CAMPSITE #22 ON COAL PIT ISLAND IN LOWER SARANAC LAKE, FRANKLIN CO., ADIRONDACK PARK & FOREST PRESERVE, NY

3

EVALUATING THE RECOVERY OF UPPER SARANAC LAKE, NY

COREY L. LAXSON,[1] SEAN REGALADO,[2] AND DANIEL L. KELTING[3]

1. Senior Research Associate, Paul Smith's College Adirondack Watershed Institute, P.O. Box 265, Paul Smiths, NY 12970; (518) 327-6101, claxson@paulsmiths.edu

2. Research Assistant, Paul Smith's College Adirondack Watershed Institute, P.O. Box 265, Paul Smiths, NY 12970; (518) 327-6101, sregalado@paulsmiths.edu

3. Executive Director, Paul Smith's College Adirondack Watershed Institute, P.O. Box 265, Paul Smiths, NY 12970; (518) 327-6213, dkelting@paulsmiths.edu

ACKNOWLEDGMENTS: This work was supported with funds from the Upper Saranac Lake Foundation and the Upper Saranac Lake Association. Special thanks to Elizabeth Yerger and Michael Martin for their contributions to this project.

KEYWORDS

Upper Saranac Lake, water quality, eutrophication, oxygen depletion, transparency

ABSTRACT

Anthropogenic impacts to the Upper Saranac Lake watershed have been occurring for over 130 years. The ecological degradation became widely recognized 1989-1990 when a series of persistent cyanobacterial blooms plagued the lake. Of the numerous nutrient sources in the watershed, the most influential discharger was believed to be the Adirondack Fish Culture Station, a hatchery operated by the New York State Department of Environmental Conservation for over 100 years. Facing litigation from the Upper Saranac Lake Association, Hatchery management initiated strategies to significantly reduce phosphorus discharge beginning in 1993. The objective of this study is to evaluate the recovery of the lake

by examining historical limnological data. Concentrations of total phosphorus and chlorophyll-a in the surface water have exhibited significant declines since the early 1990s. Oxygen depletion rate in the bottom strata has also exhibited positive signs of recovery; however, the re-occurring hypoxia in the shallow north basin shows no sign of recovery. Despite reductions in nutrients and algal abundance, the transparency of the lake has significantly decreased over the study period. Analysis of 26 years of data indicates that the trophic condition of Upper Saranac Lake has experienced substantial recovery from the degraded state observed in the early 1990s, although impact from multiple environmental stressors may be masking the typical signals of trophic recovery.

INTRODUCTION

Upper Saranac Lake is one of the more intensely studied lakes in the Adirondack region. The water quality of the lake was first described in 1930, and thanks to the efforts of the Upper Saranac Lake community, has been continually monitored since 1989 (reviewed by Kelting 2013). In addition to routine monitoring, an impressive amount of research has been published from Upper Saranac Lake, including studies on: degradation of water quality (Stager, Leavitt, and Dixit 1997), environmental activism (Perry and Vanderklein 1996), impact of Eurasian water milfoil *Myriophyllum spicatum* (Wilson and Ricciardi 2009), management of aquatic plants (Kelting and Laxson 2010), fate of septic tank effluent (Chen 1988), use of bioindicators (Benson 2008), spawning of lake trout *Salvelinus namaycush* (Royce 1951), and accumulation of DDT in fish (Burdick, Harris, Dean, Walker, Skea, and Colby 1964).

Perhaps the most important component of all this research occurred when Upper Saranac served as a highly publicized example of the effects that persistent nutrient enrichment can have on water quality, even in seemingly pristine areas such as the Adirondacks. Anthropogenic impact to the watershed began with extensive logging in the mid 1800s followed by fish hatchery establishment (1885), hotel development (1888-1946), road construction (1909), and the establishment of cottages, private homes, and large camps, many with insufficient wastewater management (1910 to current; Stager et al. 1997). Additional sources of nutrients within the watershed include an agricultural field, public campsites, and a golf course. By the late 1970s it was evident to shore owners that the water quality was deteriorating (Handler 1991). From late 1989 through 1990 a persistent series of cyanobacterial blooms occurred throughout the lake comprised primarily of *Anabaena*, *Aphanizomenon*, and *Planktothrix* (formerly *Oscillatoria*). The blooms were documented in 9 out of 12 months in 1990 and often extended downstream to the Saranac River as well as Middle and Lower Saranac Lakes (Martin and Stager 1994, Handler 1991). In addition, the bottom waters of the lake were found to be anoxic during the summer months, causing significant strain to the salmonid fishery of the lake (Martin 1993). Of the numerous nutrient sources in the watershed the most influential discharger was believed to be the Adirondack Fish Culture Station, a hatchery operated by the New York State Department of Environmental Conservation (NYSDEC) From 1885 to 1989 the fish hatchery operated without any waste water treatment. For over 100 years it was a common practice to rake nutrient rich sludge from the runways into the outlet of Little Clear Pond which flows into Mill Brook, a class AA tributary stream of the north basin of Upper Saranac Lake (De Angelo and Smith 1991). The hatchery went offline between 1989 and 1990 for a 2.8 million dollar facility expansion and upgrade. However, due to cost, the NYSDEC did not add adequate effluent treatment, only installation of a primary treatment facility (solid settling). An unusually rainy period in the fall of 1989 coincided with the facility upgrade and likely resulted in large unquantified pulses of phosphorus from the flooded former rearing areas (De Angelo and Smith 1991). During the early 1990s the hatchery was discharging approximately two pounds of phosphorus per day, with a total discharge of 3.6 million gallons per day. While this concentration is below the phosphorus limit for most wastewater discharge, the sheer volume of the discharge, coupled with the fact that most of the phosphorus was in a bio-available form, made the hatchery a significant polluter within the Upper Saranac Lake watershed. In 1993 the Upper Saranac Lake Association representing 550 residents filed suit against the NYSDEC for failure to adhere to water pollution control laws (reviewed by Perry and Vanderklein 1996). In response to litigation, and after lengthy back-and- fourth battles, hatchery management initiated several strategies to decrease phosphorus loading to the lake in 1993, including: facility upgrades, raceway maintenance, reduced phosphorus content in food, and targeted feeding methods. In addition, Upper Saranac Lake produced a watershed management plan that spurred further reduction in point and non-point source pollution to the lake (Martin 1998).

