Upper Saranac Lake

2014 Water Quality Report

Adirondack Watershed Institute

Paul Smith's College

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Report No. PSCAWI 2015-77

Paul Smith's College
THE COLLEGE OF THE ADIRONDACKS

Acknowledgements

The narrative and results presented in this report were produced by Corey Laxson, Sean Regalado and Dan Kelting of the Adirondack Watershed Institute of Paul Smith's College. Field work was conducted by Corey Laxson and Elizabeth Yerger. Laboratory work was conducted by Corey Laxson, Elizabeth Yerger, Sean Patton, Brandon Morey, and Dan Kelting. Michael Martin provided numerous pieces of historical data. Ross Whaley, Curt Stiles, Peter Woll and Guy Middleton were instrumental in the helping to redesign the water quality monitoring program for Upper Saranac Lake. Paul Smith's College provided office and laboratory space in the Spaulding-Paolozzi Environmental Science and Education Center. The water quality monitoring program and this report were both funded by a grant from the Upper Saranac Foundation.

Please cite this report as:

Laxson*, C.L., Regalado, S.M. and D.L. Kelting. 2015. Upper Saranac Lake: 2014 Water Quality Report. Adirondack Watershed Institute of Paul Smith's College. Report No. PSCAWI 2015-77. 29p.

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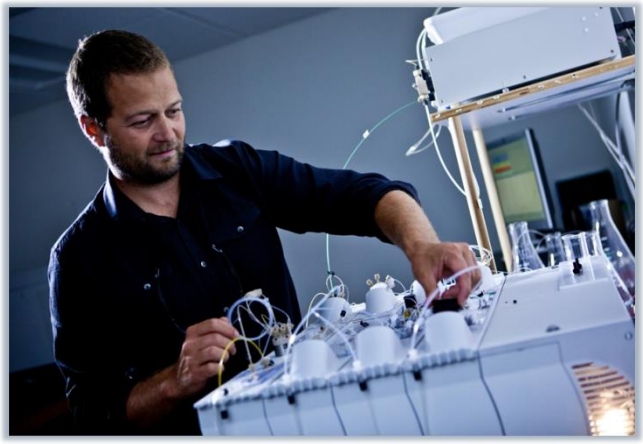

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Elizabeth Yerger working in the AWI Environmental Research Laboratory

Executive Summary

The Upper Saranac Lake water quality monitoring program has been in place since 1989. The purposes of this program are to (1) assess the health of Upper Saranac Lake with respect to its designated uses, (2) identify likely sources of impairments to these uses, and (3) provide reliable information to support lake management. This report presents results from the 2014 monitoring season as well as long term trends in key trophic and water quality indicators. The report highlights are:

1. Substantial evidence exists that indicates that the trophic condition of Upper Saranac Lake has experienced significant recovery from its degraded state in the late 1980's and early 1990's. In both Lake basins the surface water concentration of total phosphorus has exhibited a significant decrease since 1988 and is currently within the target range of 12 mg/L outlined in the Upper Saranac Lake Management Plan. The surface water concentration of chlorophyll-a (a surrogate for algal productivity) has also decreased over the last 26 years. However, the decreasing trend was only statistically significant for the north basin.

2. Despite reductions in phosphorus and chlorophyll the transparency of the lake has significantly decreased over the study period in both the north and south basins of the lake at a rate of 5 cm/year and 6 cm/year respectively. Numerous other water bodies in the Adirondacks are experiencing similar trends. Reduction in transparency may be related to recovery from acid deposition as well as changes to our regional climate. Both of these environmental changes can influence decomposition rates within the watershed and lead to changes in lake transparency.

3. Dissolved oxygen depletion continues to be an issue in Upper Saranac Lake, particularly in the north basin where nearly one half of the water column experiences hypoxia, or complete lack of oxygen. The re-occurring pattern of summer hypoxia in the north basin has not exhibited and any sign of recovery over the study period. Lack of oxygen in the hypolimnion influences the solubility of phosphorus, and allows the release of dissolved reactive phosphorus from the lake sediments. This pattern is clearly evident in the bottom water of the north basin, where total phosphorus concentrations average three times higher than in the surface water.

4. The dissolved oxygen dynamics of the south basin has showed substantial improvement since the early 1990's. The total areas of hypoxic water as well as the oxygen depletion rate of the hypolimnion have exhibited significant reduction since 1991.

