Mirror Lake

2016 Water Quality Report

AUSABLE RIVER Association

ADIRONDACK WATERSHED INSTITUTE
PAUL SMITH'S COLLEGE

Acknowledgments

This project was supported with funding provided by the New York State Department of State under Title 11 of the Environmental Protection Fund, Mirror Lake Watershed Association, Town of North Elba, Village of Lake Placid, and IRONMAN Foundation. We would also like to thank the Lake Placid Shore Owners' Association for funding the early water quality testing on Mirror Lake and Lake Placid. Without this work, we would not be able to put the current state of Mirror Lake in the context of a longer time frame. Finally, we would like to thank Paul Smith's College Adirondack Watershed Institute (AWI) for years of commitment to understanding and monitoring Adirondack water bodies. Three sets of data from Paul Smith's College classes are included in this report. AWI is committed to advancing research on Mirror Lake and has provided multiple in-kind services to this project.

We would also like to acknowledge the Adirondack Mountain Club for co-running a five-day teen aquatic stewardship program with the Ausable River Association. As part of this program, high-school age youth conduct a comparative study of Mirror Lake and Heart Lake. Photographs on pages 4, 10, and 25 show participants in this program participating in water quality data collection on Mirror Lake. We appreciate and thank the many youth that have participated in this program.

Cover photo by Larry Master, all other photos by Brendan Wiltse.

This report was prepared with funding provided by the New York State Department of State under Title 11 of the Environmental Protection Fund.

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2016 Water Quality Report

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Please cite this work as: Wiltse, B., Yerger, E.C., Pionteck, N.C., & Laxson, C.L. 2017. Mirror Lake 2016 Water Quality Report. Ausable River Association, Wilmington.

Executive Summary

Mirror Lake has been enrolled in a variety of water quality monitoring programs over the past 45 years. These range from citizen volunteer water quality monitoring programs to studies conducted by a variety of contractors and researchers. The purpose of this report is to summarize all the available water quality data on Mirror Lake to develop a comprehensive understanding of the current state of the lake. This report will serve as the basis for future decisions on how best to continue to monitor the health of Mirror Lake, and how to develop effective programs to reduce water quality impairments. Report highlights include:

1. There are challenges with comparing historical data to current monitoring efforts due to inconsistency in sampling methodology, frequency, and location over time. Developing a rigorous, methodologically sound, monitoring program is important to understanding future and ongoing changes in the health of Mirror Lake.
2. Measures of the lake's trophic status (total phosphorus, nitrate, chlorophyll-*a*, transparency, and trophic state index) do not show significant long-term trends. Earlier reports of increasing total phosphorus may be the result of inconsistency in sampling location.
3. The lake experiences seasonal anoxia (no oxygen) in the bottom waters during the summer stratified period. There is not enough long-term data to assess whether this a natural condition of the lake or the result of urban development in the watershed. This condition, coupled with potentially longer periods of stratification, may pose a long-term threat to the lake trout population.
4. Calcium concentrations are higher today than measurements made in 1971. Current concentrations are within the reported ranged need to support a viable zebra mussel population.
5. There are significant long-term trends of increasing sodium and chloride in the lake. Concentrations are 9- and 11-times higher than the early 1970s, and 52- and 239-times higher than Adirondack lakes not impacted by road salt, respectively. Chloride builds up in the bottom waters of the lake during winter and spring.
6. Stormwater directly entering the lake through outfalls contributes high concentrations of total suspended solids, chloride, and total phosphorus to the lake. High concentrations of all three parameters are found at locations that drain state maintained roads and areas that drain village and town maintained roads and sidewalks.

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Introduction

Mirror Lake is an iconic Adirondack waterbody located directly adjacent to downtown Lake Placid. The lake is a focal point for activities in the Village of Lake Placid. In the summer months, residents and visitors ply the waters in canoes, kayaks, and stand up paddle boards or swim at the public beach. The lake is home to the swim portion of the IRONMAN triathlon held each year in Lake Placid. In the winter months, there is a flurry of activity including ice skating, hockey tournaments, tobogganing, and dog sled rides. Throughout the year, Mirror Lake serves as a valuable resource to the Village of Lake Placid.

Mirror Lake is in western Essex County in the Town of North Elba and Village of Lake Placid. The lake has a surface area of 50 ha (124 acres) and watershed area of 301 ha (741 acres). The watershed is mostly covered by several forest types (Figure 1; Table 1). Although, 27% of the total watershed area is developed. The percentage of developed area rises to 34% if we only consider land area (Table 1). Much of the developed area is covered in impervious surfaces (Figure 2). Mirror Lake has over twice the percentage of developed land compared to any other lake in the Adirondack Lake Assessment Program (ALAP; Laxson et al. 2016). As a more direct comparison, 1% of Lake Placid's watershed is developed, and 8% of the Lake George's watershed is developed (Laxson et al. 2015; The Lake George Association 2016). When viewed in the context of other Adirondack lakes, Mirror Lake is one of the most developed lakes in the Adirondack Park.

The headwaters of the watershed include Echo Lake which drains into the north bay of Mirror Lake. This upstream portion of the watershed is mostly forested. Downstream, in the areas surrounding Mirror Lake, much of the land is developed (Figure 1). The lake drains to the south, into the Chubb River which flows into the West Branch of the Ausable River. Mirror Lake's outlet stream has been manipulated to run underground for much of its length and is connected to a network of storm drains. The outlet comes above ground just before it enters the Chubb River at Mill Pond.

The entire shoreline of the lake is developed and encompassed by roads. 1.1 km (0.68 mi) of state roadway and 7.6 km (4.72 mi) of local roadway drain into Mirror Lake. For the most part, the roads and impervious surfaces around the lake flow directly into the lake through more than 20 stormwater outfalls. The Village of Lake Placid, with the encouragement of the Mirror Lake Watershed Association, has been proactive in installing hydrodynamic separator units for stormwater from the streets around

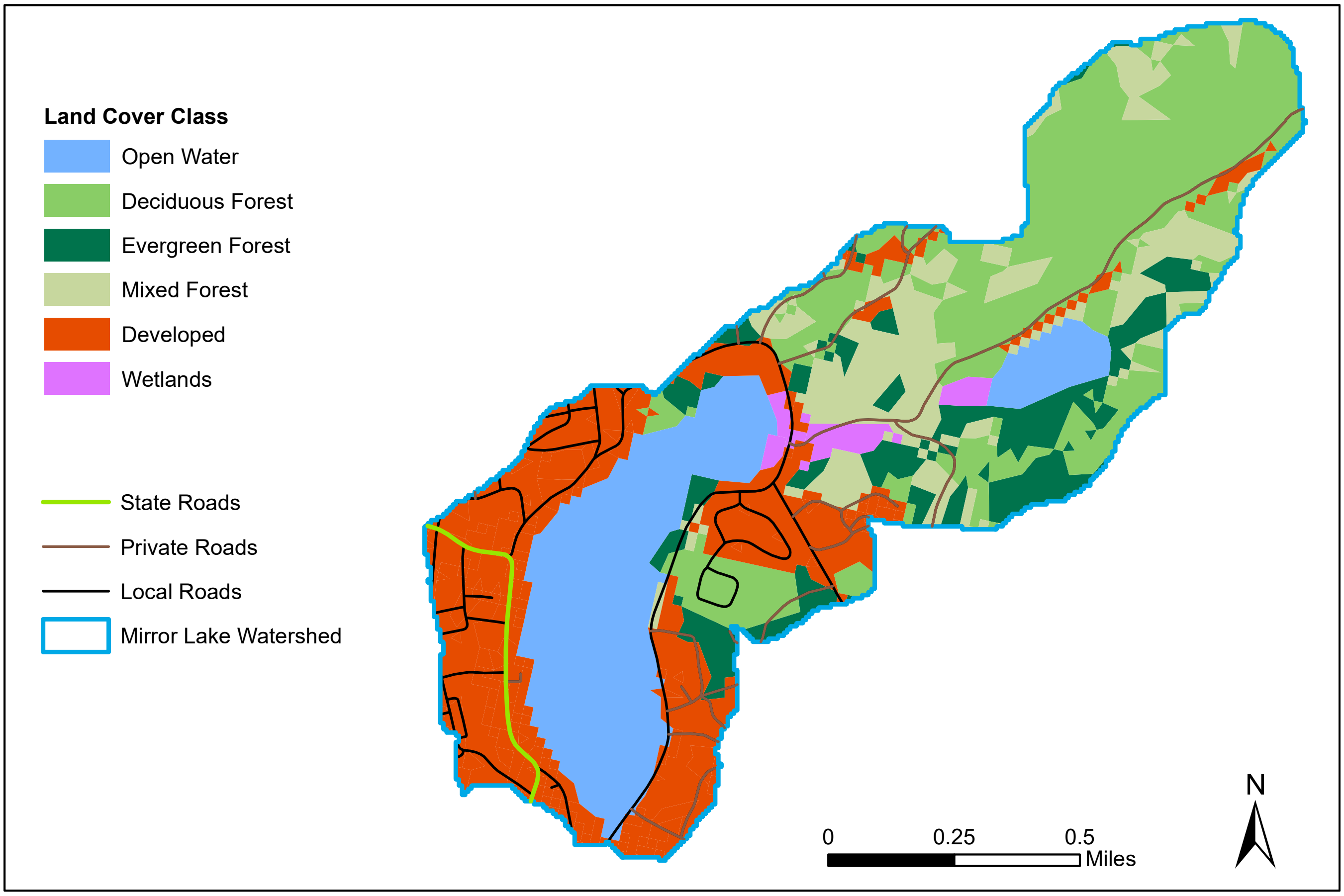

Figure 1. Distribution of land cover class and road types within the Mirror Lake watershed.

Mirror Lake. The Village and Town of North Elba retrofitted several stormwater outfalls along Main Street to flow through these units. The Village has also sought funding to consolidate the stormwater collection along Main Street and divert it away from the lake. A project for stormwater consolidation along the southeast side of the lake has been funded and construction is expected to begin in 2017. The stormwater from this area will be diverted to a pump station that will move it to a retention pond on the Lake Placid Club Golf Course.