Although this story of Upper Saranac Lake was highly publicized in the region and numerous detailed reports and papers were generated throughout the 1990s (e.g., Martin et. al 1998, Stager et al 1997), no assessment has been done on the long-term response of the lake to the pollution mitigation strategies initiated in the early 1990s. In this paper we document historical trends in key trophic indicators of Upper Saranac Lake for a 22 year interval (1993-2015), a period in which reduced phosphorus loading from the Adirondack Fish Culture station were enacted.

METHODS

Site Description

Upper Saranac Lake is a 2,167 hectare (4,843 acre) lake located in Franklin County, New York (Figure 1). The lake is located within a 20,042 hectare (49,504 acre) watershed dominated by forest cover. Detailed characteristics of the lake and its watershed can be found in Martin et al. (1998) as well as Kelting and Laxson (2014). The lake is morphologically divided into two distinct basins referred to as the north and south basins. The two basins are also distinct in their limnology. The north basin is relatively shallow with a maximum depth of 16 meters (54 feet) and does not support a well-developed hypolimnion during late summer stratification. The bottom waters of the north basin routinely experience hypoxic conditions during the summer months (dissolved oxygen less than 2 mg/L) with anoxic conditions (dissolved oxygen less than 0.5 mg/L) common from August through fall turn over. In contrast, the south basin reaches a depth of 28 meters (92 ft) and develops a well-defined hypolimnion that experiences only periodic hypoxia (dissolved oxygen less than 2.0 mg/L).

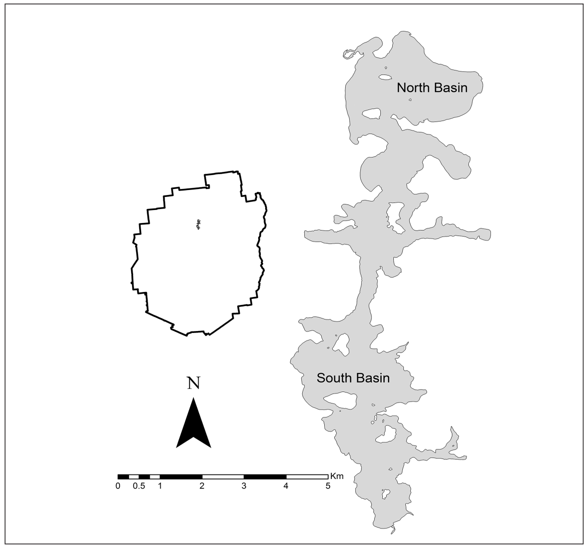


Figure 1. *Upper Saranac Lake and its location in the northern Adirondacks.*

Data Collection

Field data for 2010-2015 was collected from the R.V. *Clearwater* at the deepest sections of the north and south basins five to seven times starting in mid-May and ending in October. Transparency was observed using a 20 cm black and white Secchi disk from the shady side of the vessel. Temperature and dissolved oxygen (DO) were determined every meter from the surface to the bottom with an HACH Quanta multi meter and data logger. Surface water samples were collected using a 2 meter integrated tube sampler. 250 mL of the surface water was immediately passed through a 0.45μm cellulose acetate filter; the filter was collected, wrapped in foil and put on ice for chlorophyll-a analysis. The hypolimnetic water was collected with a 1 L Kemmerer bottle from approximately 1 meter off the bottom. The water samples were kept on ice and transported to the Adirondack Watershed Institute Environmental Research Lab where they were chemically preserved to a pH of 2.0 and stored at 4°C until analysis for total phosphorus could be completed (within 30 days). Chlorophyll-a concentration was determined spectrophotometrically using the trichromatic method after extracting the pigment from the macerated cellulose acetate filter into 6 mL of 90% acetone (APHA 2005). Total phosphorus concentration was determined following EPA method 365. Unfiltered water was digested in an autoclave with ammonia persulfate and sulfuric acid prior to colorimetric analysis on a Lachat QC8500 flow injection analyzer (Loveland, CO).

Field and laboratory data from 2010-2015 was combined with historical limnological data from Upper Saranac Lake, which had been collected by various research groups in a similar manner since 1989 (reviewed by Kelting 2013). The majority of data was collected by the Paul Smith's College Adirondack Watershed Institute, followed by Cedar Eden Environmental, and the New York State Citizen Science Lake Assessment Program (CSLAP). Historically, monitoring has occurred at the same locations in the lake, one to three times per month typically during the May to October interval.

Table 1. *Trophic classifications of lakes based on Carlson's Trophic State Index (TSI).*

TSI VALUE	TROPIC CLASSIFICATION	LIKELY ATTRIBUTES
<30	Oligotrophic	Clear water, high oxygen throughout hypolimnion during the entire year.
30-40	Oligotrophic	Clear water, periods of hypolimnetic anoxia possible during the summer in relatively shallow lakes.
40-50	Mesotrophic	Moderately clear, increased probability of hypolimnetic anoxia during the summer.
50-60	Eutrophic	Mildly eutrophic. Decreased transparency, hypolimnetic anoxia and warm water fishery only. Supports all recreational and aesthetic uses but threatened.
60-70	Eutrophic	Dominance of blue-green algae likely, extensive macrophyte growth in shallow water
70-80	Hyper-eutrophic	Heavy algal blooms possible throughout summer. Recreational and aesthetic uses greatly impacted.
>80	Hyper-eutrophic	Algal scum, summer fish kills, few macrophytes due to algal shading.

Data Analysis – Trophic Indicator Trends

Transparency depths, chlorophyll-a, and total phosphorus concentration were tabulated and time series graphs were constructed from the annual average value for each indicator from 1989-2015. Trend analysis was conducted on the data from 1993-2015 to determine the lakes response to pollution abatement strategies enacted by the Adirondack Fish Culture station beginning in 1993. Because the water quality data lacked independence between years, we used Kendall's Tau, a rank correlation coefficient used to test the null hypothesis that there was no association between water quality variables and time. Average annual values for secchi disk transparency, total phosphorus, and chlorophyll-a in the lake were also used to calculate Carlson's Trophic Status Index (TSI), a commonly used quantitative index for classifying lakes based on trophic status (Carlson 1977). Lakes with TSI values less than 40 are classified as oligotrophic, TSI values between 40 and 50 are classified as mesotrophic, and TSI values greater than 50 are classified as eutrophic. A detailed description of TSI values and likely lake attributes is found in Table 2.