5. Adirondack lakes in watersheds without paved roads typically have sodium and chloride concentrations less than 0.55 and 0.24 mg/L, respectively (Kelting et al 2012). The Upper Saranac Lake watershed has 27 km of salted roads and the 2014 sodium and chloride concentrations averaged 5 mg/L for sodium and 8 mg/L for chloride. The chloride concentration and the electrical conductivity of the water (a surrogate for ion concentration) have both exhibited a significant positive trend over time. The concentrations of these chemicals are above the EPA drinking water standard established for sodium (20 mg/L) and below the guideline recommended for chloride (250 mg/L).

Introduction

This year represents the 25th consecutive year of the water quality monitoring program on Upper Saranac Lake. The purposes of the water quality monitoring program are to assess the health of Upper Saranac Lake with respect to its designated uses, identify likely sources of impairments, and provide reliable information to support lake management.

Upper Saranac Lake is one of the most intensely studied lakes in the Adirondack region. The water quality of the lake was first described in 1930, and has been continually monitored and reported on 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 et al. 1987), environmental activism (Perry and Vanderklein 1996), impact of Eurasian water milfoil (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 (Royce 1951), and accumulation of DDT in fish (Burdick et al 1964).

Bloom of cyanobacteria on Upper Saranac Lake, 1990. Photo by R. Handler.

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 of the Adirondacks. Anthropogenic impact to the watershed began with extensive logging in the late 1800's followed by hotel development (1888-1946), fish hatchery establishment (1885), road construction (1909), and the establishment of cottages and private homes, many with insufficient wastewater management (1910-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 1970's 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 permeated

downstream to Middle and Lower Saranac Lakes (Martin and Stager 1994, Handler 1991). The bottom waters of the lake were found to be anoxic during the summer months, severely straining the salmonid fishery of the lake (Martin 1993). Of the numerous nutrient sources in the watershed the most influential discharger was suspected to be the Adirondack Fish Culture Station, a hatchery operated by the New York State Department of Environmental Conservation (NYSDEC). Since 1885 the fish hatchery had been discharging nutrient rich effluent in the form of fish excrement and uneaten food into the outlet of Little Clear Pond which flows into Mill Brook, a class AA tributary stream of the north basin of Upper Saranac. During the early 1990's the hatchery effluent contributed roughly 1lb of phosphorus to USL per day. Periodic runway maintenance and a facility upgrade during 1990 were also implicated in larger unquantified pulses of phosphorus to the lake (Perry and Vanderklein 1996, Deangelo and Smith 1991). Data from Martin et al. (1998) suggested that hatchery effluent represented 3% of the annual phosphorus load to the lake, but 8% of the load to the limnologically distinct north basin. Martin further argued that this load was misleading because most of the nutrient rich discharge occurred during the summer months. In 1993 the Upper Saranac Lake Association representing 550 residents filed suit against the NYSDEC for failure to adhere to water pollution control laws. In response to litigation hatchery management initiated strategies to decrease phosphorus effluent in 1993; however these measures were not sufficient. After lengthy debates and delays, an agreement was met in 1994 that resulted in substantial reduction in phosphorus discharge from the hatchery through facility upgrades and implementation of best management practices. In addition Upper Saranac Lake produced a watershed management plan (Martin 1998) that spurred further reduction in point and non-point source pollution to the lake.

The objectives of this report are to: (1) present results from the 2014 monitoring season, and (2) provide analysis of the historical trends in water quality, with particular focus on the changes in lake trophic indicators and dissolved oxygen content in the 21 years since the Adirondack Fish Culture Station enacted a reduced phosphorus discharge permit.

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 s can be found in Kelting and Laxson (2014) and Martin et al. (1998). 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 approximately 16 meters (53 ft.) and does not support a well-developed hypolimnion during stratification. The bottom waters of the north basin routinely experience anoxia during the summer months (dissolved oxygen less than 0.5 mg/l as defined by the EPA). In contrast, the south basin reaches a depth 28 meters (92 ft.) and develops a well-defined hypolimnion that experiences only periodic hypoxia (dissolved oxygen less than 2.0 mg/L). The south basin receives 68% of the water input from the watershed through Fish Creek, and contains the outlet to the Saranac River at the Bartlet Carry Dam.

