yr	From data or model	1.57
C	Coefficient of Attenuation	fraction/yr	2.7183^(0.5541(ln(F))-0.367)	0.274678

THE MODELS					***LOAD ANALYSIS***			***PREDICTED WATER CLARITY***		
		PREDICTION			**ESTIMATED**					
		CONC.	**LOAD**			**LOAD**		***PREDICTED CHL AND WATER CLARITY***		
NAME	**FORMULA**	**(ppb)**	**(g/m2/yr)**		**MODEL**	**(kg/yr)**				
Mass Balance	TP=L/(Z(F))*1000	114			***Phosphorus***					
(minimum load)	L=TP(Z)(F)/1000		0.04		Mass Balance (no loss)	32		**MODEL**	**Value**	**Mean**
Kirchner-Dillon 1975	TP=L(1-Rp)/(Z(F))*1000	18								
(K-D)	L=TP(Z)(F)/(1-Rp)/1000		0.24		Kirchner-Dillon 1975	202		**Mean Chlorophyll (ug/L)**		
Vollenweider 1975	TP=L/(Z(S+F))*1000	30						Carlson 1977	8.5	
(V)	L=TP(Z)(S+F)/1000		0.15		Vollenweider 1975	120		Dillon and Rigler 1974	7.1	
Reckhow 1977 (General)	TP=L/(11.6+1.2(Z(F)))*1000	14						Jones and Bachmann 1976	8.2	
(Rg)	L=TP(11.6+1.2(Z(F)))/1000		0.31		Reckhow 1977 (General)	259		Oglesby and Schaffner 1978	10.6	
Larsen-Mercier 1976	TP=L(1-Rlm)/(Z(F))*1000	34						Modified Vollenweider 1982	11.6	9.2
(L-M)	L=TP(Z)(F)/(1-Rlm)/1000		0.13		Larsen-Mercier 1976	104		**Peak Chlorophyll (ug/L)**		
Jones-Bachmann 1976	TP=0.84(L)/(Z(0.65+F))*1000	21						Modified Vollenweider (TP) 1982	35.2	
(J-B)	L=TP(Z)(0.65+F)/0.84/1000		0.20		Jones-Bachmann 1976	168		Vollenweider (CHL) 1982	25.4	
								Modified Jones, Rast and Lee 1979	29.4	30.0
verage of Model Values		23			Model Average			**Secchi Transparency (M)**		
(without mass balance)			0.21		(without mass balance)	170		Oglesby and Schaffner 1978 **(Avg)**	2.1	
								Modified Vollenweider 1982 **(Max)**	4.0	
Reckhow 1977 (Anoxic)	TP=L/(0.17(Z)+1.13(Z(F)))*1000	56								
(Ra)	L=TP(0.17(Z)+1.13(Z(F)))/1000		0.08		Reckhow 1977 (Anoxic)	64		**Bloom Probability**		
								Probability of Chl >10 ug/L **(% of summer)**	33.7%	
From Vollenweider 1968								Probability of Chl >15 ug/L **(% of summer)**	10.9%	
Permissible Load	Lp=10^(0.501503(log(Z(F)))-1.0018)		0.13		Permissible Load	106		Probability of Chl >20 ug/L **(% of summer)**	3.5%	
Critical Load	Lc=2(Lp)		0.26		Critical Load	213		Probability of Chl >30 ug/L **(% of summer)**	0.4%	
								Probability of Chl >40 ug/L **(% of summer)**	0.1%	
Mass Balance	TN=L/(Z(F))*1000	944			***Nitrogen***					
(minimum load)	L=TN(Z)(F)/1000		1.39		Mass Balance (no loss)	1153				
Bachmann 1980	TN=L/(Z(C+F))*1000	384								
	L=TN(Z)(C+F)/1000		3.43		Bachmann 1980	2836				