Table 2. *Trophic indicator values in the surface water and bottom water of the north basin (upper panels) and south basin (lower panels) of Upper Saranac Lake during the 2015 sampling season. ND indicates no data, and ± indicates a value that is below the practical quantitation level of the lab, thus it represents an estimated value.*

TROPHIC INDICATOR NORTH BASIN	SAMPLING DATE 2015 5/18	6/17	7/16	8/10	9/3	9/23	10/1	AVERAGE
Surface water (0-2 meter integrated)								
Transparency (m)	2.4	3.2	2.5	2.9	3.3	3.9	1.9	2.9
Total phosphorus (µg/L)	14.5	10.3	7.5	5.6	7.2	4.5	11.7	8.8
Chlorophyll-a (µg/L)	5.5	6.9	9.0	2.2	4.1	4.4	6.3	5.5
Bottom Water (16 meters)								
Total phosphorus (µg/L)	39.8	58.2	47.1	33.8	63.8	64.3	38.8	39.4
Dissolved Oxygen (mg/L)	8.8	3.0	0.9	1.0	0.9	0.7	1.3	2.2

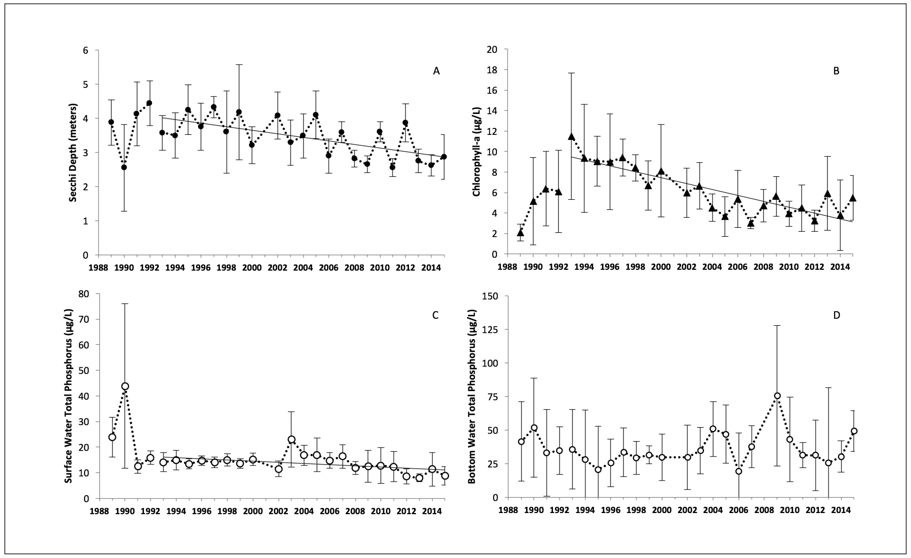
TROPHIC INDICATOR SOUTH BASIN	SAMPLING DATE 2015 5/18	6/17	7/16	8/10	9/3	9/23	10/1	AVERAGE
Surface water (0-2 meter integrated)								
Transparency (m)	3.3	3.5	2.5	3.0	4.1	4.2	3.0	3.4
Total phosphorus (µg/L)	11.7	9.6	7.2	7.5	6.3	± 3.2	8.3	7.7
Chlorophyll-a (µg/L)	2.7	4.2	6.6	2.8	4.3	6.0	7.2	4.8
Bottom Water (25 meters)								
Total phosphorus (µg/L)	8.9	9.3	16.1	51.3	43.1	33.1	6.8	24.1
Dissolved Oxygen (mg/L)	9.9	7.2	6.0	4.1	3.9	4.1	1.9	5.3

Data Analysis – Dissolved Oxygen Dynamics

The maximum areal extent (km^2) of hypoxic and anoxic waters were quantified and compared between years by combining late summer dissolved oxygen profiles with lake bathymetry. Bathymetric analysis was performed using ArcMap's "Topo to Raster" tool to interpolate a bathymetric raster of Upper Saranac Lake from 471 bathymetric points downloaded from the New York State GIS clearing house (https://gis.ny.gov/gisdata) and 3,815 appended points representing shorelines with depth of zero. Bathymetric contours at 1 m intervals were derived from the bathymetric raster using the "Contour" tool. Artifacts of interpolation produced contour lines outside the lake boundary; these contours were edited to fit within the lake boundary.

The rate of dissolved oxygen loss in the hypolimnion normalized for hypolimnion surface area, known as areal hypolimnetic oxygen depletion rate (AHOD), was calculated for each summer using bathymetric data and the historical DO profiles following the methods used by Matthews and Effler (2006). The volume weighted DO concentration and total hypolimnetic DO mass were calculated from profile data and the volumes of the corresponding 1 m layers. Rates of hypolimnetic oxygen depletion were calculated for each year from the slopes (g/day) of hypolimnetic DO mass versus time during the period of near linearity, divided by the area of the upper boundary of the hypolimnion. The data range for DO profiles was from 1990-2015, however there was insufficient DO profiles for AHOD analysis in years 1993, 2000-2001, 2006, 2007, and 2012. Because the north basin is too shallow for a consistent hypolimnion to develop, AHOD rates were only calculated for the south basin.

Figure 2. *Time series of the average annual trophic indicators for the north basin of Upper Saranac Lake 1989-2015. Vertical bars represent one standard deviation of the mean. Significant trends (P < 0.05) since 1993 are indicated with a trend line. (A) Secchi disk transparency: T = -0.43, P = 0.006; (B) chlorophyll-a concentration in the surface water: T = -0.63, P <0.001; (C) total phosphorus concentration in the surface water: T = -0.43, P = 0.006; and (D) total phosphorus concentration in the bottom water: T = 0.21, P = 0.194.*