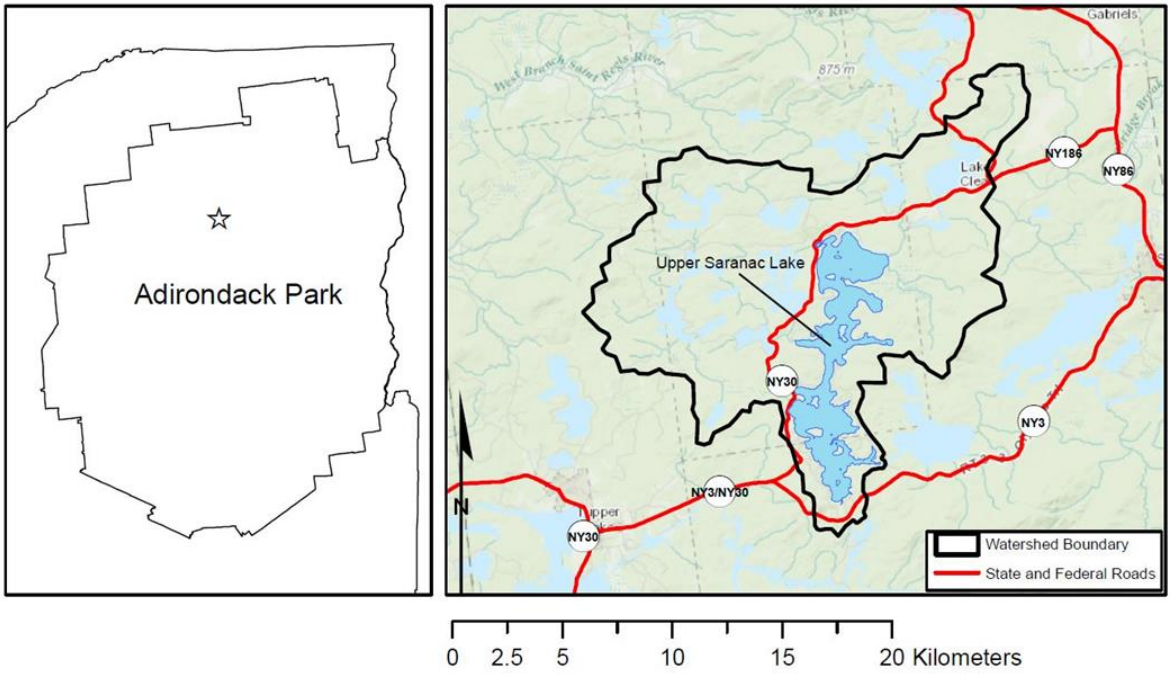

Figure 1. Upper Saranac Lake and its watershed, located in the northern Adirondacks.

Data Collection

Field data for 2014 was collected from the R.V. *Clearwater* at the deepest sections of the north and south basins seven times starting on May 25th and ending on September 29th 2014. 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 DO/Temp data logger. Surface water samples were collected using 2 meter integrated tube sampler. The hypolimnetic water was collected with a 1 L Kemmerer Bottle from approximately 1 meter off the bottom. 250 mL of the surface water was immediately passed through a 0.45µm cellulose membrane filter. The filter was collected, wrapped in foil and put on ice for chlorophyll-a analysis. All samples were kept on ice after collection and chemically preserved or stored at 4°C until analysis could

be completed. 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 analytical methods described in Table 1.

Table 1. Analytical methods performed in 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
Sulfate & Chloride	Automated ion chromatography	EPA 300.0
Metals	Inductively coupled plasma optical emission spectroscopy	EPA 200.7

Field and laboratory data from 2014 was combined with historical limnological data from Upper Saranac Lake, which has 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 (AWI, formerly AAI), followed by Cedar Eden Environmental (CE) and the NYS Citizen Science Lake Assessment Program (CSLAP). Monitoring occurred at the deepest portion of both the north and south basin, one to three times per month typically during the May to October interval.