The water quality and health of Mirror Lake has been a topic of interest to residents and scientists alike for many years (Table A1). The first known report on the water quality of Mirror Lake was published by Ray Oglesby (1971). The report was commissioned by the Lake Placid Shore Owners' Association as part of a study of Lake Placid. Its objectives were specific. "(1) To establish a baseline scientific description of Lake Placid and Mirror Lake by means of which future significant changes in water quality could be assessed through comparison with the present state. (2) To obtain evidence as what substance or substances are now critical to the growth of phytoplankton (free-floating algae) in the lake. In other words, what would increase the growth of algae if added to the water in increased amounts. (3) Based on the data available, to make recommendations for the protection and/or improvement of water quality in the two lakes." Oglesby conducted a previous study in March 1971, which we have not been able to obtain. The initial study was followed up by Oglesby in 1974 with a second report (Oglesby & Mills 1974). The objectives of this report were to "further establish baselines" and "determine what, if any, actions

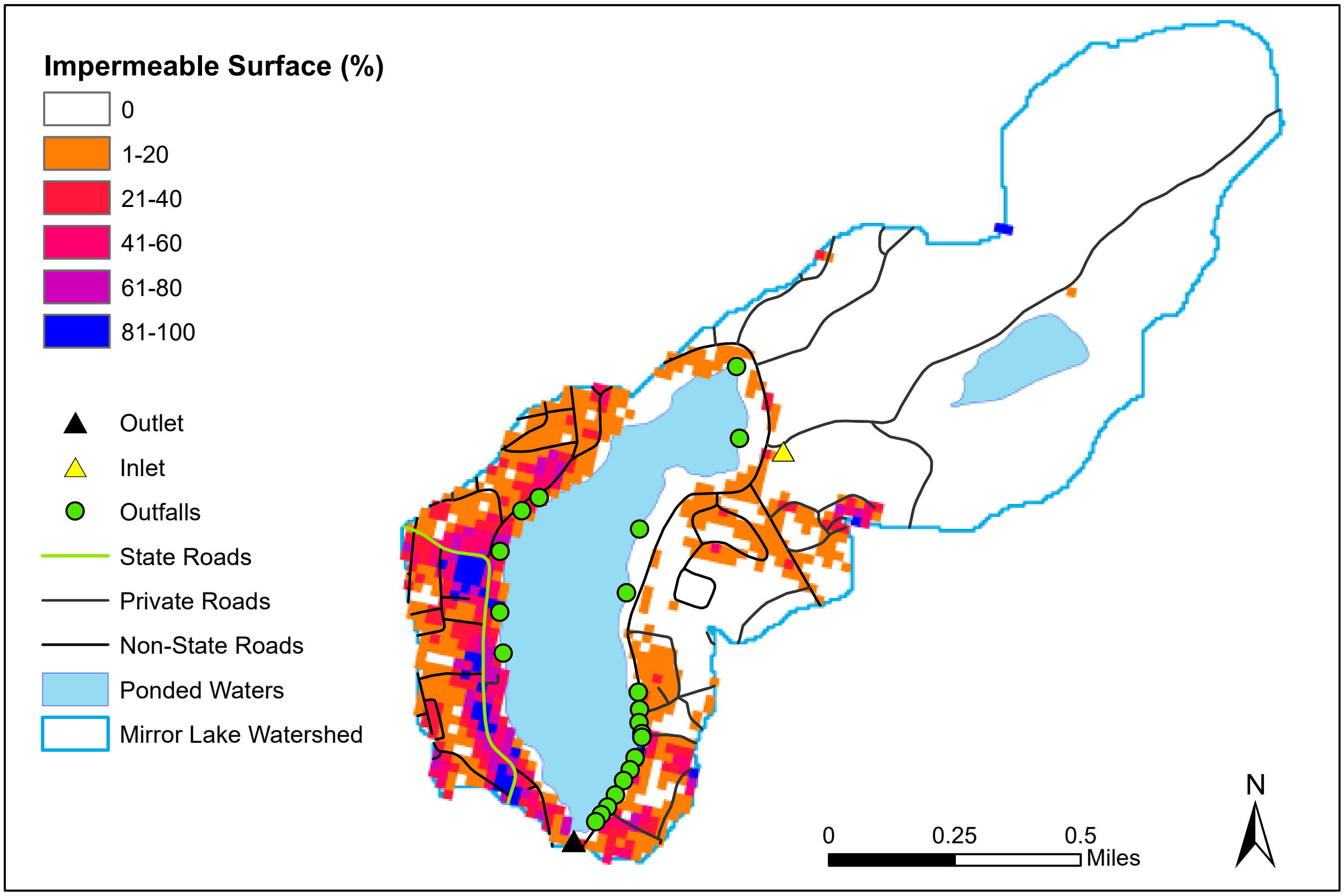

Figure 2. Distribution of impermeable surfaces and stormwater outfalls within the Mirror Lake watershed.

should be taken to safeguard or improve the water quality of the two lakes."

Then there was a long period when no data was collected on the lake. Although, a few visits to the lake were made by Don Charles in 1976 and 1978 as part of work he was doing with the Paleoecological Investigation into Recent Lake Acidification (PIRLA) project to study recent lake acidification (Whitehead et al. 1990). Paul Smith's College students did a series of reports on the lake during the winters of 1996, 1998, and 2000 (Martin 1998; Muray et al. 2000; Schmall et al. 1996). In 2001, the lake was studied by Upstate Freshwater Institute as part of a study of Lake Placid funded by the Lake Placid Shoreowners Association (UFI 2002). In 1998, a volunteer started monitoring the lake through the Citizens Statewide Lake Assessment Program (CSLAP)(Kishbaugh 2016). That monitoring effort has continued through 2016 with the exceptions of 2002 and 2012. In 2014, the lake was enrolled in the Adirondack Lake Assessment Program (ALAP). The lake remained enrolled in this program in 2015 but the monitoring was taken over by the Ausable River Association, which added additional parameters to the standard ALAP sampling.

In 2016, the Ausable River Association (AsRA) and the Adirondack Watershed Institute (AWI) initiated a partnership to expand the monitoring of the lake. This effort was supported by the Mirror Lake Watershed Association, Village of Lake Placid, Town of North Elba, IRONMAN Foundation, and NYS Department of State. The goal of this partnership and for developing a more comprehensive understating of Mirror Lake's water quality is that the lake is an iconic, valuable resource that faces challenges from the ring of urban development that surrounds it – making scientifically informed management essential to its continuing health.

Objectives

The objectives of the current monitoring program and this report are to: 1) establish a comprehensive picture of Mirror Lake that incorporates all known historical water quality data; 2) develop a better understanding of the impact of road salt, and elevated sodium and chloride concentrations on the lake; 3) investigate recent reports of long-term increases in total phosphorus; and, 4) lay the ground work necessary to establish a scientifically rigorous monitoring program to provide baseline data about Mirror Lake.

Methods

2016 field data were collected from a canoe over the deepest location of the lake bi-weekly during the open-water season, and monthly when the lake was covered with ice of sufficient thickness for access by foot. During each sample visit a surface water sample, hypolimnetic sample, and profiles of temperature, dissolved oxygen, specific conductance, and pH were collected. The surface water samples were collected from a depth of 0 to 2 meters with an integrated tube sampler. The tube sampler was emptied into a field rinsed 1L sample bottle. A portion was poured off into an acid-washed and field rinsed sample bottle for laboratory analysis, and 250ml was filtered through a 0.45 µm cellulose membrane filter. The filter was folded in half twice, wrapped in foil and stored on ice for chlorophyll-*a* analysis. Hypolimnetic samples were collected using a 1.5L Kemmerer bottle from approximately 1 meter above the bottom. This sample was immediately transferred to an acid-washed and field rinsed sample bottle and stored on ice. All water samples and the chlorophyll-*a* sample were transported on ice until they could be frozen before being transported to the Adirondack Watershed Institute. Samples were analyzed for pH, conductivity, alkalinity, total phosphorus, nitrate, chlorophyll-a, chloride, sodium, and calcium at the Adirondack Watershed Institute Environmental Research Lab following the analytic methods described in Table A2. Transparency was measured during the ice-free period using a 20cm black and white Secchi disk from the shady side of the boat. Profiles of temperature, dissolved oxygen, specific conductance, and pH were collected at 1m intervals from the surface to 17m using a YSI Professional Plus hand held sonde.

Field and laboratory data have been combined from multiple sources for this report to provide a record of water quality from 1971 to 2016. Sampling frequency and methodology, as well as laboratory methodology, is slightly different between these sources. Data points in each figure have been categorized into those following the methodology outlined in this report (circles) and those that have not (triangles). Nevertheless, as an exploratory analysis, linear regressions were fit to the annual average data for each parameter and plotted if a significant trend was detected. This analysis should be approached cautiously due to the inconsistency in the data throughout the period of record.

Table 1. Summary of land area of different cover classes for the Mirror Lake watershed. Values are also represented as percentage of the total watershed area (301.23 ha) and percentages of the watershed land area (236.93 ha). Percentage of land area is useful when considering the amount of a particular land cover class, such as development, compared to the potential area that cover class could occupy.

Cover Type	Area (ha)	% Watershed Area	% Land Area
Evergreen	29.99	9.96	12.66
Deciduous	87.06	28.90	36.74
Mixed Forest	38.73	12.86	16.35
Wetlands	5.34	1.77	-
Surface Water	58.95	19.57	-
Developed	81.16	26.94	34.25
Agriculture	0.00	0.00	0.00
Commercial	0.00	0.00	0.00
Total	301.23	100.00	100.00

Findings

Total Phosphorus

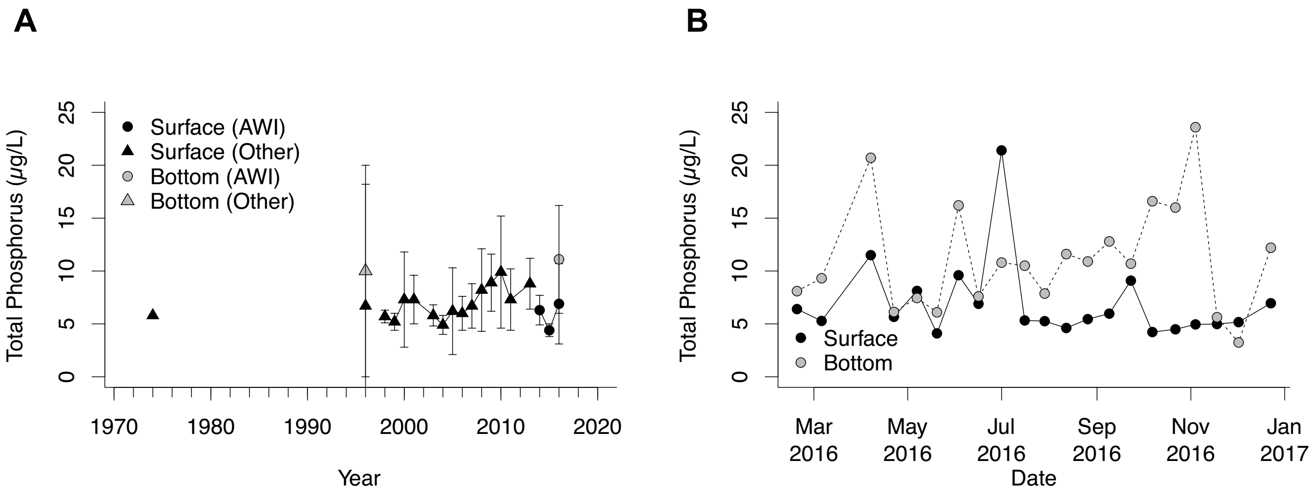

Figure 3. Annual average (a) and 2016 (b) total phosphorus. Black triangles represent data collected by other programs from the epilimnion, black circles represent 2m integrated samples collected by AsRA and AWI. The gray triangles and circles are from discrete samples collected 1m off the lake bottom. Vertical bars represent one standard deviation of the mean.

Phosphorus is relatively common in igneous rocks such as those found in the Adirondacks and is also abundant in sediments. The concentration of phosphorus in natural waters is low however, because of the low solubility of these inorganic forms (Wetzel 2001). Phosphorus is also a component of wastewater and this is a primary source of phosphorus in many waters. Typical concentrations of phosphorus in surface water are a few micrograms per liter. Additions of phosphorus to the aquatic environment enhance algal growth and accelerate eutrophication of waterbodies that leads to depletion of dissolved oxygen (Schindler 1977; Wetzel 2001).

Phosphorus is also added to surface waters from non-point sources such as eroding soils, stormwater runoff, runoff from fertilized fields, lawns, and gardens, and runoff from livestock areas or poorly managed manure pits. Poorly maintained or sited septic systems can also add phosphorus to surface waters. In addition, analyses of water chemistry in Adirondack upland streams shows that streams coming off old growth forest have higher phosphorus concentrations than those flowing off managed forests (Myers et. al, 2007).