RESULTS

Trophic Indicators – North Basin

Secchi disk transparency in the north basin ranged from 1.9 to 3.9 meters in 2015 (Table 2). Since monitoring began in 1989 the annual average transparency has ranged from a low of 2.5 meters to as high as 4.4 meters, and has exhibited a significant downward trend since 1993 at a rate of approximately 5 cm/year (T = -0.43, P = 0.006, Figure 2). Total phosphorus concentration in the surface water averaged 8.8 µg/L in 2015 (Table 2), with the highest concentration of 14.5 µg/L detected on May 18. In the bottom water average total phosphorus concentration was four times higher, with the highest concentration of 64.3 µg/L occurring in late September. Historically, the highest concentration of total phosphorus in the surface water occurred in 1990, with a summer average of 45 µg/L. Total phosphorus concentration was substantially lower in all subsequent years, with a slight yet significant downward trend in the surface water concentration since 1993, decreasing at a rate of 0.2 µg/L/year (T = -.037, P=0.016, Figure 2). The bottom water total phosphorus concentration has remained elevated throughout the monitoring period, and has not exhibited a significant positive or negative trend (P=0.194, Figure 2). Chlorophyll-a concentration in 2015 ranged from a low of 2.2 µg/L to a maximum of 9.0 µg/L observed on July 17. The average chlorophyll-a concentration in 2015 was 5.5 µg/L, which was similar to average values over the last decade (Figure 2). However, we did detected a significant downward trend in chlorophyll-a concentration since 1993 at a rate of 0.30 µg/L/year (T = -0.64, P<0.001, Figure 2). Carlson's TSI calculated from total phosphorus (35) indicates an oligotrophic condition, while the TSI calculated from transparency (47) and chlorophyll-a both indicates a mesotrophic condition. Historically the TSI values for the north basin have been highly variable (Figure 3).

Figure 3. *Time series of the average annual value for Carlson's Trophic Status Index in the north basin of Upper Saranac Lake calculated from transparency, total phosphorus, and chlorophyll-a data. The horizontal grey box represents the mesotrophic condition, with the eutrophic and oligotrophic conditions above and below it.*

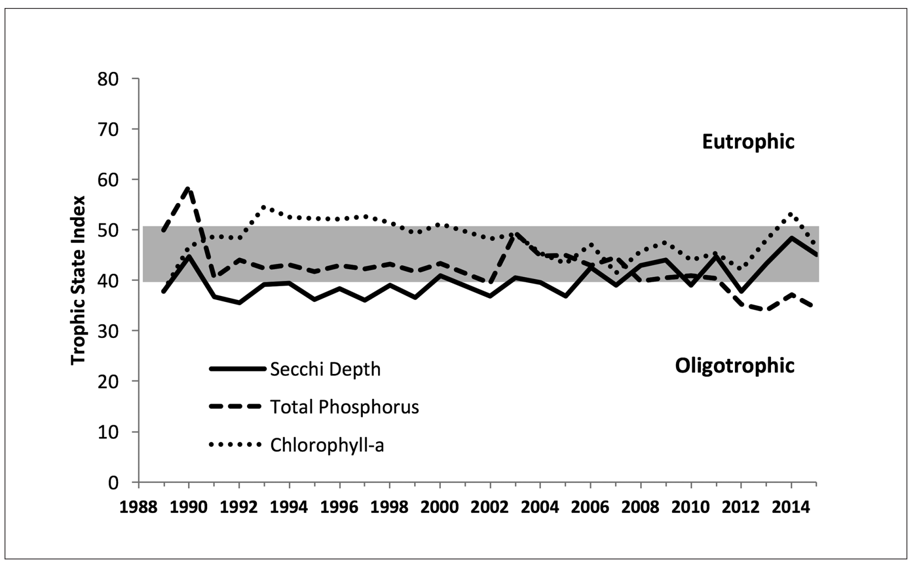
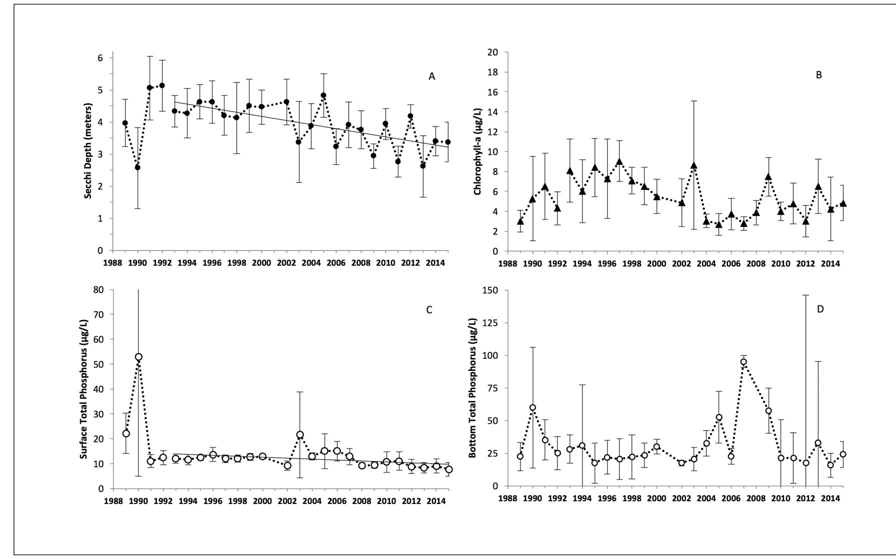


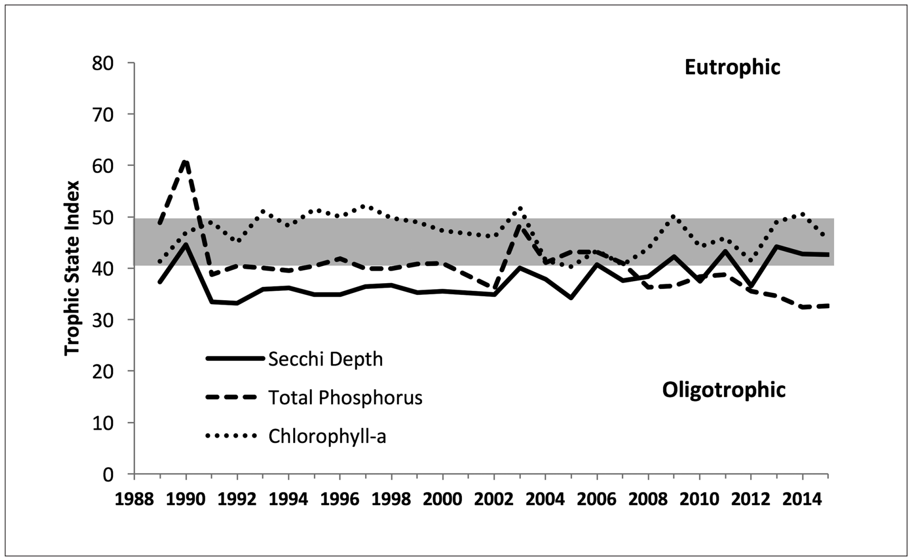
Figure 4. *Time series of the average annual trophic indicators for the south basin of Upper Saranac Lake 1989-2015 Vertical bars represent one standard deviation of the mean. Significant trends (P < 0.05) since 1993 are indicated with a trend line. A) Secchi disk transparency: T = -0.39, P = 0.006; (B) chlorophyll-a concentration in the surface water: T = -0.19, P = 0.190; (C) total phosphorus concentration in the surface water: T = -0.39, P = 0.005; and (D) total phosphorus concentration in the bottom water: T = -0.93, P = 0.528.*