Data Analysis –trophic and water quality trends

Results for 2014 were tabulated and time series charts were constructed from the annual average value for each indicator. Trend analysis on the data from 1993 to present was conducted using Kendall's non-parametric regression to test the hypothesis "there is no relationship between the indicator and time". Simple linear trend lines were fit to data with statistically significant ($P<0.05$) trends and displayed on the corresponding chart. Thus, absence of a line means there was no statistically significant trend in the indicator over time. Average annual values for secchi disk transparency, total phosphorus, and chlorophyll-a in the lake were used to calculate Carlson's Trophic Status Index, (TSI), a commonly used quantitative index for classifying lakes based on trophic status (Carlson 1977). Typically TSI values are between 0 and 100. Lakes with TSI values less 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 classification of lakes based on Carlson's Trophic State Index (TSI)

TSI Value	Trophic 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, increasing probability of hypolimnetic anoxia during the summer
50-60	Eutrophic	Mildly eutrophic. Decreased transparency, hypolimnetic anoxia, and warm water fishery only. Supports all recreational / aesthetic uses but threatened.
60-70	Eutrophic	Dominance of blue-green algae, algal blooms likely, extensive macrophytes growth in shallow water
70-80	Eutrophic	Heavy algal blooms possible throughout summer, hyper eutrophic
>80	Eutrophic	Algal scum, summer fish kills, few macrophytes due to algal shading

Data Analysis – dissolved oxygen dynamics

The areal extent (km^2) of hypoxia and anoxia were quantified and compared between years using the dissolved oxygen (DO) profiles and 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 3815 appended points representing shorelines with depth of zero. Bathymetric contours at 1m 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 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 1990-2014, however there was insufficient DO profiles for this 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.

Results

Trophic and Water Quality Trends – North Basin

Secchi disk transparency in the north basin ranged from 2.3 to 3.0 meters and averaged 2.6 meters (Table 3). Since monitoring began annual average transparency has ranged from a low of 2.5 meters to as high as 4.4 meters with a significant downward trend since 1993 at a rate of 5 cm/year (P = 0.01, Figure 2 and Table 4). Total phosphorus concentration in the surface water averaged 11.3 µg/L in 2014 (Table 3), with the highest concentration of 25.5 µg/L detected on August 18th. In the bottom water average total phosphorus concentration was nearly three times higher, with the highest concentration of 64.4 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. Concentration was substantially lower in all other 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 (P=0.006, Figure 2 and Table 4). The bottom water total phosphorus concentration has remained elevated throughout the monitoring period, and has not exhibited a significant positive or negative trend (P=0.472, Figure 3 and Table 4). Chlorophyll-a concentration in 2014 ranged from below laboratory detection in May to a maximum of 10.1 µg/L on August 18th. The average concentration in 2014 was 3.8 µg/L and similar to average values over the last decade (Figure 2). However, we did detected a significant downward trend in chlorophyll concentration since 1993 at a rate of 0.32 µg/L/year (P=0.005, Table 4). Carlson's trophic status calculated from total phosphorus (53) indicates a mildly eutrophic condition for the north basin, while the TSI value based on transparency (48) indicates a mesotrophic condition, and the TSI value calculated from chlorophyll-a concentration (37) points to an oligotrophic classification (Figure 2).

The apparent color of the surface water of the north basin ranged from 16.4 to 41.1 PtCo units and averaged 32.5 in 2014. Color intensity was much higher in the bottom water samples with a range from 35.1 to as high as 184.8 PtCo units (Table 3). The average color value for the bottom strata in 2014 was 89.9 PtCo units. Due to variation in color methodology over the monitoring period (apparent color vs true color, vs color units) trend analysis was not performed for this report.

Table 3. Water quality indicator values in the epilimnion (surface waters) and hypolimnion (bottom waters) of the north basin of Upper Saranac Lake in 2014. BDL = below laboratory detection level, ± indicates an estimated value.