Phosphorus plays an important role in biology and is an important nutrient in aquatic ecosystems. Phosphorus is often a limiting nutrient in lakes, meaning that it is a lack of phosphorus that limits aquatic primary production (Schindler 1977). Phosphorus normally enters a lake bound to soil and sediment through overland flow. In developed or urban areas, excess phosphorus can enter a lake due to application to the land as fertilizer or through poor wastewater management. This increase in phosphorus may lead to increased primary production, resulting in aesthetic changes to the lake. If the increase in primary production is large enough, there may be subsequent problems with oxygen depletion because of decomposition. The reduction in oxygen can lead to fish kills and other negative

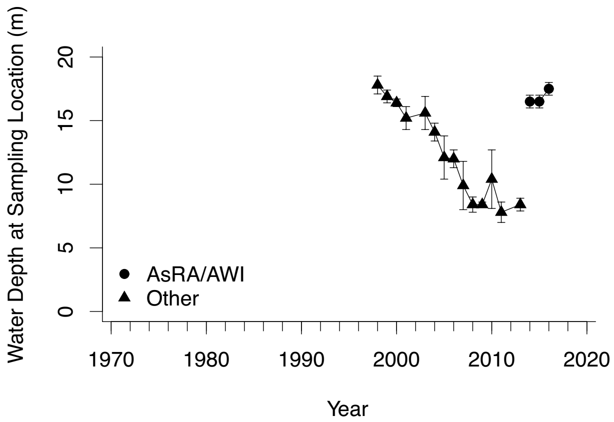

Figure 4. Water depth at the water sampling location. CSLAP samples are represented as open squares, ALAP data are closed circles.

impacts (Carpenter et al. 1998).

The 2014 ALAP and CSLAP reports indicated a long-term trend of increasing total phosphorus in Mirror Lake (Laxson et al 2015; Kishbaugh 2015). Closer analysis and comparison of the CSLAP and ALAP data reveals concerns about the interpretation of this trend. First, recent water samples analyzed by AWI using standard protocols with samples collected over the deep hole (confirmed with hand held depth sounder), are more similar to measurements in the late 1990s and early 2000s than recent CSLAP samples (Figure 3). Second, a close examination of the CSLAP data reveals the sampling location has drifted over time (Figure 4). During the period from 2003 to 2008 the water depth at the sampling station changed from 15.6m to 8.4m. This drift in sampling location may be responsible for the trend towards slightly higher total phosphorus concentrations, if the sampling location moved closer to a source of phosphorus. Alternatively, there may be higher concentrations of phosphorus near shore due to greater availability from near shore sediments (Søndergaard et al. 2003). We have chosen not to plot the bottom water chemistry reported by CSLAP because of this inconsistency in sampling location. When only looking at samples that we are reasonably sure were collected over the deep hole of the lake, we do not see a trend in total phosphorus over time.

CSLAP uses differences in surface and bottom water chemistry to infer whether the bottom waters have low dissolved oxygen (Kishbaugh 2016). Under anoxic (low to no oxygen) conditions phosphorus becomes liberated from lake sediments, increasing the concentration in the associated water. Higher concentrations of phosphorus in the bottom water compared to the surface is an indication of anoxic conditions. CSLAP reports indicate that Mirror Lake does not experience anoxic conditions in the bottom waters, but that interpretation is biased because their bottom samples are collected nearly 10m shallower than the deepest part of Mirror Lake. In fact, the bottom water sample is being collected in a portion of the water column that is well oxygenated (Figure 9) and misrepresents the real chemistry of the bottom waters of Mirror Lake.

Nitrogen

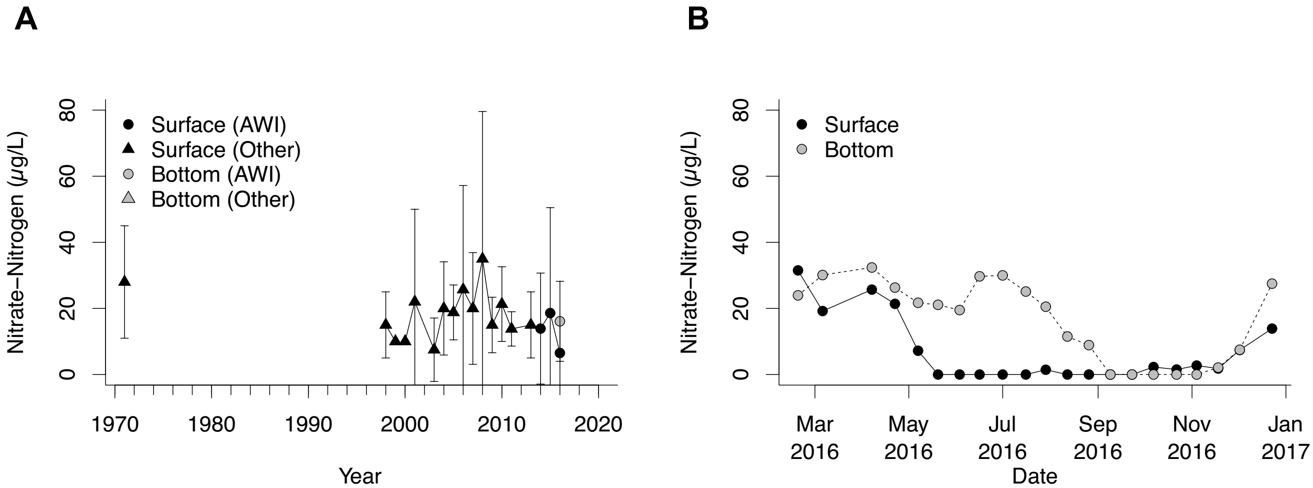

Figure 5. Annual average (a) and 2016 (b) nitrate-nitrogen. Black triangles represent data collected by other programs from the epilimnion, black circles 2m integrated samples collected by AsRA and AWI. The gray triangles and circles are from discrete samples collected 1m off the lake bottom. Vertical bars represent one standard deviation of the mean.

Nitrogen is present in many forms in the atmosphere, hydrosphere, and biosphere. It is the most common gas in the earth's atmosphere. The behavior of nitrogen in surface waters is strongly influenced by its vital importance to plant and animal nutrition. Nitrogen occurs in water as nitrite (NO_2-) or nitrate (NO_3-) anions, ammonium (NH_4+) cations, or organic nitrogen. Excessive, or high levels of nitrite are an indicator of organic waste or sewage. Nitrate or ammonium may also be from a pollutant source, but, generally, are introduced at a site far removed from the sample point. This is because nitrate is stable over a range of conditions, but nitrite rapidly volatilizes in oxygenated water. Ammonium is an important nutrient for primary producers, but, at high concentrations, is a dangerous pollutant in lakes and rivers, because the bacterial conversion of NH_4 to NO_3 robs the water of oxygen. Generally, nitrogen is not a limiting nutrient in aquatic ecosystems (Schindler 1977).

Nitrate is the only reported form of nitrogen for this study. There are no long-term trends in nitrate in Mirror Lake (Figure 5a). Nitrate concentrations are low, indicating it is not likely the lake is receiving significant additional inputs of nitrogen from the watershed. Throughout the year, nitrate varies considerably due to rapid utilization by primary producers in the water column (Figure 5b). Concentrations of nitrate were higher in the hypolimnion than the epilimnion through the spring and summer months. This is a common pattern for lakes in our area. The nitrification process carried out by chemoautotrophic bacteria convert ammonium to nitrate in the presence of oxygen. Production by photosynthetic organisms is substantially lower in the hypolimnion so the concentration of nitrate builds through the summer. When the hypolimnion goes anoxic in the later summer, the nitrification process works in reverse, resulting in a sharp decrease in nitrate in the hypolimnion that persists until the late fall when the water completely mixes, returning oxygen to the bottom of the lake.

Chlorophyll-a

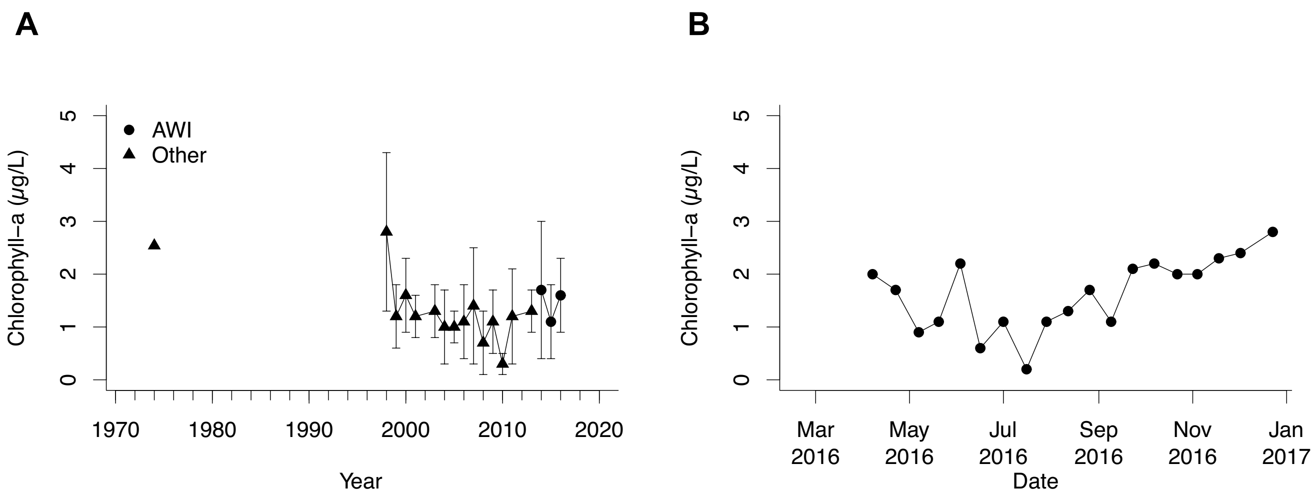

Figure 6. Annual average (a) and 2016 (b) chlorophyll-a. Black triangles represent data collected by other programs from the epilimnion, black circles 2m integrated samples collected by AsRA and AWI. Vertical bars represent one standard deviation of the mean.

Chlorophyll-*a* is the primary photosynthetic pigment in all photosynthetic organisms including algae and cyanobacteria. The concentration of chlorophyll-*a* is used as an index for algal biomass, or productivity. Nutrient concentrations, light, and water temperature all control algal productivity. Depending on the time of year, these three variables change and can limit algal production. Therefore, we expect to see variability in chlorophyll-*a* throughout the year. Major shifts in chlorophyll-*a* concentration over many years can usually be attributed to changes in nutrients (phosphorus, nitrogen, and silica) (Wetzel, 2001).

In Mirror Lake, chlorophyll-*a* concentrations vary throughout the year (Figure 6b), with the highest concentrations occurring in the spring and fall/winter. These times of the year typically see the highest productivity in the surface waters due to increased nutrient availability and relatively low zooplankton herbivory. During these times of the year, lake turnover, complete mixing of the water column, redistributes the nutrient rich bottom waters up to the lake surface where there is plenty of light. The high concentration under the ice during the winter may be from cyanobacteria and other algae that thrive in low light conditions.

Analysis of the annual data shows no significant trend in chlorophyll-*a* (Figure 6a). There was a particularly high concentration reported in 1971 (Ogelsby 1971). It is possible that these measurements were inaccurate as there is not a corresponding low secchi readings, both of which would be expected if there was significantly higher primary production during that time. Therefore, we have omitted this measurement from Figure 6a. During the period (2003 to 2010) that total phosphorus was increasing in the CSLAP dataset, chlorophyll-*a* concentrations were not changing. This is further evidence that the increase in total phosphorus reported by CSLAP may be the result of inconsistent sampling.