Trophic Indicators – South Basin

Historically secchi disk transparencies have been greater in the south basin than in the north basin. This was also the case in 2015 when transparency in the south ranged from 2.5 to 4.1 meters and averaged 3.4 meters (Table 2). Since monitoring began annual average transparency has ranged from a low of 2.6 meters in 1990 to as high as 5.1 meters in 1993. A significant downward trend in transparency exists since 1993, at a rate of 6 cm/year (T = -0.39, P = 0.006, Figure 4). Total phosphorus concentration in the surface water was also lower than in the north basin, and averaged 7.7 µg/L in 2015 (Figure 5), with the highest concentration of 11.7 µg/L detected on May 18. In the hypolimnion average total phosphorus concentrations were considerably higher, with the highest concentration of 51.3 µg/L occurring on August 10. Similar to the north basin, the highest average phosphorus concentration observed over the monitoring period occurred in 1990, with a summer average of 53 µg/L. Concentration was substantially lower in subsequent years, with a significant downward trend in the surface water concentration since 1993, decreasing at a rate of 0.2 µg/L/year (T = -0.39, P = 0.005, Figure 4). Despite the downward trend in surface water phosphorus, hypolimnetic phosphorus concentrations in the south basin exhibited no significant positive or negative trend (P = 0.52, Figure 4) and has been elevated and highly variable. Chlorophyll-a concentration in 2015 ranged from 2.7 µg/L in June to a maximum of 7.2 and averaged 4.2 µg/L (Table 2). Chlorophyll-a concentrations have been highly variable in the south basin over the course of study and have exhibited no significant trend over time (P=0.192, Figure 4) Carlson's TSI calculated from total phosphorus (32) indicates an oligotrophic condition for the south basin, while the TSI value based on transparency (43) and chlorophyll-a (47) both indicate a mesotrophic condition Historically the TSI values for the north basin have been highly variable (Figure 5).

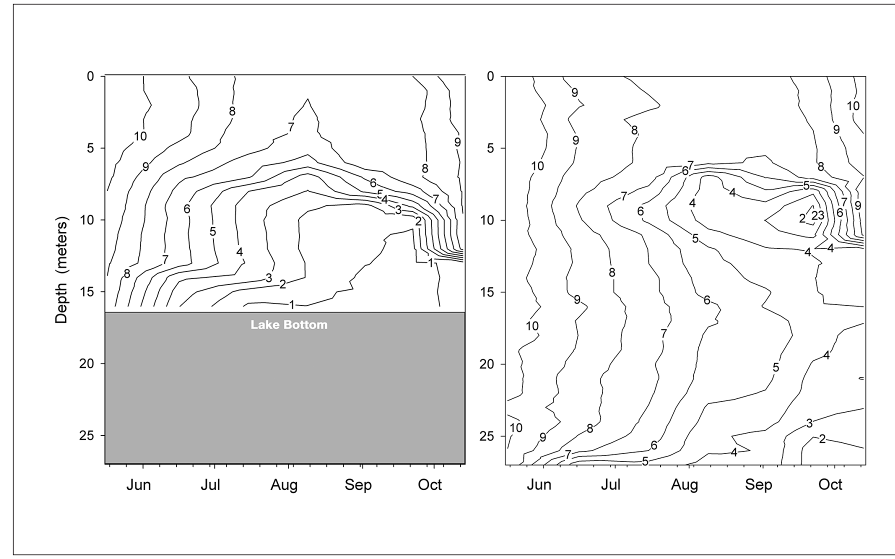
Figure 5. *Time series of the average annual value for Carlson's Trophic Status Index in the north basin of Upper Saranac Lake calculated from transparency, total phosphorus, and chlorophyll-a data. The horizontal grey box represents the mesotrophic condition, with the eutrophic and oligotrophic conditions above and below it.*



Hypolimnetic Dissolved Oxygen Dynamics

During the 2015 season Upper Saranac Lake exhibited its typical clinograde oxygen profile, where the dissolved oxygen is elevated in the epilimnion (surface water of uniform temperature) and decreases with depth (Figure 6). In the north basin the bottom meter of water became hypoxic (DO<2.0 mg/L) by early July. By early September, 30% water of the water column had a dissolved oxygen concentration less than 1.0 mg/L. Oxygen depletion occurred in the south basin as well, but not to the extent observed in the north basin. Hypoxia was only observed in the bottom meter of water in the south basin starting in late September.

Figure 6. *Time series isopleth graphs of dissolved oxygen concentration (milligrams/liter) for the north basin (left graph) and south basin (right graph) of Upper Saranac Lake for the 2015 field season.*



Historically, the zone of oxygen depletion was greatest in the early 1990s. In the summer of 1990 the greatest extent of the hypoxic zone covered a region of approximately 6.6 km^2 (Figure 7). The size of this zone increased in 1991 to an area of approximately 10 km^2. After 1991 the hypoxic zone was substantially reduced, and typically ranged between 2 and 4 km^2. The vast majority of the reduction in hypoxic area was observed in the south basin, with a particularly strong decrease in hypoxic region since 2002 (P = 0.005, r^2 = 0.75, Slope = 0.05 km^2/year), while the hypoxic area in the north basin has remained relatively unchanged since monitoring began (Figure 8). Hypolimnetic oxygen depletion rates (the amount of oxygen utilized in the hypolimnion/day) in the south basin have decreased in a fairly progressive fashion, with a significant decrease in oxygen depletion since 1993 (Figure 9, P = 0.01, r^2= 0.40, Slope = -0.006).