Water Quality Indicator North Basin	Sampling Date							Average
	5/15	6/2	6/26	7/24	8/18	9/17	9/29	
	Surface water (0-2 meter integrated)							
Transparency (m)	3.0	ND	2.7	2.4	2.5	3.0	2.3	2.6
Total Phosphorus (µg/L)	11.5	6.0	8.0	8.3	25.5	10.2	9.8	11.3
Chlorophyll-*a* (µg/L)	BDL	0.4	5.4	3.6	3.3	3.9	10.1	±3.8
Laboratory pH	6.7	6.5	6.1	7.1	6.7	6.4	7.6	6.7
Sp. Conductance (µS/cm)	43.9	55.0	53.2	54.9	54.4	49.9	51.2	51.8
Color (Pt-Co)	35.1	32.0	38.3	28.9	35.1	16.4	41.4	32.5
Alkalinity (mg/L)	11.3	10.8	11.1	11.6	10.2	12.3	12.1	11.3
Nitrate-Nitrogen (µg/L)	95.5	24.3	BDL	2.0	15.2	4.4	BDL	±20.0
Chloride (mg/L)	4.8	6.9	6.5	7.8	8.7	9.3	9.3	7.6
Calcium (mg/L)	4.2	4.0	4.0	4.2	4.4	4.2	4.0	4.1
Sodium (mg/L)	4.7	4.5	4.7	5.1	5.1	4.8	4.8	4.8
	Bottom Water (~17 meters)							
Total Phosphorus (µg/L)	22.1	12.2	33.0	28.7	40.8	11.0	64.4	30.3
Laboratory pH	6.8	6.5	6.5	6.6	6.6	6.2	6.8	6.6
Sp. Conductance (µS/cm)	53.9	59.5	61.9	57.6	59.4	53.4	85.0	61.5
Color (Pt-Co)	47.6	35.1	78.8	72.6	184.8	66.3	144.3	89.9
Alkalinity (mg/L)	11.5	11.9	11.9	11.6	11.9	13.6	21.9	13.5
Nitrate-Nitrogen (µg/L)	134.0	109.0	150.0	257.0	93.8	166.0	1.7	130.2
Chloride (mg/L)	5.9	7.9	7.1	8.4	9.0	9.3	9.6	8.2
Calcium (mg/L)	4.3	4.4	4.2	4.4	4.9	4.6	5.0	4.5
Sodium (mg/L)	5.0	5.2	5.1	5.2	5.3	4.9	5.0	5.1