Transparency

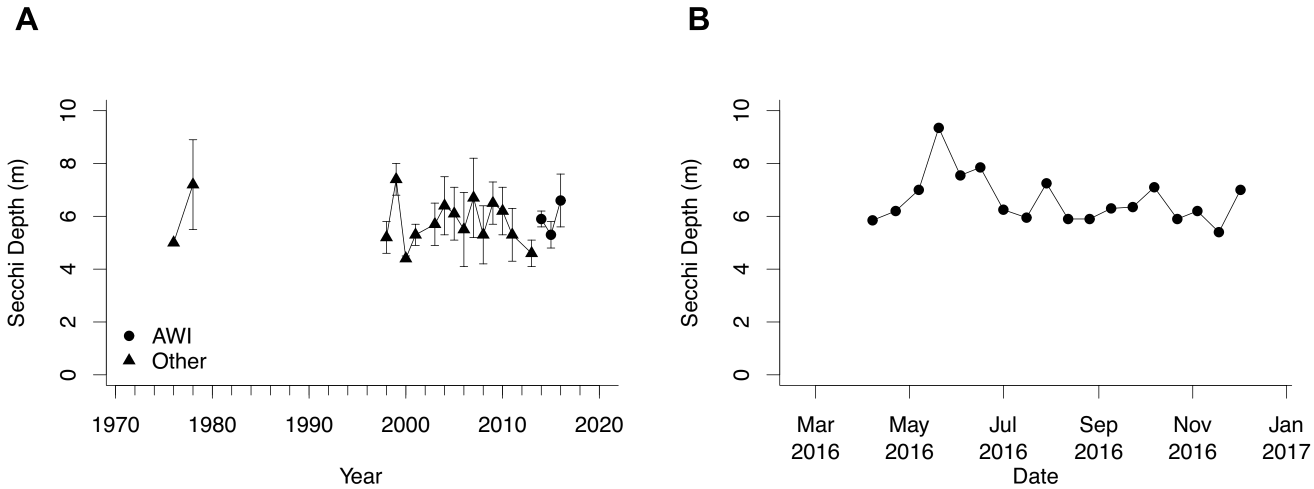

Figure 7. Annual average (a) and 2016 (b) transparency. Black triangles represent data collected by other programs from the epilimnion, black circles 2m integrated samples collected by AsRA and AWI. Vertical bars represent one standard deviation of the mean.

Water column transparency is a simple measure of lake productivity. Generally, secchi depth is lower in highly productive eutrophic lakes and higher in less productive oligotrophic lakes. Secchi depth can also be influenced by other water quality parameters that impact clarity, such as dissolved organic carbon, total suspended solids, colloidal minerals, and water color. Therefore, it is valuable to keep other water quality parameters, such as total phosphorus and chlorophyll-a, related to lake productivity in mind when looking at changes in transparency. Changes in watershed characteristics, such as the amount of runoff from precipitation or the export of organic matter, can also influence transparency.

No significant change in lake water transparency was detected in Mirror Lake (Figure 7a). The highest water column transparency during 2016 was observed in May. During the remainder of the year transparency measurements are consistent. In some Adirondack Lakes water column transparency is declining as a result of dissolved organic carbon (DOC) increasing due to recovery from acid deposition (Warren et al. 2016). The exact mechanism driving regional increases in DOC is not fully understood. Cultural eutrophication can also lead to a decline in water column transparency (Wetzel 2001). Neither appears to be the case in Mirror Lake (Figure 7a).

Trophic Status

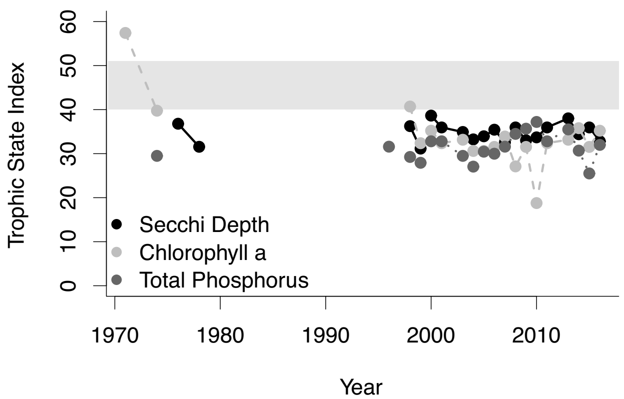

Figure 8. Annual average trophic state index based on secchi depth (black), chlorophyll-a (light gray), and total phosphorus (dark gray).

Trophic status is used by limnologists to refer to the overall productivity of a lake. Lake productivity is influenced by the nutrient supply, regional climate, watershed characteristics, and lake morphology. The term cultural eutrophication is often used to describe the process whereby human activities increase lake productivity through an increase in the nutrient supply. This process usually results in unwanted outcomes such as declines in lake aesthetics, increase chance of harmful algal blooms, and fish kills due to elevated bacterial decomposition utilizing all the available oxygen in the water column.

Lakes can be assigned to three main classification categories based on their overall productivity; oligotrophic, mesotrophic, eutrophic. Oligotrophic lakes have the lowest productivity due to low nutrient content. These lakes are often characterized by clear, highly transparent water, with low phytoplankton biomass. The entire water column is often well oxygenated, making these lakes capable of supporting cold water fish species such as lake trout. Mesotrophic lakes are an intermediate state between oligotrophy and eutrophy. Eutrophic lakes are characterized by high productivity and high nutrient content. As a result, the water column is less clear due to increased phytoplankton production. The greater production of organic matter leads to higher rates of bacterial decomposition at the bottom of the lake. Bacteria utilize oxygen, resulting in a decrease in oxygen availability in the bottom waters during the summer stratified period. This reduction in oxygen is referred to hypoxic (low oxygen) or anoxic (no oxygen) conditions and is not conducive to supporting cold water fish.

Carlon's Trophic Status Index (TSI) can be used to identify which of these trophic classifications a lake belongs to. TSI uses phytoplankton biomass as a measure for the trophic state of the lake. It utilizes independent estimates of phytoplankton biomass using chlorophyll-*a* pigment concentrations, secchi depth, and total phosphorus concentrations (Carlson 1997). Values of less than 40 are common among oligotrophic lakes, 40-50 is common for mesotrophic lakes, and greater than 50 is common for eutrophic lakes.

TSI has been calculated based on annual average of chlorophyll-*a*, secchi depth, and total phosphorus for Mirror Lake (Figure 8). Over the period of record Mirror Lake has consistently stayed within the oligotrophic classification with no significant trends over time. An early estimate using chlorophyll-*a* placed the lake in the eutrophic category, but as discussed in the chlorophyll-*a* section this is likely an erroneous measurement. The estimate using total phosphorus indicated an increasing trend during the period which showed an increase in this parameter. As discussed in the total phosphorus section, these data are questionable due to the inconsistency in the sample location. Mirror Lake does not show evidence of cultural eutrophication or any obvious shifts in its trophic status since the late 1970's.

Dissolved Oxygen

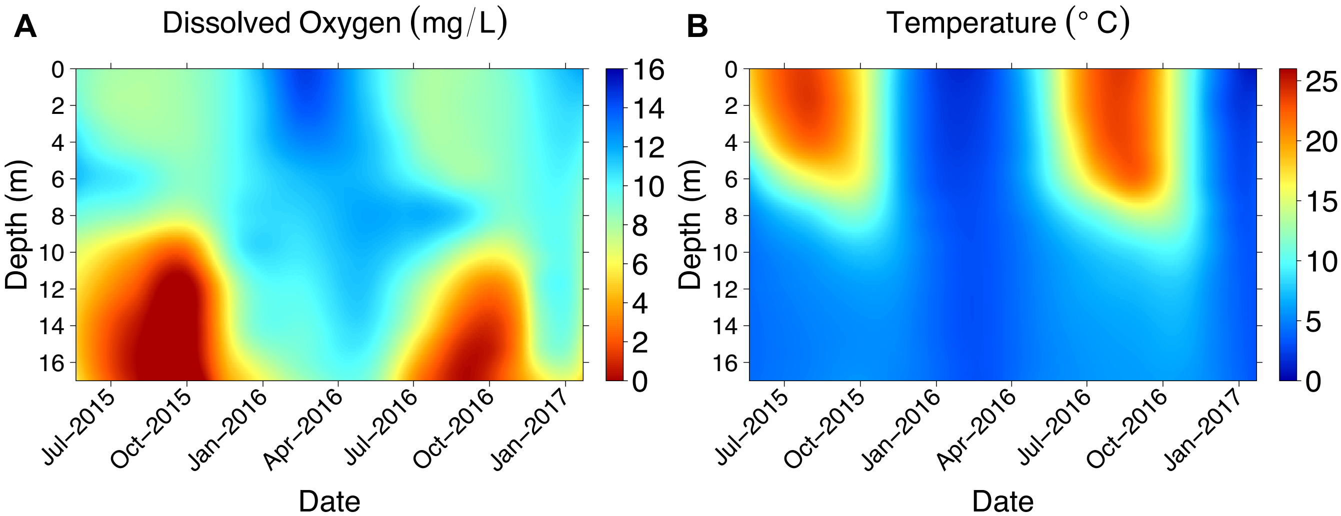

Figure 9. Dissolved oxygen (a) and temperature (b) from vertical profiles collected at 1m intervals over the deepest location of the lake during 2015 and 2016. A second order loess smoother was fit to the data to create the continuous plots depicted above.

The primary sources of dissolved oxygen in lakes occur through diffusion from the atmosphere and primary production. Dissolved oxygen is consumed through respiration and decomposition. The solubility of oxygen in water is directly related to temperature and salinity, and decreases as both increase. Oxygen is vital to aerobic forms of life such as aquatic insects, zooplankton, and fish. Oxygen availability from the atmosphere and primary production vary throughout the year. During periods of lake turnover (spring and fall), oxygen is redistributed throughout the water column. During the summer stratified period, warm water at the surface of the lake prevents the cold bottom waters from mixing and cuts off the source of atmospheric oxygen. Similarly, during the winter months, while the lake is covered with ice, the supply of atmospheric oxygen is cut off and contributions from primary production are low.

Generally, oxygen depletion in the hypolimnion is a problem in eutrophic lakes with high rates of decomposition. It can also be prevalent in lakes that have a shallow hypolimnion and large sediment surface area to volume ratio. Reductions in hypolimnetic dissolved oxygen are of primary concern to native salmonid species. During the summer months, these fish species seek out an optimal zone in the lake, an area which is both cool (<18 °C) and well oxygenated (>7 mg/L). In lakes with low hypolimnetic dissolved oxygen, this often pushes these species into a narrow range of depths as oxygen concentrations decline throughout the summer. Many lakes are experiencing longer periods of stratification due to climate change (De Stasio et al. 1996). This is causing the cold hypolimnetic waters to be cut off from atmospheric sources of oxygen for longer periods of time and threatening the ability of cold water fish species to find both cold and well oxygenated water.

Mirror Lake experienced hypoxic conditions (<2 mg/L dissolved oxygen) in the hypolimnion during the summer of both 2015 and 2016 (Figure 9a). By the end of the summer stratified period, only a few meters of the water column fit the optimal criteria for cold water fish (Figure 9a & b). When sampling

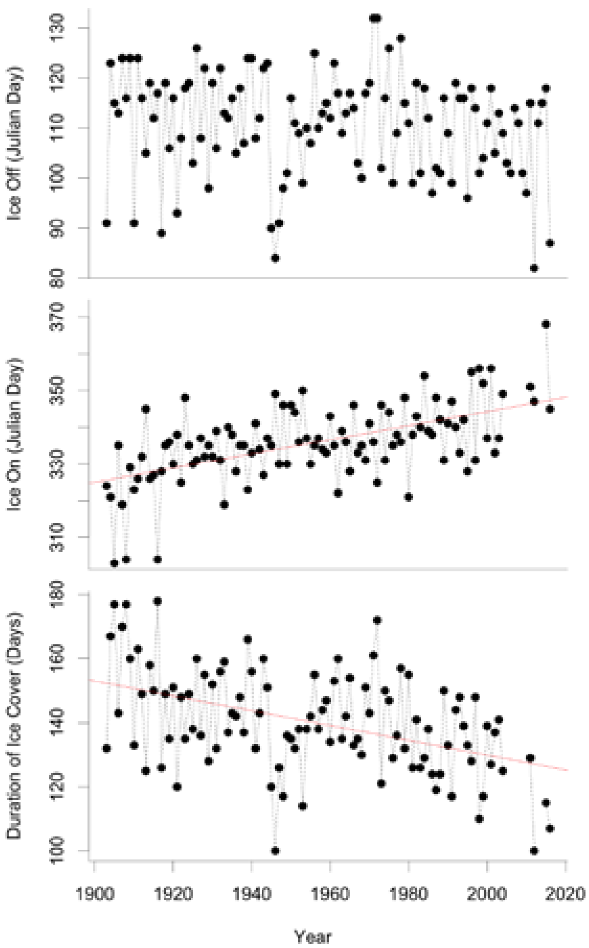

Figure 10. Ice record for Mirror Lake. There is no significant trend in ice off. Ice on (y=0.19x-39, R^2=0.33, p<0.01) and duration of ice cover (y=-0.23x+593, R^2=0.20, p<0.01) both show significant trends.

started in June 2015, the bottom waters were low in dissolved oxygen and the size of the anoxic zone in the lake during the summer of 2015 was extensive. In the fall of 2015, the lake turned over, redistributing oxygen throughout the water column. Oxygen concentrations declined slightly throughout the winter, but the water column remained well oxygenated. This is typical for an oligotrophic lake with low rates of decomposition. In the spring of 2016, the lake turned over, again redistributing oxygen throughout the water column. During the summer of 2016, anoxic conditions again appeared in the hypolimnion but to a lesser extent than in 2015.