Figure 7. *Time series maps of the maximum areal extent of anoxic (dissolved O_2 < 0.5 mg/L) and hypoxic (Dissolved O_2 < 2.0 mg/L) regions of Upper Saranac Lake for the years 1990 – 2015.*

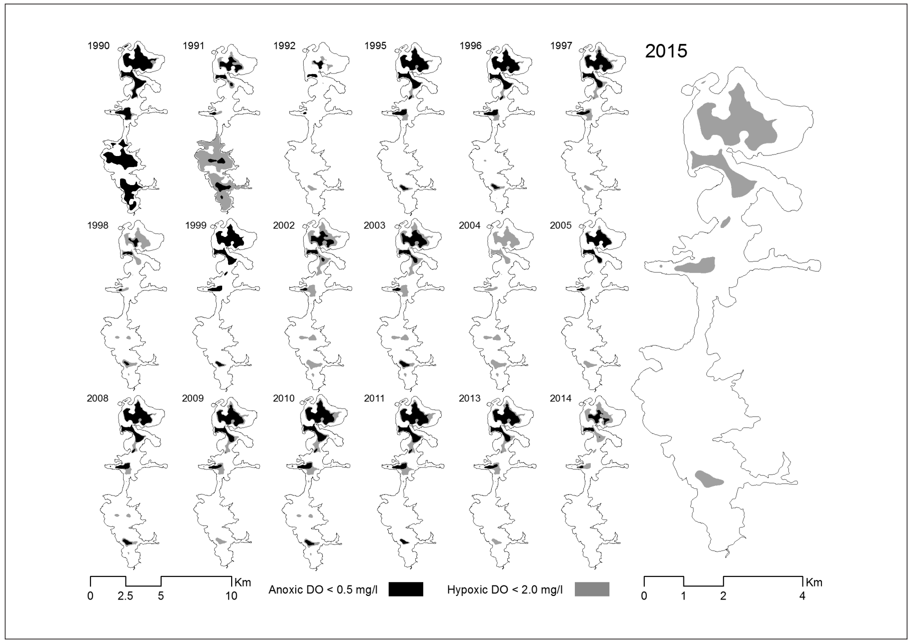


Figure 8. *Maximum areal extent of the hypoxic region of Upper Saranac Lake by basin, 1989-2015. Inset graph shows a zoomed in view of the south basin, for the period of 2002-2015 (P = 0.005, r^2 = 0.75, slope = 0.05 km^2/year).*

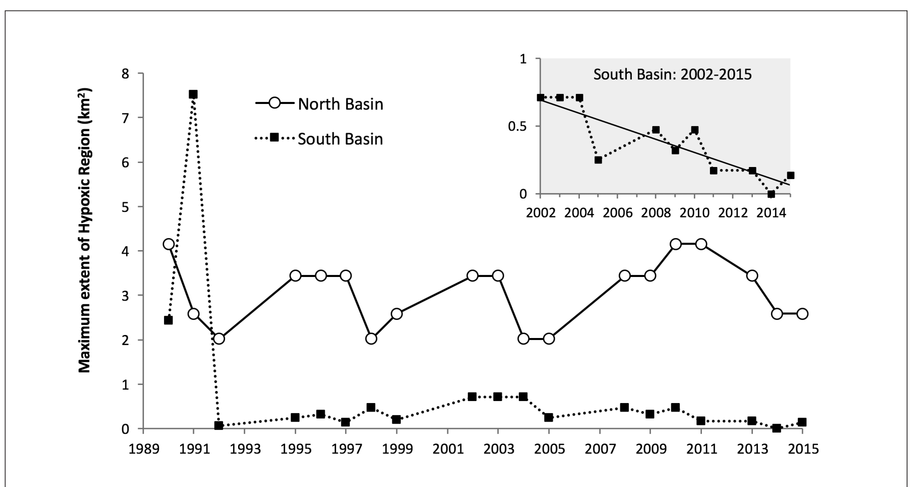
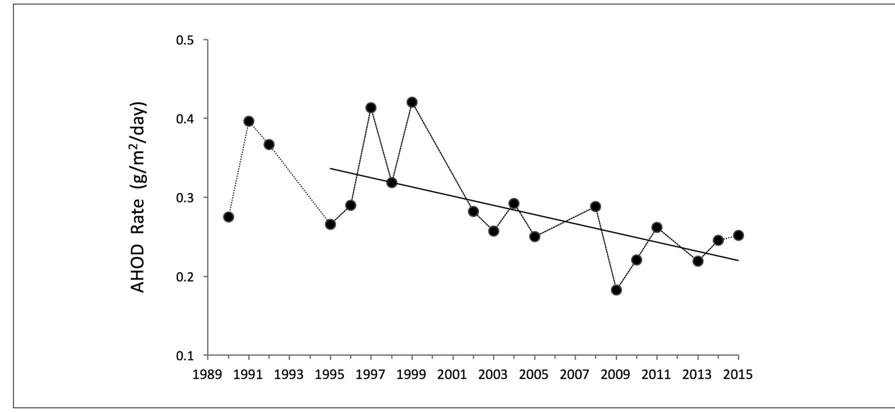


Figure 9. *Average hypolimnetic oxygen depletion rate of the south basin of Upper Saranac Lake. Solid line denotes significant trend since 1993 (P = 0.01, r^2= 0.40, slope = -0.006).*

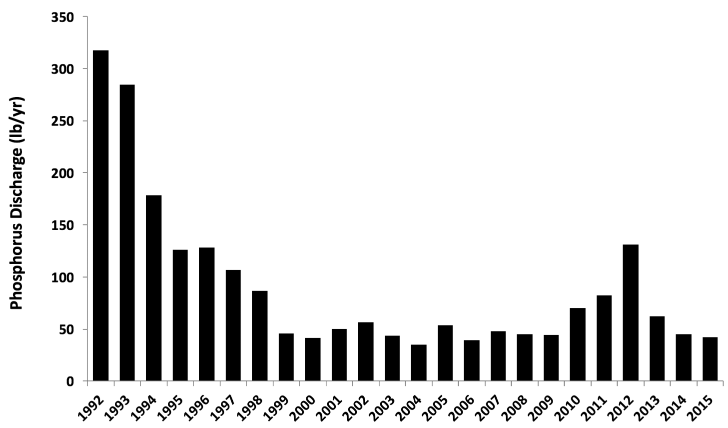


DISCUSSION

Substantial evidence exists that indicates that the trophic condition of Upper Saranac Lake has experienced significant recovery from the degraded state observed in the late 1980s and early 1990s. The most pronounced indicators of the recovery are the decreased concentrations of total phosphorus and chlorophyll-a in the surface water of both lake basins. Total phosphorus concentration is currently below the target of 12 mg/L outlined in the Upper Saranac Lake Management Plan (Martin 1998), and the extensive cyanobacterial blooms that plagued the lake have not been observed since 1991.