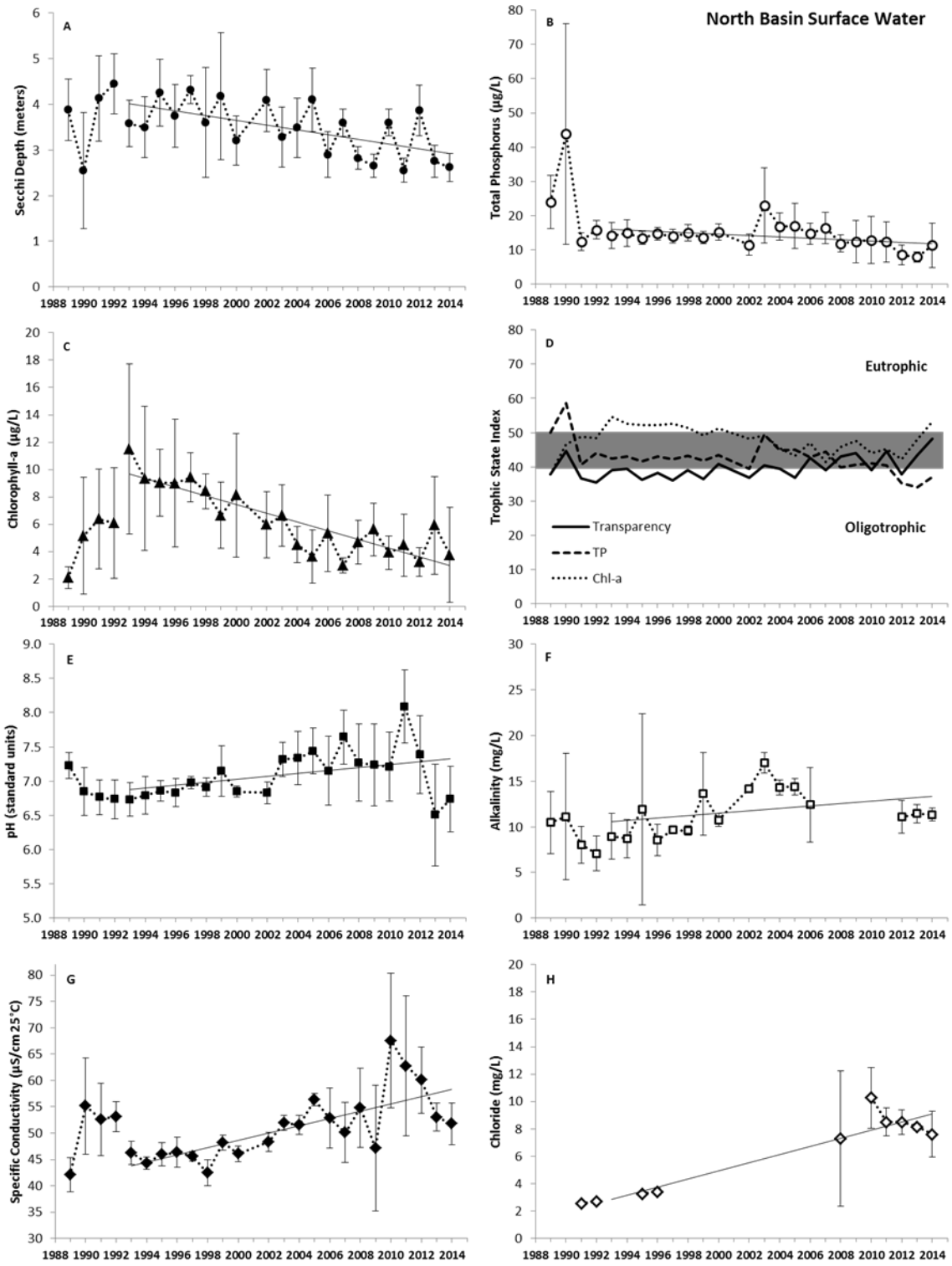

Figure 2 Time series of the average annual trophic and water quality indicators for the surface water of the north basin of Upper Saranac Lake. Significant trends (P<0.05) are indicated with a trend line. Vertical bars represent one standard deviation of the mean.

The acidity of the north basin varies from slightly acidic to neutral throughout the sampling season. The pH values in 2014 ranged from 6.1 to 7.6 pH units in the surface water and 6.2 to 6.8 units in the bottom water (Table 3). The pH of both the surface and bottom strata of the north basin has exhibited a significant positive trend (less acidic) at a rate of 0.02 pH units/year (P= 0.02 and 0.04 respectively, Figure 2 and 3). The 2014 average alkalinity (the acid neutralizing ability) was 11.3 mg/L in the surface water and 13.5 mg/L in the bottom water (Table 3). Alkalinity has also significantly increased since 1993 at a rate of 0.13 mg/L/year in the surface water and 0.50 mg/L/year in the bottom water (P=0.01 for both strata, Figures 2 and 3).