The anoxic conditions in the hypolimnion of Mirror Lake are a concern for the long-term survival of lake trout within the lake. This problem is expected to worsen as the regional climate warms and the period of stratification lengthens (De Stasio et al. 1996). The ice record for Mirror Lake shows a three-week increase in the open water season over the past 100 years (Figure 10). If the longer open water season is also resulting in a longer period of stratification, the lake may reach a point where there is no lake trout habitat left at the end of the summer stratified season. Dissolved oxygen concentrations and temperature profiles in Mirror Lake should continue to be monitored closely. Further understanding of the internal mixing dynamics would help understand the issue of low dissolved oxygen in Mirror Lake.

Acidity

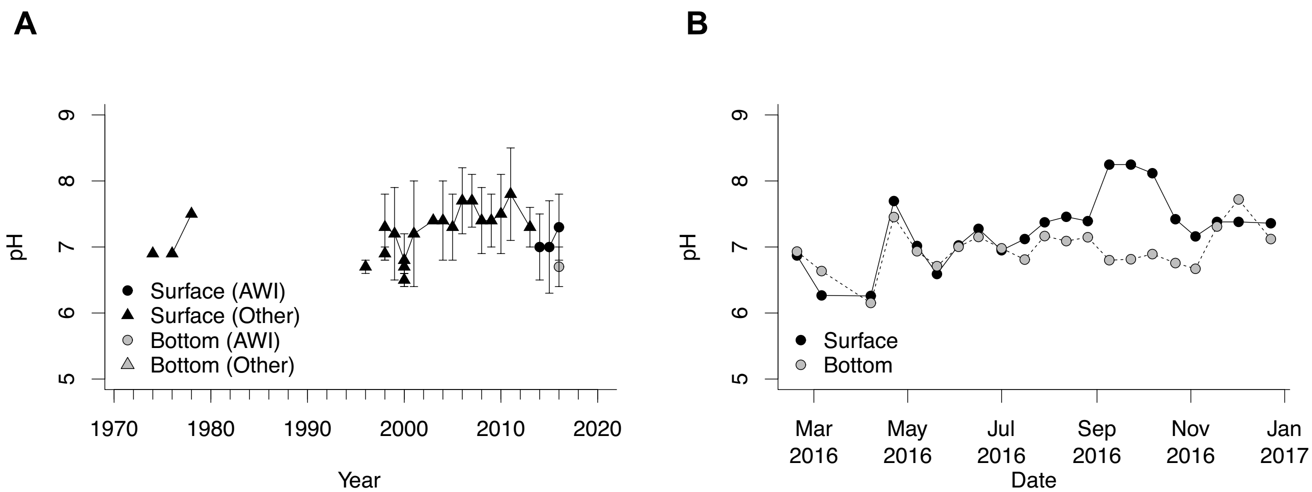

Figure 11. Annual average (a) and 2016 (b) pH. Black triangles represent data collected by other programs from the epilimnion, black circles 2m integrated samples collected by AsRA and AWI. The gray triangles and circles are from discrete samples collected 1m off the lake bottom. Vertical bars represent one standard deviation of the mean.

pH is an index of the hydrogen ion activity in solution, it is defined as the logarithm of the reciprocal of the concentration of free hydrogen ions in solution. Therefore, high pH values represent lower hydrogen ion concentrations than low pH values, and there is a 10-fold difference in hydrogen ion concentration across a single pH unit. The pH scale extends from 0 to 14, with 7 being neutral. pH values below 7 indicate acidic conditions and pH values greater than 7 indicate alkaline conditions.

Acidity in Adirondack surface waters has two sources: acid deposition (rain, snow, and dry deposition) and organic acids from evergreen needles and other plant matter. Long-term monitoring by the Adirondack Lakes Survey Corporation shows that 25% of lakes in the Adirondacks have a pH of 5.0 or lower and another 25% are vulnerable to springtime acidification (ALSC, 1990).

Shifts in pH can have major effects on the dominant biological and chemical process present within a lake. Many organisms have narrow pH tolerances, resulting in significant declines in individual health and population numbers if pH values stray outside of their tolerances. Changes in pH also influence the mobility of ions and heavy metals which can result in issues related to nutrient availability and toxicity (Driscoll 1985; Schindler et al. 1985).

Over the period of record, Mirror Lake has stayed within the circumneutral (6.5-7.5) to slightly alkaline (>7.5) range (Figure 11a). There is no long-term trend in pH present in Mirror Lake, but pH appeared to increase from 2003 to 2012. Data from the National Atmospheric Deposition Monitoring Program in Huntington Forest (central Adirondacks) reveals that the primary indices of acid deposition, pH, and the acid anions sulfate and nitrate, are all exhibiting significant reductions over the past 35 years. Likewise, recent research from 74 lakes in Northeast (60% in the Adirondacks) illustrate that several acid indicators such as sulfate concentration and ANC are exhibiting significant recovery (Strock et al 2014). Thus, it is reasonable to expect acid reduction in Mirror Lake.

Alkalinity

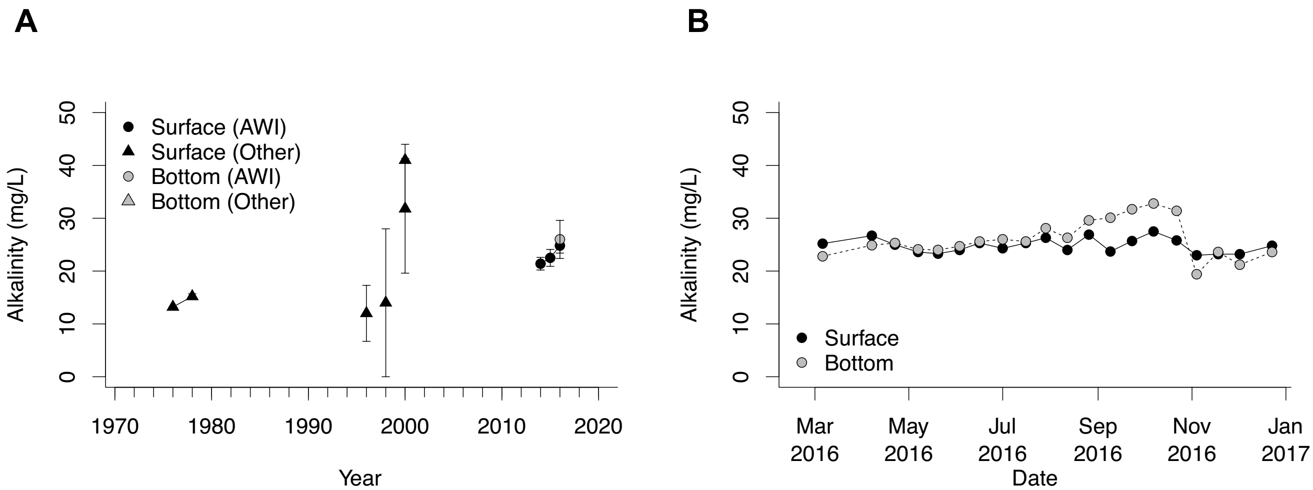

Figure 12.. Annual average (a) and 2016 (b) alkalinity. Black triangles represent data collected by other programs from the epilimnion, black circles 2m integrated samples collected by AsRA and AWI. The gray triangles and circles are from discrete samples collected 1m off the lake bottom. Vertical bars represent one standard deviation of the mean.

Alkalinity is a measure of buffering capacity of a waterbody, typically expressed as mg/L of calcium carbonate ($CaCO_3$). The amount of calcium carbonate in a waterbody is primarily related to the bedrock geology of its watershed. Lakes with watersheds underlain by granitic bedrock tend to have low alkalinity due to slow rates of weathering of the bedrock and low amounts of calcium carbonate in the rock. Conversely, lakes underlain by sedimentary rocks such as limestone tend to both weather faster and contain more calcium carbonate. Many lakes in the Adirondacks are underlain by granitic bedrock, and therefore have lower alkalinity.

While there appears to be a in increase in alkalinity, we detected no significant trend over the period of record (Figure 12a). Mirror Lake's current alkalinity (2016 average = 24.8 mg/L) indicates that it has low sensitivity to acidification (Figure 12b). In other words, Mirror Lake has sufficient buffering capacity to resist acidification. The potential long-term increase may be a result of regional declines in acid deposition or may be related to development within the watershed. Increases in limestone based concrete associated with the development around the lake may be associated with an increase in alkalinity

Calcium

The primary source of calcium in lakes is $CaCO_3$, thus the discussion of calcium is closely tied to that of alkalinity. $CaCO_3$ is not very soluble in water, but in the presence of carbonic acid it is converted to more soluble forms. The primary source of calcium in lakes is from weathering of parent material. Calcium is an important element in biology because it serves a role in the structure and physiology of many organisms. In the Adirondacks, the granitic parent material contains little calcium, and therefore Adirondack lakes tend to be low in calcium. Regionally, lakes are showing calcium declines, in part

Calcium continued

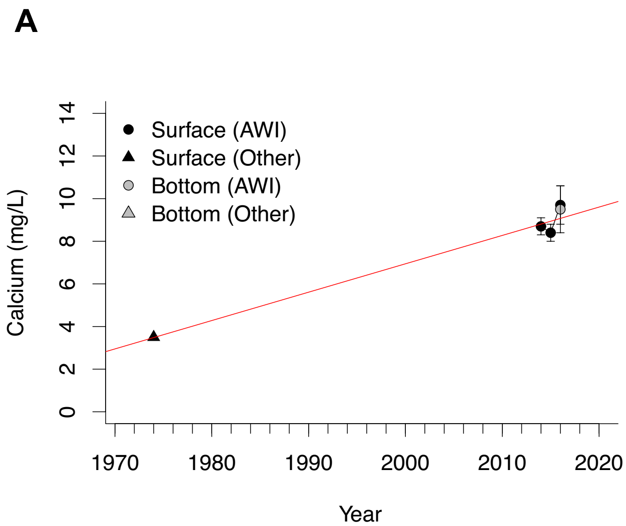

Figure 13. Annual average (a) and 2016 (b) calcium. Black triangles represent data collected by other programs from the epilimnion, black circles 2m integrated samples collected by AsRA and AWI. The gray triangles and circles are from discrete samples collected 1m off the lake bottom. Vertical bars represent one standard deviation of the mean. Calcium shows a significant trend over the period of record (y=0.13x-259.2, R^2=0.97, p=0.02

because of acid deposition. Acid deposition resulted in increased calcium leaching from watershed soil, eventually reducing the pool available for export to lakes (Keller et al. 2001). Concentrations are low enough in some lakes (<2 mg/L) to cause declines in zooplankton that utilize calcium to build their carapace (Jeziorski et al. 2008).