The observed decrease in surface water phosphorus concentration is likely due to numerous improvements made to both point and non-point pollution sources. Perhaps the most important of these improvements was the permit modification and implementation of best management practices at the Adirondack Fish Culture Station in the early 1990s. Phosphorus discharge from the hatchery has experienced a seven-fold reduction since 1993 (Figure 10), and the facility currently operates well below its permitted discharge rate of 0.20 kg/day to a maximum of 74.4 kg/year (EPA 2016). Phosphorus concentrations in the surface water have trended down despite the fact that internal loading of phosphorus from the lake sediments is evident. Phosphorus concentration in the bottom strata of the lake are on average three to four times greater than surface water concentrations with no trend detected. The role internal loading of phosphorus plays in the phosphorus budget of Upper Saranac is not well understood. Internally loaded phosphorus did not affect epilimnetic concentrations in 2015 until late autumn. In fact, epilimnetic phosphorus declines during the summer as hypolimnetic phosphorus concentrations increase. This is certainly not the case in all years. The relatively shallow depths and unstable stratification of the north basin make it susceptible to hypolimnetic upwelling during particularly strong wind events. (Osgood 1988, Martin et al. 1998).

Figure 10. *Annual total phosphorus discharge reported for the Adirondack Fish Culture Station.*



With a statistical decrease in phosphorus and algal biomass in the lake surface, we would expect to see an overall increase in water transparency; however, this has not been the case in Upper Saranac Lake. Both lake basins have seen a significant reduction in water transparency since the early 1990s, as a rate of approximately 5 cm/year. Reductions in water transparency appear to be a regional phenomenon. A recent analysis of historical transparency data from 125 Adirondack lakes reveals that 22% of the lakes have exhibited a statistical reduction in transparency (Kelting and Laxson 2015). Current research supports that decreasing transparencies in lakes is related to increased concentrations of dissolved organic carbon (DOC) (Williamson et al 2014. Montieth et al 2007). DOC has a strong ability to absorb light, thus when a lake becomes enriched with DOC, the transparency of the lake decreases. The primary source of DOC is decomposition in the terrestrial landscape. Warmer and wetter climatic patterns may be increasing the decomposition rate and flushing a greater pool of DOC to receiving lakes (Tranvik et al. 2009, Curtis and Schindler 1997). Increased DOC may also be a signal of recovery from acid deposition. As lakes acidify they tend to exhibit an increase in transparency due to a decrease in DOC (Yan 1983; Schindler, Curtis, Parker, and Strainton 1996), so it is possible that acidification recovery may result in an opposite effect. Unfortunately long term data on DOC does not exist for Upper Saranac Lake, and is scarce for many lakes in the region.

Dissolved oxygen depletion continues to be an important component of the limnology of Upper Saranac Lake, particularly in the north basin where more than half of the water column is hypoxic or completely devoid of oxygen from late summer to fall turnover. Several ecological processes are influenced by hypolimnetic hypoxia. The most obvious impact is loss to the fishery. The combination of warm surface water and hypoxic bottom water has contributed to, if not driven, the loss of the salmonid fishery in the north basin. For example, brook trout and lake trout have temperature preferences of 16°C and 10°C respectively (Coutant 1977, Smith 1985), these preferred temperatures can be found in the deeper waters of the north basin but the dissolved oxygen in these areas are well below the optimal range of 5 mg/l (Spoor 1990). Conditions in the south basin are more favorable to salmonids, yet dissolved oxygen concentrations are less than optimal by late summer. The NYS Department of Environmental Conservation currently manages Upper Saranac Lake as a put-and-take lake trout fishery, having stocked 14,500 lake trout in 2014, and 10,500 in 2015 (NYSDEC Fish Stocking Information).

Various features of the DO regime have showed improvement since the 1990s when the oxygen depletion problem was at its worst. In 1991 the hypoxic region of the lake covered over 10 km^2, but has reduced in size to between 2 and 4 km^2 in most years. However, we found that the reduction in hypoxic area has only occurred in the south basin, the areal extent of hypoxia in the north basin remains relatively unchanged. Improvements to the south basin were further validated by examining the time series data on the areal oxygen depletion rates (AHOD). We found the AHOD to be trending down significantly over time. Oxygen depletion in the lower strata of lakes results from bacterial decomposition of organic matter that has settled to the bottom. Elevated oxygen depletion in the hypolimnion is often a symptom of excessive nutrient loading and an indicator of cultural eutrophication. In the case of Upper Saranac Lake, the observed progressive decrease in oxygen depletion rate should serve as an indicator of recovery, at least for the south basin.

With 26 years of consistent limnological data, Upper Saranac Lake represents a unique long term monitoring site for the Adirondacks. Long term monitoring data is incredibly valuable for understanding slow ecological processes, rare phenomena, and highly variable processes (Magnuson et al. 2006, Dodds et al. 2012). Evaluation of the historical data suggests that the pollution mitigation strategies enacted in the early 1990s along with elevated stewardship from the lake community has resulted in significant improvement to the water quality of the lake, particularly in terms of nutrient content, algal abundance, and oxygen content in the south basin. However, the transparency of the lake has decreased over the past two decades, likely in response to regional phenomena such as reduced acid deposition and/or climate change. This surprising finding is an excellent example of how multiple environmental stressors may affect water quality and the need to consider in-watershed and external factors when interpreting long term lake data.

REFERENCES

APHA, American Public Health Association. 2005. *Standard methods for the examination of water and wastewater.* 21st ed. Washington DC.

Benson, E.R., O'Neil, J.M., and W.C. Dennison. 2008. "Using the aquatic macrophyte *Vallisneria americana* (wild celery) as a nutrient bioindicator," *Hydrobiologia*, 596(1): 187-196.

Burdick, G.E., Harris, E.J., Dean, H.J., Walker, T.M., Skea, J., and D. Colby. 1964. "The accumulation of DDT in lake trout and the effect on reproduction," *Transactions of the American Fisheries Society*, 93(2): 127-136.

Carlson, R.E. 1977. "A trophic state index for lakes," *Limnology and Oceanography*, 22(2): 361-369.

Chen, M. 1988. "Pollution of ground water by nutrients and fecal coliforms from lakeshore septic tank systems," *Water, Air, and Soil Pollution*, 37(3-4): 407-417.

Coutant, C.C. 1977. "Compilation of temperature preference data," *Journal of the Fisheries Board of Canada*, 34(5): 739-745.