Relationships between key WQ variables


Surface Chl-a vs. Secchi depth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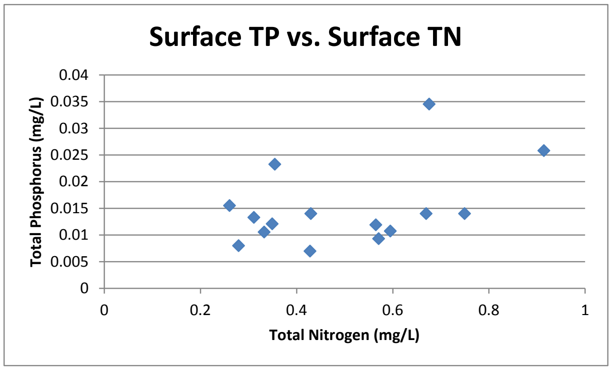
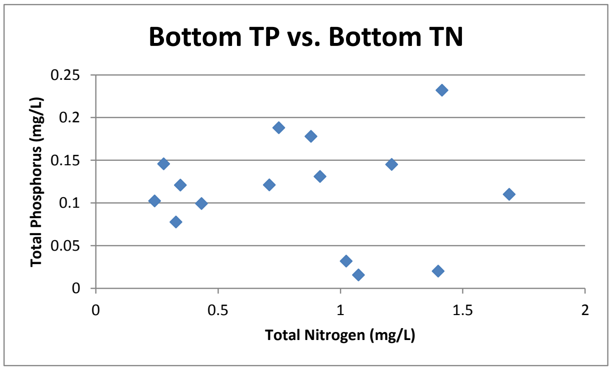
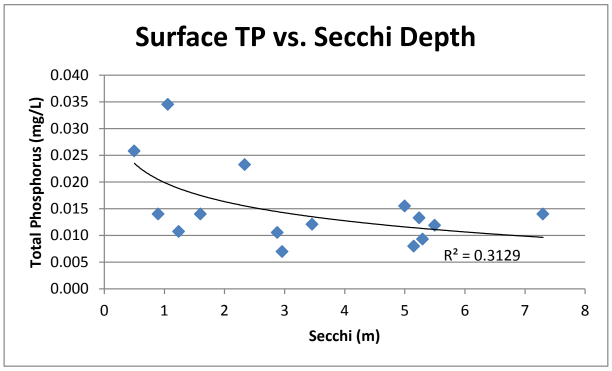
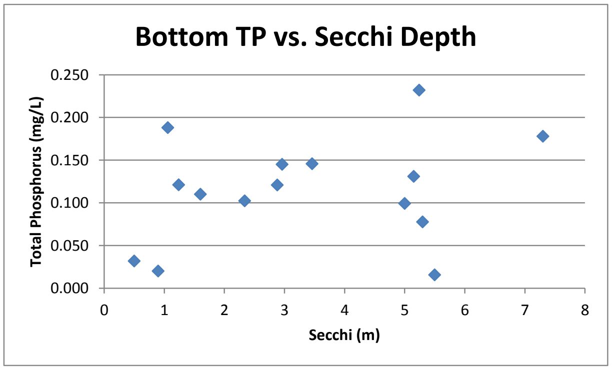
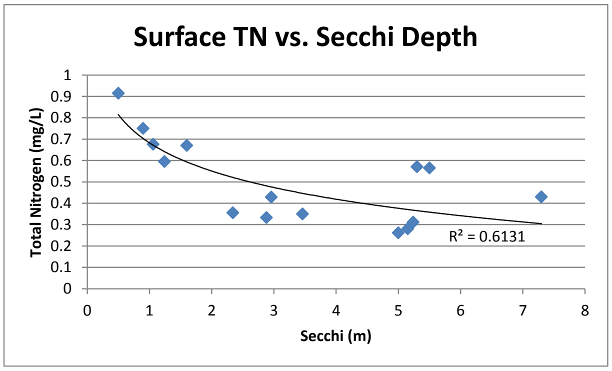
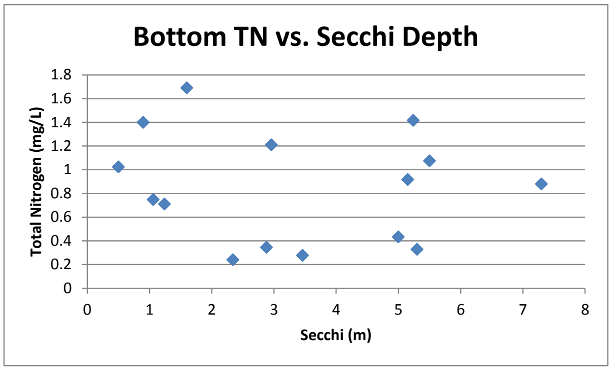