Contrary to regional declines in calcium, Mirror Lake has exhibited an increase over time. Current concentrations are well above other Adirondacks lakes. Mirror Lake is above the 90th percentile for lakes monitored as part of the Adirondack Lake Assessment Program (Laxson et al. 2016). Kelting and Laxson (2017) observed 62% higher concentrations of calcium, magnesium, and potassium in lakes with paved roads in their watersheds. Application of sodium chloride (NaCl) as a road deicer results in increased export of these ions from the watershed to the lake when sodium replaces calcium, magnesium, and potassium on soil cation exchange sites (Kelting and Laxson 2017; Mason et al. 1999). Also, these ions are commonly used with alternative road deicing agents (calcium chloride, magnesium chloride, and calcium magnesium acetate). It is also possible that the elevated calcium concentrations in Mirror Lake are the result of development. The import of calcium rich materials for construction, primarily limestone based concrete, and the subsequent weathering may be a significant source of calcium to Mirror Lake.

Calcium is an important, and sometimes limiting, nutrient to mussels such as the zebra mussel. In many Adirondack lakes, calcium concentrations are too low (<12 mg/L) to support zebra mussel populations (Whittier et al. 2008). Calcium concentrations measured by Oglesby in 1971 were well below this threshold, but recent concentrations are high enough where it may be possible for a zebra mussel population to become established if they were introduced to Mirror Lake (Oglesby 1971; Whittier et al. 2008).

Conductivity

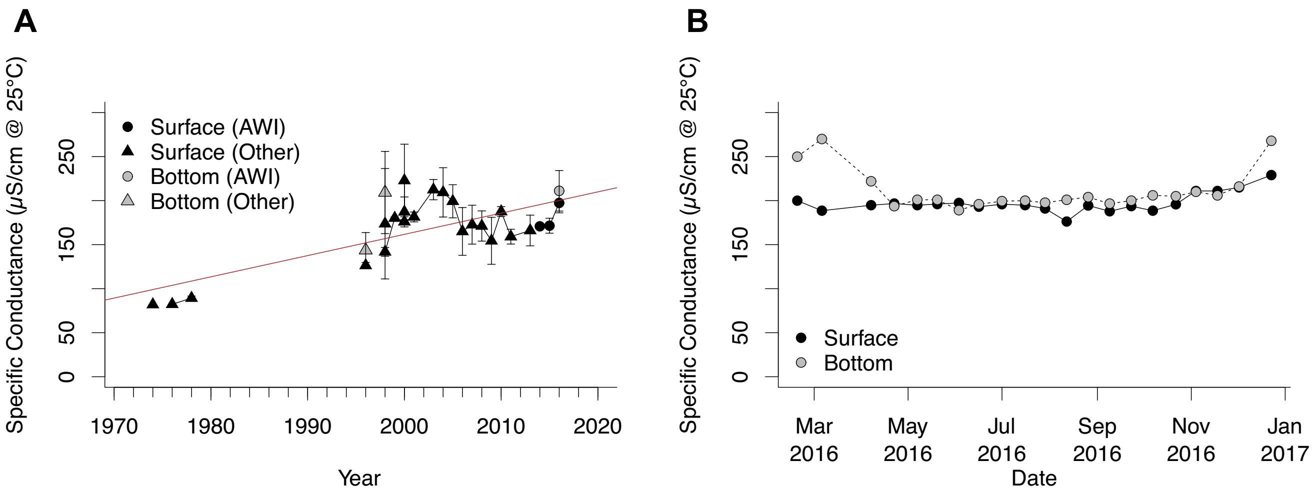

Figure 14. Annual average (a) and 2016 (b) nitrate-nitrogen. Black triangles represent data collected by other programs from the epilimnion, black circles 2m integrated samples collected by AsRA and AWI. The gray triangles and circles are from discrete samples collected 1m off the lake bottom. Vertical bars represent one standard deviation of the mean. Conductivity shows a significant trend over the period of record (y=2.41x-4662, R^2=0.53, p<0.01

Conductivity—the ability of water to pass an electrical current because of the presence of dissolved ions—is often called the "watchdog" environmental test since it is informative and easy to perform. Calculations of specific conductance standardize conductivity measurements to the temperature of 25 °C for the purposes of comparison. Rain, erosion, snow melt, runoff carrying livestock waste, failing septic systems, and road salt raise conductivity because of the presence of ions such as chloride, phosphate, nitrite etc. Oil spills lower water conductivity. Temperature, shade, sunlight, and sampling depth all affect conductivity. A conductivity probe does not identify the specific ions in a water sample—it simply measures the level of total dissolved solids (TDS) in the water body.

Mirror Lake has experienced a significant increase in conductivity over the period of record (Figure 14a). This trend is indicative of the lake being affected by the application of rock salt to roads and sidewalks in the watershed, and the subsequent runoff into Mirror Lake. The data from the early 1970s pre-dates the widespread increase in use of rock salt on Adirondack roadways, and is at the early period of widespread use of road salt nationally (Langen et al. 2006; TRB 1991). Over the course of 2016, we saw a difference in conductivity between the surface and hypolimnion during the winter months (Figure 14b). This indicates an accumulation of dense salt laden water at the lake bottom. During the spring of 2016 the lake turned over returning the water column to uniform conductivity.

Sodium & Chloride

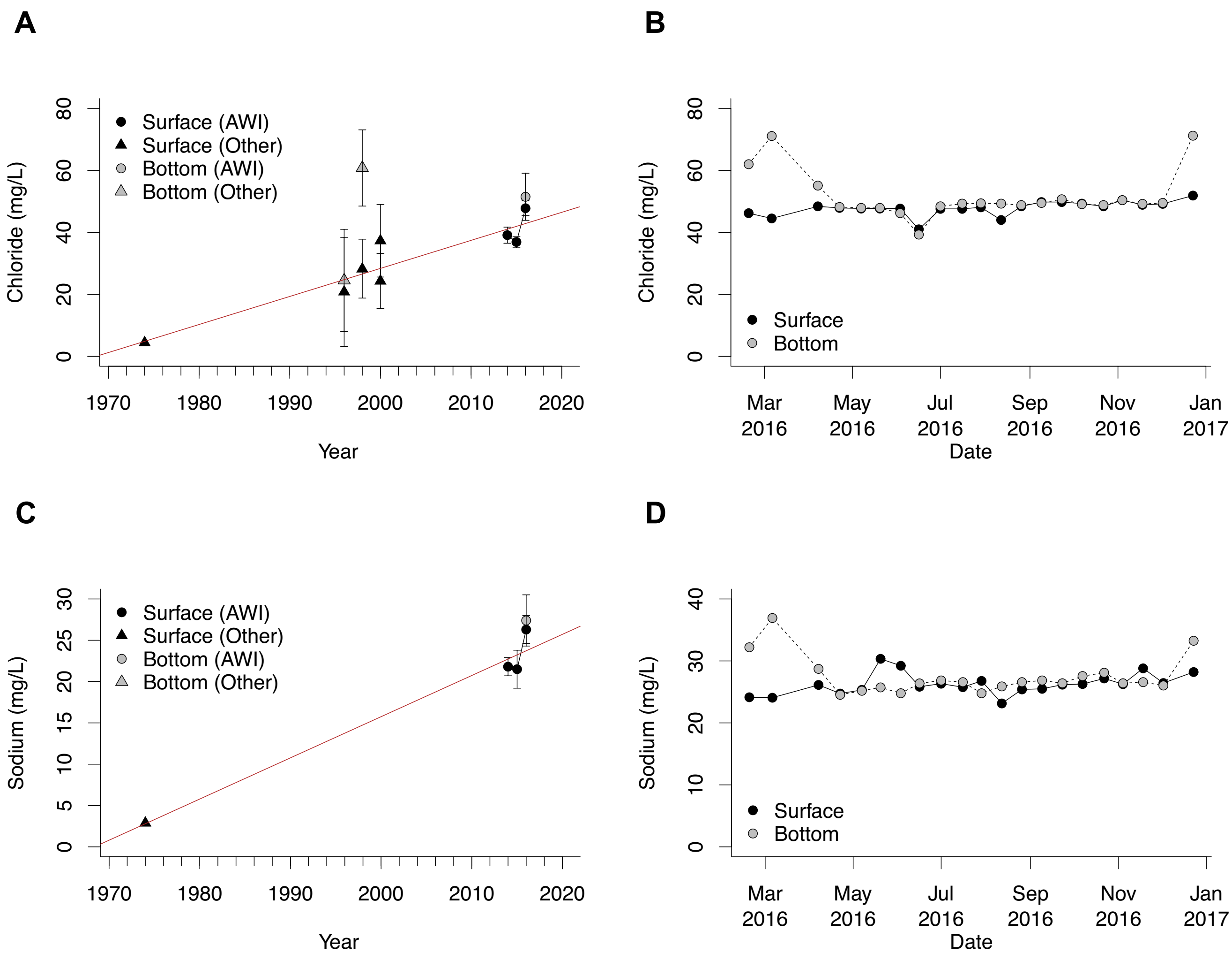

Figure 15. Annual average (a) and 2016 (b) chloride and annual average (c) and 2016 (d) sodium. Open squares represent data collected by other programs from the epilimnion, closed black circles 2m integrated samples collected by AsRA and AWI. The closed gray circles are from discrete samples collected 1m off the lake bottom. Vertical bars represent one standard deviation of the mean. Both chloride (y=0.91x-1781, R2=0.87, p=<0.01) and sodium (y=0.50x-981, R2=0.98, p=0.02) show a significant trend over the period of record.

The element chlorine can occur in various forms or states of oxidation, but the chloride form (Cl-) is most common in surface waters. There are several natural sources of sodium and chloride, including various rocks that contain sodium- and chlorine-bearing minerals. The most abundant natural mineral form of sodium and chloride is NaCl or Halite, also known as rock salt. Large halite deposits form when ocean water evaporates and mineral deposits are buried, eventually becoming rock.

Chloride is present in most natural waters at very low concentrations, except where surface or groundwater mixes with ocean water. Minimally impacted Adirondack lakes have average chloride and sodium concentrations of 0.2 mg/L and 0.5 mg/L, respectively (Kelting et al. 2012). Another source of

Sodium & Chloride continued

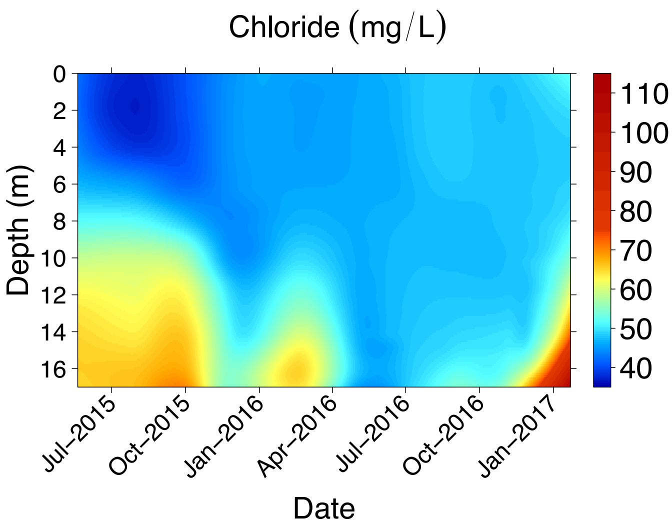

Figure 16. Chloride concentration inferred from conductivity measurements taken at 1m intervals over the deepest location of the lake during 2015 and 2016. A second order loess smoother was fit to the data to create the continuous plots depicted above.

chloride is road runoff, in regions where rock salt is used as a road deicing agent in winter. New York has one of the highest rock salt application rates per lane mile in the United States (Kelting & Laxson 2010). These application rates are mandated on state roads across the state, regardless of proximity to surface waters. Within the Village of Lake Placid, significant amounts of rock salt are applied to the sidewalk around Mirror Lake. The runoff from this area, and the adjacent roadways, goes directly into Mirror Lake.