Curtis, P.J. and D.W. Schindler. 1997. "Hydrologic control of dissolved organic matter in low-order Precambrian Shield lakes," *Biogeochemistry*, 36 (1): 125-138.

De Angelo, M, and C. Smith. 1991. Upper Saranac Lake Association Water Quality Study. 1990 Final Report by the MERI Research Group of Paul Smith's College, Paul Smiths, New York.

Dodds, W.K., Robinson, C.T., Gaiser, E.E., Hansen, G.J., Powell, H., Smith, J.M., Morse, N.B., Johnson, S.L., Gregory, S.V., Bell, T. and T.K. Kratz. 2012. "Surprises and insights from long-term aquatic data sets and experiments," *BioScience*, 62 (8): 709-721.

EPA, Environmental Protection Agency. 2016. EPA discharge monitoring report for year 2016. Accessed 15 May 2016 from https://cfpub.epa.gov/dmr.

Handler, P.R. 1991. "The sliming of Upper Saranac Lake," *Adirondac*, Sep/Oct: 9-12.

Kelting, D.L. 2013. *Upper Saranac Lake: water quality database and monitoring program*. Adirondack Watershed Institute, Paul Smith's College, Paul Smiths New York. PSCAWI #: 2013-02.

Kelting, D. L., and C.L. Laxson. 2010. "Cost and effectiveness of hand harvesting to control the Eurasian watermilfoil population in Upper Saranac Lake, New York," *Journal of Aquatic Plant Management*, 48, pp. 1-5.

Kelting, D.L., and C.L. Laxson. 2014. *Upper Saranac Lake: 2013 water quality report*. Adirondack Watershed Institute, Paul Smith's College, Paul Smiths, New York. PSCAWI #: 2014-67.

Kelting, D.L. and C.L. Laxson. 2015. *State of Adirondack Lakes*. Annual meeting of the Adirondack Lake Alliance. June 2015, Paul Smith's College of Arts and Science.

Magnuson, J.J., Kratz, T.K. and B.J. Benson. 2006. *Long-term dynamics of lakes in the landscape: long-term ecological research on north temperate lakes*. Oxford University Press on Demand.

Martin, M.R. 1993. *The limnological condition of Upper Saranac Lake. Final Report on the 1992 monitoring program.* Adirondack Watershed Institute, Paul Smith's College, Paul Smiths, New York.

Martin, M.R. 1998. Watershed Management Plan for Upper Saranac Lake. Prepared for the Upper Saranac Lake Foundation.

Martin, M.R. and J.C. Stager. 1994. *The limnological condition of Upper Saranac Lake. Final Report on the 1993 monitoring program.* Adirondack Watershed Institute, Paul Smith's College, Paul Smiths, New York.

Martin, M.R., Sutherland, J.W., Bonham, R., Bloomfield, J.A., Gallinger, G., Siegfried, C.A., Gill, R.J. Eichler, L.W., and C.W. Boylen. 1998. *The State of Upper Saranac Lake, NY*. Prepared for the United States Environmental Protection Agency under Section 314 of the Federal Clean Water Act. 239 pp.

Matthews, D.A. and Effler, S.W. 2006. "Long-term changes in the areal hypolimnetic oxygen deficit (AHOD) of Onondaga Lake: Evidence of sediment feedback," *Limnology and Oceanography*, 51(1): pp. 702-714.

Monteith, D.T., Stoddard, J.L., Evans, C.D., de Wit, H.A., Forsius, M., Høgåsen, T., Wilander, A., Skjelkvåle, B.L., Jeffries, D.S., Vuorenmaa, J. and B. Keller. 2007. "Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry," *Nature*, 450(7169): 537-540.

NYSDEC, New York State Department of Environmental Conservation. 2016. Fish Stocking Data, Accessed 15 May 2016 from http://www.dec.ny.gov/outdoor/23260.html.

Osgood, R.A. 1988. "Lake mixis and internal phosphorus dynamics," *Archiv Für Hydrobiologie*. 113(4): 629-638.

Perry, J., and E.L. Vanderklein. 1996. *Water quality: management of a natural resource*. New York: John Wiley & Sons.

Royce, W.F. 1951. "Breeding habits of lake trout in New York," *Fishery Bulletin of the Fish and Wildlife Service*. 52: 59-76.

Schindler, D.W., Curtis, P.J., Parker, B.R. and M.P. Stainton. 1996. "Consequences of climate warming and lake acidification for UV-B penetration in North American boreal lakes," *Nature*, 379(6567): 705-708.

Smith, L.C. 1985. The Fishes of New York State. Albany. Department of Environmental Conservation

Spoor, W.A. 1990. "Distribution of fingerling brook trout, *Salvelinus fontinalis* (Mitchill), in dissolved oxygen concentration gradients," *Journal of Fish Biology*, 36(3), 363-373.

Stager, J.C., Leavitt, P. R., and S.S. Dixit. 1997. "Assessing impacts of past human activity on the water quality of Upper Saranac Lake, New York," *Lake and Reservoir Management*, 13(2): 175-184.

Tranvik, L.J., Downing, J.A., Cotner, J.B., Loiselle, S.A., Striegl, R.G., Ballatore, T.J., Dillon, P., Finlay, K., Fortino, K., Knoll, L.B. and P.L. Kortelainen. 2009. "Lakes and reservoirs as regulators of carbon cycling and climate," *Limnology and Oceanography*, 54(6): 2298-2314.

Williamson, C.E., Brentrup, J.A., Zhang, J., Renwick, W.H., Hargreaves, B.R., Knoll, L.B., Overholt, E.P. and K.C. Rose. 2014. "Lakes as sensors in the landscape: Optical metrics as scalable sentinel responses to climate change," *Limnology and Oceanography*, 59(3): 840-850.

Wilson, S. J., and A. Ricciardi. 2009. "Epiphytic macroinvertebrate communities on Eurasian watermilfoil (*Myriophyllum spicatum*) and native milfoils (*Myriophyllum sibericum* and *Myriophyllum alterniflorum*) in eastern North America," *Canadian Journal of Fisheries and Aquatic Sciences*, 66(1): 18-30.

Yan, N.D., 1983. "Effects of changes in pH on transparency and thermal regimes of Lohi Lake, near Sudbury, Ontario," *Canadian Journal of Fisheries and Aquatic Sciences*, 40(5): 621-626.