Surface TP vs. Surface TN

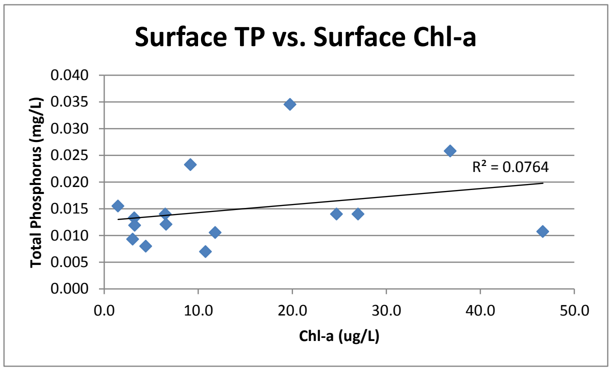

Bottom TP vs. Bottom TN

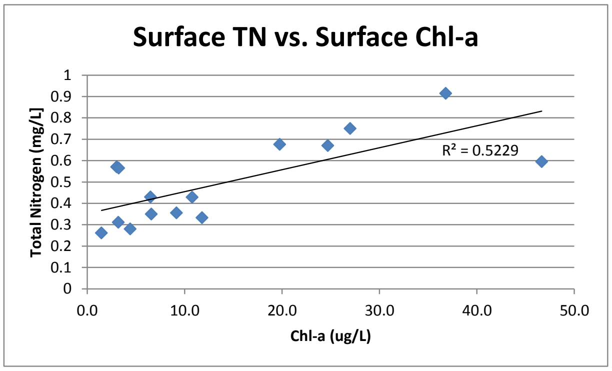

Surface TP vs. Secchi Depth

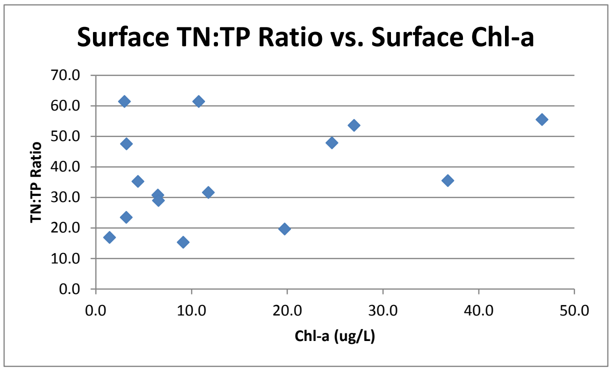

Bottom TP vs. Secchi Depth

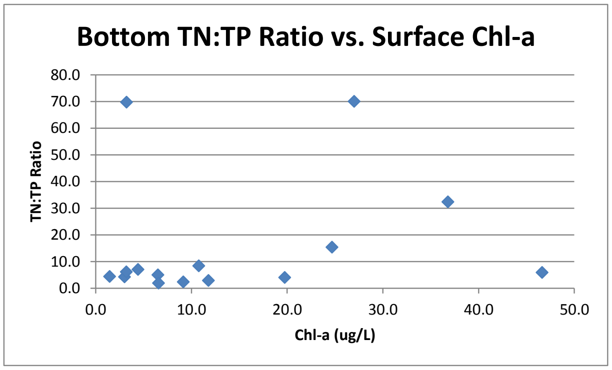

Surface TN vs. Secchi Depth
Total Nitrogen (mg/L)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
8
Secchi (m)
R² = 0.6131

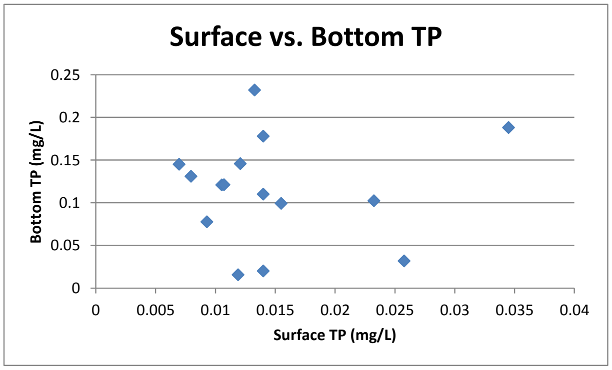

Bottom TN vs. Secchi Depth
Total Nitrogen (mg/L)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
Secchi (m)

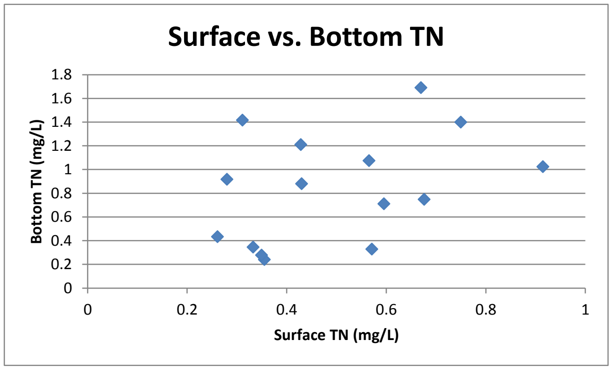

Surface TP vs. Surface Chl-a
Total Phosphorus (mg/L)
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.0
10.0
20.0
30.0
40.0
50.0
Chl-a (ug/L)
R² = 0.0764


Surface TN vs. Surface Chl-a
Total Nitrogen (mg/L)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.0
10.0
20.0
30.0
40.0
50.0
Chl-a (ug/L)
R² = 0.5229


Surface TN:TP Ratio vs. Surface Chl-a
TN:TP Ratio
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
Chl-a (ug/L)


Bottom TN:TP Ratio vs. Surface Chl-a
TN:TP Ratio
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
Chl-a (ug/L)


Surface vs. Bottom TP
Bottom TP (mg/L)
0.25
0.2
0.15
0.1
0.05
0
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
Surface TP (mg/L)


Surface vs. Bottom TN
Bottom TN (mg/L)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
Surface TN (mg/L)