Chloride toxicity to organisms is complex and not well understood. Toxicity standards (based on LD50 or LC50 values, the dosage or concentration lethal to 50% of the tested population) are set by state and federal agencies as the result of laboratory studies. They do not take into consideration the complex interactions that occur in natural ecosystems—effects of chronic exposure, or regional differences in sensitivity that may result from adaptations to local conditions. EPA chloride guidelines for aquatic life are 230 mg/L for chronic exposure (four-day average) and 860 mg/L for acute exposure (one-hour average) (EPA 1998). The NYS DEC Water Quality Regulation for chloride in surface waters is 250 ppm for class A, AS, and AA-S waterbodies.

Some researchers have observed negative effects from chloride levels much lower than the EPA and NYS DEC guidelines. Certain zooplankton species may be affected at concentrations as low as 5 to 30 ppm (Dalinsky et al., 2014; Palmer and Yan, 2013), while others have observed the ability of these species to evolve a tolerance to high chloride concentrations (Coldsnow et al. 2017). A study by the US Geological Survey showed very low tolerances (3.1 ppm) to chloride for brook trout (Meador and Carlisle, 2007). Research on the impact of road salt on rainbow trout development showed reduced growth rates in trout exposed to sodium chloride (9% reduced length; 27% reduced mass at 3000 mg Cl/L) and calcium chloride (5% reduced length; 16% reduced mass at 860 mg Cl/L), but not effected by magnesium chloride (Hintz & Relyea 2017). Chloride toxicity may also depend upon a variety of biotic and abiotic factors. Eurasian water milfoil, an invasive aquatic plant, has been shown to have higher tolerances to chloride than native milfoil species (Dalinsky et al., 2014). A study of chloride toxicity to zooplankton found that decreases in the quantity of food increase chloride toxicity (Brown & Yan, 2015). This means zooplankton in Mirror Lake may experience toxic effects at lower chloride concentrations than lakes with greater nutrient availability. Finally, while little is known about the impact of road salt additives to freshwater ecosystems, a recent study shows that they can alter aquatic food webs (Schuler et al. 2017).

Sodium and chloride concentrations have increased significantly over the period of record (Figure 15a

Sodium & Chloride continued

& c). The surface water samples collected by Oglesby in 1974 had sodium and chloride concentrations of 2.9 and 4.4 mg/L, respectively. In 2016, average concentrations were 26.3 and 47.8 mg/L, respectively. This is a 9 to 11-fold increase in concentration over that period, and 52 to 239-times higher than minimally impacted Adirondack lakes (Kelting et al. 2012). In Adirondack lakes without paved roads in their watersheds the median molar ratio of sodium to chloride is 3.63:1 (Kelting et al. 2012). If the primary source of sodium and chloride to a lake is road salt we would expect the lake water to have a molar ratio of 1:1, because this is the ratio of these ions in road salt (Novotny et al. 2008). In 1974, the molar ratio of sodium to chloride was 1.14:1, indicating that even though the concentrations of sodium and chloride were much lower at that time, the lake was likely being influenced by road salt. The current molar ratio is 0.96:1, which is also indicative of influence by road salt. The reduction in sodium relative to the expected ratio is likely explained by the greater affinity of sodium to ion exchange sites in the soil (Norrström et al. 2001).

To better understand the distribution of chloride throughout the water column we modeled chloride concentrations based on conductivity measurements. Under a linear model, field specific conductance explains 78% of the variation in chloride concentration ($y=0.27x-11.59$, $R^2=0.78$, $p<0.01$). Using this relationship, we modeled chloride concentrations at 1-m intervals throughout the water column on a bi-weekly basis during the open water season, and monthly while the lake is frozen.

The chloride data show that during the summer of 2015, the chloride concentrations in the hypolimnion were 60-70 mg/L while surface water concentrations were 35-40 mg/L (Figure 16). During the winter of 2015-16, elevated chloride concentrations were observed in the hypolimnion (Figure 15b & d, Figure 16). The onset of this rise in concentration coincides with two runoff events in late-February and early-March. The water column mixed completely in the spring of 2016 and stayed relatively uniform in concentration until a runoff event in January 2017.

The elevated surface water chloride concentration in 2016, compared to 2015, is the result of the lake mixing in the fall of 2015 and again in the spring of 2016, redistributing the higher concentration hypolimnetic water throughout the water column. This underscores the importance of studying the entire water column, as the change in surface water concentration would appear to contradict the expected trend after a mild winter.

The gradient of chloride concentrations through the water column should be investigated further. There are several possible mechanisms that could lead to this gradient. One is that stormwater that has high concentrations of salt, and is therefore denser, flows along the lake bottom and settles into the deepest portion of the lake. It is also plausible that there is an exchange with groundwater that has a higher chloride concentration than the ambient lake water. These two situations are not mutually exclusive, it's possible that both are occurring.

Stormwater Monitoring

Mirror Lake receives direct discharge from over twenty-one stormwater outfalls around the lake (Figure 2). These discharge points contain runoff from state and local roads, sidewalks, parking lots, rooftops, and lawns. As a result, the discharge from these outfalls has the possibility of transporting contaminants from these locations directly to Mirror Lake in quantities that can adversely affect water quality.

The Ausable River Association and Paul Smith's College Adirondack Watershed Institute sampled 21 stormwater discharge points, plus the lake inlet and outlet, during two separate runoff events (Feb. 25th and Mar. 9th, 2016) during the winter of 2015-2016. All outfalls that were flowing and accessible were sampled on each day. On the second sampling day, 3 of the discharge points were not accessible or not flowing and, therefore, were not sampled. Water samples were processed at the Adirondack Watershed Institute for a variety of analytes. In this report, we present data on chloride, total phosphorus, and total suspended solids.

These data are reported as a concentration, which does not indicate the total load of these substances entering the lake. To calculate loadings, discharge would need to be measured at each outfall. Collecting discharge data was not within the scope of this project but should be considered in the future.

Chloride

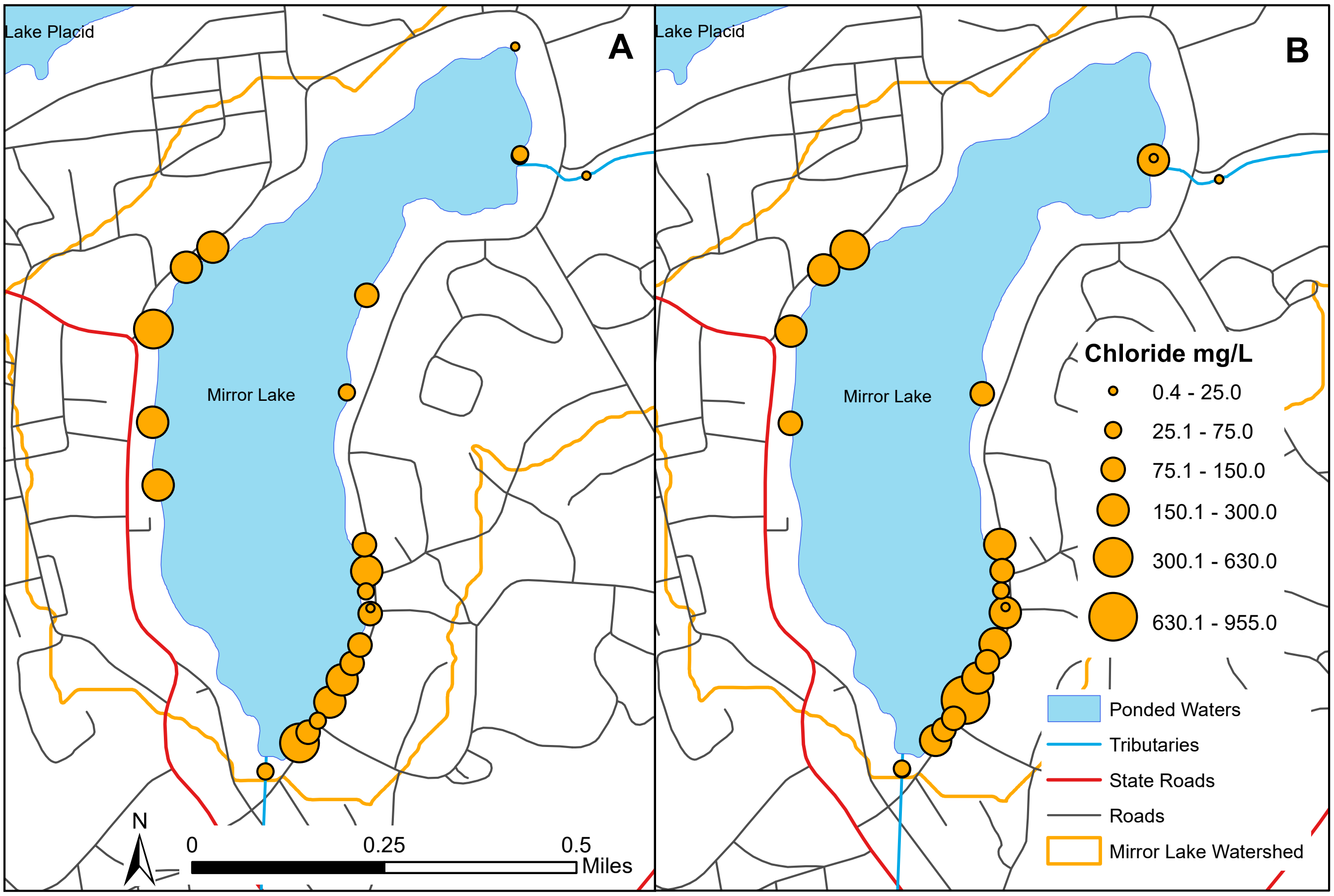

Figure 17. Chloride concentrations measured at stormwater outfalls, the inlet, and outlet of Mirror Lake during stormwater runoff events on February 25th (a) and March 9th (b), 2016.

Chloride concentrations were highest along both the west and southeast portions of the lake on both sampling days (Figure 17a & b). There was no difference in the concentration of chloride at discharge points draining state and local roads versus discharge points draining only local roads. Concentrations at the inlet, just above Mirror Lake Drive, were 1.0 and 2.5 mg/L on the respective sampling days. This is slightly above the expected concentration for a water body that has no roads within its watershed (0.24 mg/L, Kelting et al. 2012) and is likely the result of the influence of Mt. Whitney Road. At the outlet, concentrations were 47.3 and 44.5 mg/L, on the respective sampling days. The stormwater discharge points had concentrations as high as 955 mg/L. As a point of reference, the EPA drinking water guideline for chloride is 250 mg/L. The difference in concentrations between the inlet and outlet, along with the known surface water concentrations, suggests that large amounts of chloride are being retained in the lake.

Total Suspended Solids

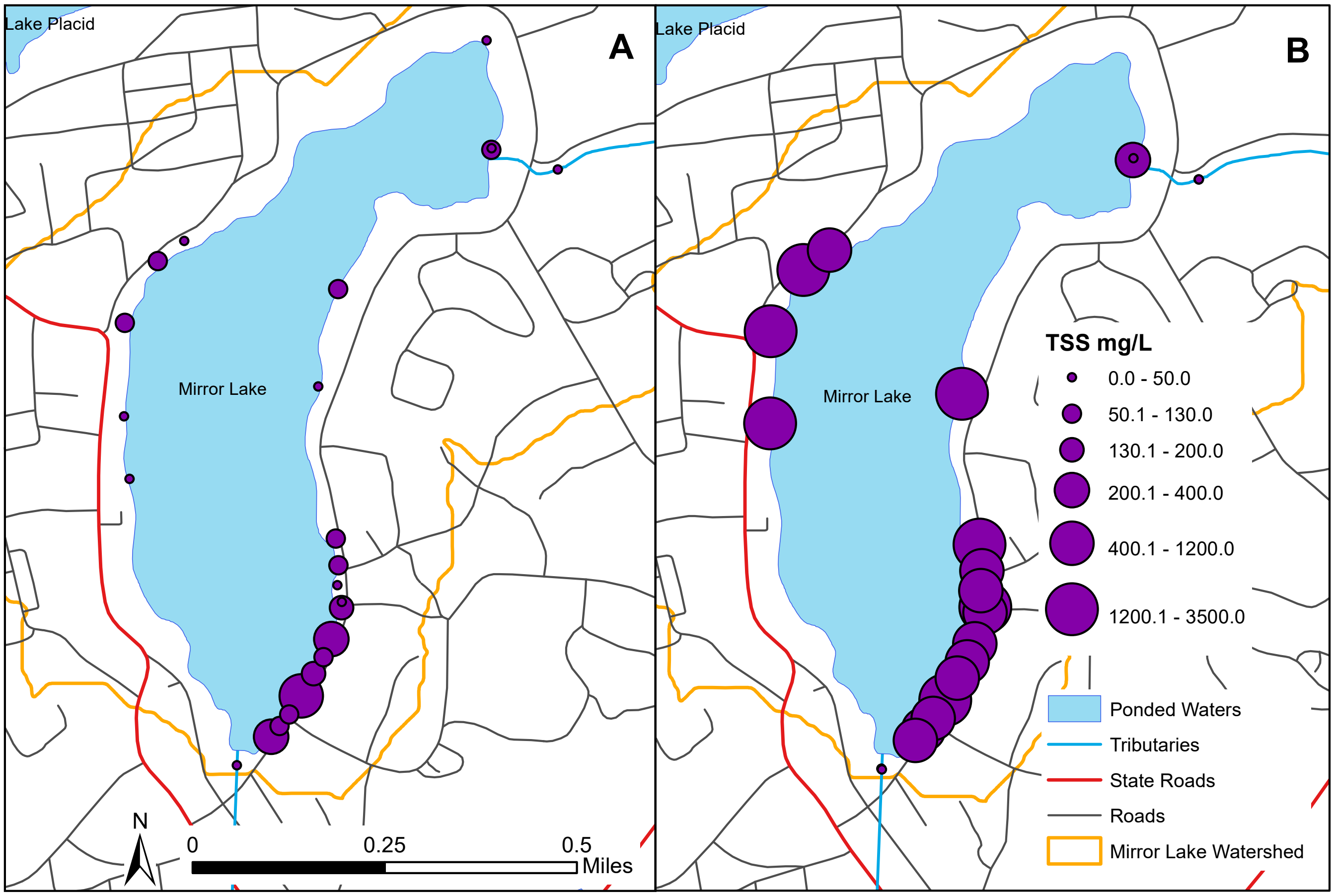

Figure 18. Total suspended solids concentrations measured at stormwater outfalls, the inlet, and outlet of Mirror Lake during stormwater runoff events on February 25th (a) and March 9th (b), 2016.

Total Suspended Solids (TSS) are solids in water that are capable of being trapped by a filter. The material can be anything from sand and silt to plant material or other debris. There was a large difference in concentrations of TSS between sampling days (Figure 18a & b). This may reflect the timing of the sampling effort within the runoff event. Concentrations at the outfalls were as high as 3,461 mg/L whereas the outlet ranged from 3.7 to 4.9 mg/L. In comparison, the inlet ranged from 5.7 to 17.3 mg/L. The road runoff represents a 200 to 607 times higher concentration of TSS entering the lake than natural runoff. This indicates, as expected, that this material is settling out and being retained in Mirror Lake. Excessive suspended solids can smother fish and other aquatic organism habitat, as well as transport nutrients and other pollutants into the lake.

On the first sampling day (Feb. 25th) TSS were lower on the west shore of the lake at the outfalls that pass through hydrodynamic separator units designed to filter out suspended material (Figure 18a). On the second sampling day (Mar. 9th) those outfalls also had high TSS (Figure 18b). This suggests that the flow was either substantial enough to cause the units to be less effective, or that they were overwhelmed with sediment and material from previous runoff events.

Total Phosphorus

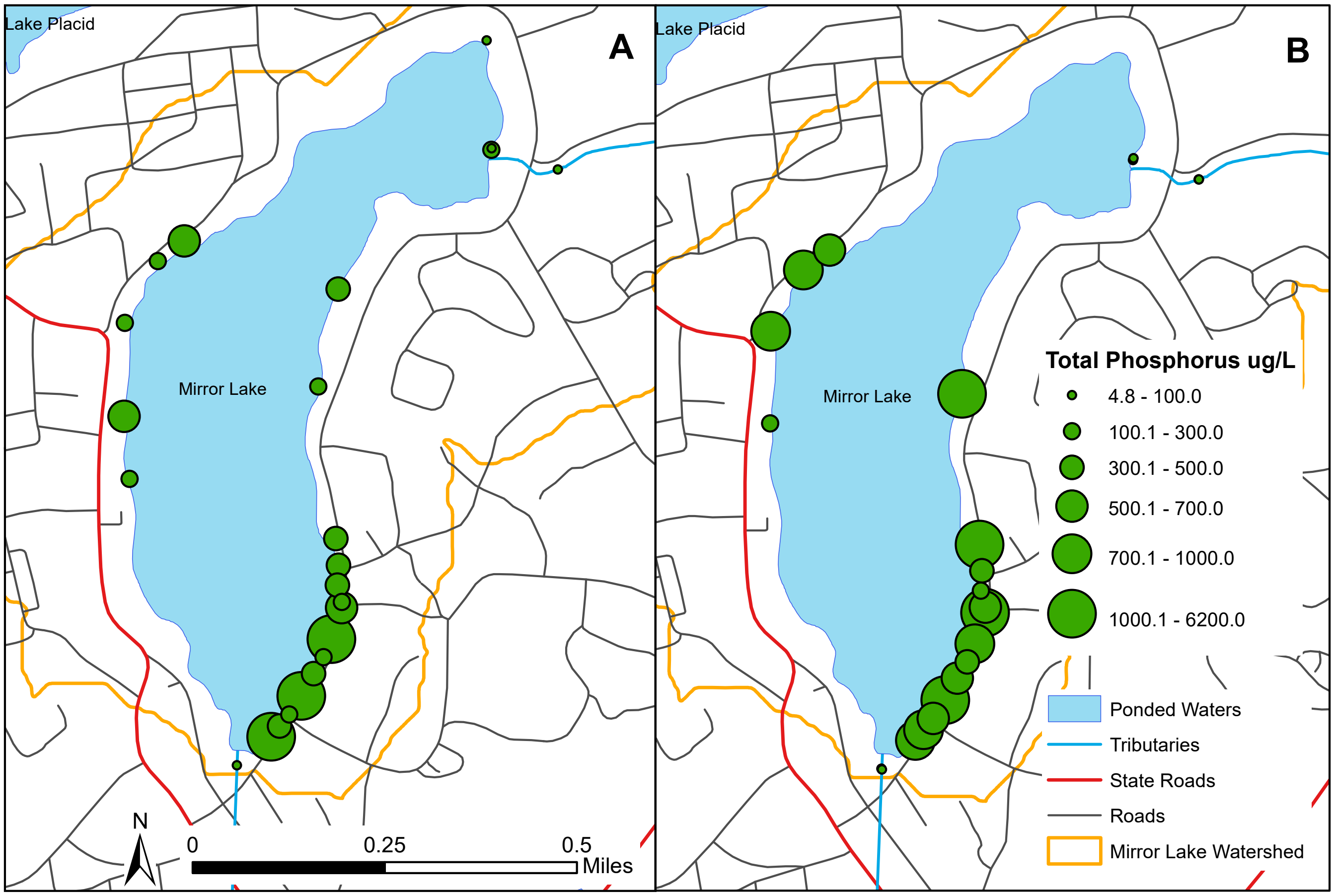

Figure 19. Total phosphorus concentrations measured at stormwater outfalls, the inlet, and outlet of Mirror Lake during stormwater runoff events on February 25th (a) and March 9th (b), 2016.

High concentrations of total phosphorus were found around the lake on both sampling days (Figure 20a & b), although there was greater variability between days and outfalls than there was in the chloride data. Particularly high concentrations were found along the southeast portion of the lake on both sampling days. The highest recorded concentration was 6,200 µg/L, which is 1,409 times higher than the concentration found in surface water of the lake. During runoff events, the total phosphorus load may have a high proportion of particulate inorganic phosphorus (PIP), a form of phosphorus not usable by primary producers. The likely source of this PIP include street dirt, sand, and soil. However, it's possible that some of this load could include usable forms of phosphorus from alternative de-icing products, wastewater ingress, and residual runoff from lawn fertilizers.

Conclusions

The large amount of watershed development, amount of impervious cover, direct stormwater runoff, and community value associated with Mirror Lake makes it an interesting lake to study. Through the effort of volunteers, we have a long-term record of water quality for Mirror Lake. The more recent data collection efforts by AsRA and AWI show the value of a more rigorous monitoring program. Through these efforts, we have a better understanding of the major water quality impairments for the lake: road runoff and low hypolimnetic oxygen concentrations. Mirror Lake has shown significant increases in sodium, chloride, and calcium over time. All are likely the result of road runoff and the application of road salt to the roads and sidewalks surrounding the lake. Stormwater monitoring conducted in 2016 shows that high concentrations of chloride and other analytes are coming from stormwater outfalls around the entire lake, not just the western side which receives runoff from the state maintained road. These data indicate that local winter road and sidewalk maintenance practices are also impacting the water chemistry of Mirror Lake. Continued bi-weekly monitoring is important to understanding the total load and distribution of sodium and chloride within the lake. Additional monitoring of the lake inlet, outlet, and select stormwater outfalls would also be beneficial to understanding how road salt enters and moves through Mirror Lake.

Low hypolimnetic dissolved oxygen concentrations, coupled with a longer open water season, are of concern for the long-term viability of the lake trout population. Currently, we do not have enough data to understand if this is natural for Mirror Lake. Continued monitoring of the lake will help us understand the mechanisms responsible for the low dissolved oxygen. Additional studies using paleolimnological approaches would allow for a better understanding of whether Mirror Lake exhibited low hypolimnetic dissolved oxygen prior to watershed development.

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Appendix

Table A1: History of water quality research on Mirror Lake

Year(s)	Researchers/Program	Report
1971	Oglesby	A study of Lake Placid and Mirror Lake during 1971.
1974	Oglesby & Mills	A further study of Lake Placid and Mirror Lake, August 5-6, 1974
1976 & 1978	Don Charles	Personal communication
1996	Schmall et al. / Paul Smith's College	Mirror Lake
1998	Martin / Paul Smith's College	Mirror Lake
2000	Murray et al. / Paul Smith's College	Mirror Lake
1998-2001, 2003-2011, 2013-2016	CSLAP	Annually issued reports
2014	ALAP	Annually issued reports
2015-2016	Wiltse et al. / AsRA & AWI	Mirror Lake: 2016 Water Quality Report

Table A2: Analytical methods performed on water samples at the AWI Environmental Research Lab.

Analyte	Method Description	Reference
Lab pH	Mettler Toledo standard pH electrode	APHA
Conductivity	Conductivity at 25°C via Mettler Toledo conductivity cell	APHA 2510 B
Apparent Color	Single wavelength method with PtCO standards	APHA 2120 C
Chlorophyll-a	Trichromatic method uncorrected for phaeophyton	APHA 10200 H
Total Phosphorus	Acid-persulfate digestion, automated ascorbic acid reduction	APHA 4500-P H
Nitrate + Nitrite	Automated cadmium reduction	APHA 4500-NO_3 I
Alkalinity	Automated methyl orange method	EPA 301.2
Chloride	Automated ion chromatography	EPA 300.0
Calcium and Sodium	Inductively coupled plasma optical emission spectroscopy	EPA 200.7