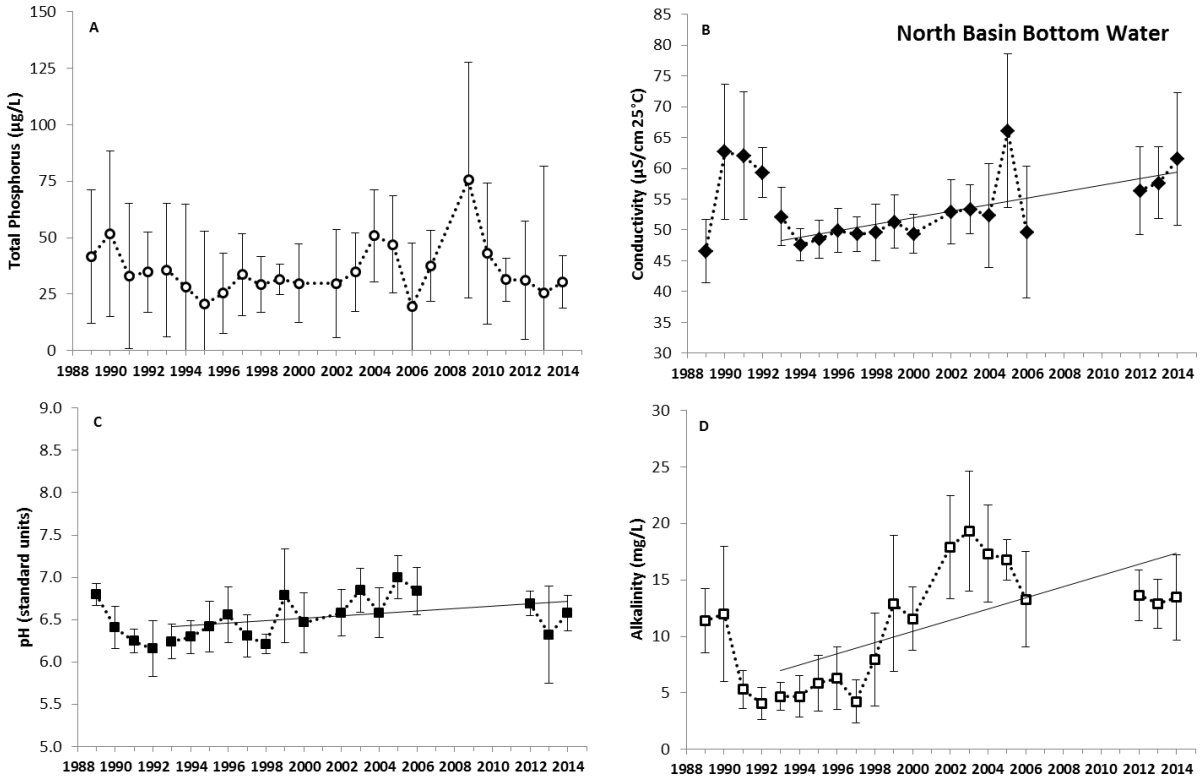

Figure 3. Time series of the average annual trophic and water quality indicators for the bottom water of the north basin of Upper Saranac Lake. Significant trends (P<0.05) are indicated with a trend line. Vertical bars represent one standard deviation of the mean.

Specific conductance exhibited little variability around the seasonal average of 51.8 µS/cm in the surface water, and 61.5 µS/cm in the bottom water in 2014. Surface water conductivity exhibited a significant positive trend since 1993 at a rate of 0.70 µS/cm/year (Figure 2), however no trend was detected in the conductivity of the bottom water. Chloride concentration averaged 7.6 mg/L in the surface water and 8.2 mg/L in the bottom water. Chloride exhibited a significant positive trend the surface water at a rate of 0.30 mg/L/year (P=0.03, Figure 2). Historical trend in bottom water chloride was not analyzed.

Sodium and calcium concentrations were similar between the surface and both water samples in 2014, averaging 4.8 mg/L and 5.1 respectively for sodium and 4.1 mg/L and 4.5 mg/L respectively for calcium. Insufficient data exist for trend analysis on sodium and calcium at this time.

Table 4. Trend analysis of changes in trophic water quality indicators over time (1993 to 2014) in the surface water and bottom water of Upper Saranac Lake.

Basin	Strata	Analytes		Slope	R-square	P-value
North Basin	Surface Water	Secchi Transparency (ft/yr)	*	-0.052	0.359	0.010
		Total Phosphorus (µg/L/yr)	*	-0.196	0.171	0.006
		Chlorophyll-*a* (µg/L/yr)	*	-0.320	0.760	0.005
		pH (/yr)	*	+0.021	0.153	0.023
		Alkalinity (mg/L/yr)	*	+0.131	0.130	0.010
		Conductance (µS/cm/yr)	*	+0.696	0.521	0.083
		Chloride (mg/L/yr)	*	+0.297	0.808	0.032
	Bottom Water	Total Phosphorus (µg/L/yr)		+0.476	0.067	0.472
		pH (/yr)	*	+0.167	0.166	0.017
		Alkalinity (mg/L/yr)	*	+0.495	0.418	0.004
		Conductance (µS/cm/yr)		+0.527	0.484	0.184
South Basin	Surface Water	Secchi Transparency (ft/yr)	*	-0.066	0.452	0.009
		Total Phosphorus (µg/L/yr)	*	-0.160	0.137	0.019
		Chlorophyll-*a* (µg/L/yr)		-0.186	0.357	0.190
		pH (/yr)	*	+0.019	0.121	0.035
		Alkalinity (mg/L/yr)	*	+0.170	0.212	0.012
		Conductance (µS/cm/yr)	*	+0.757	0.620	0.002
		Chloride (mg/L/yr)	*	+0.278	0.850	0.018
	Bottom Water	Total Phosphorus (µg/L/yr)		+0.450	0.026	0.472
		pH (/yr)	*	+0.021	0.345	0.017
		Alkalinity (mg/L/yr)	*	+0.406	0.423	0.004
		Conductance (µS/cm/yr)		+0.503	0.543	0.184

Trophic and Water Quality Trends – South Basin

Historically secchi disk transparencies are greater in the south basin than in the north basin. This was also the case in 2014 when transparency in the south ranged from 2.8 to 4.0 meters and averaged 3.4 meters (Table 5). 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 7 cm/year (P = 0.009, Figure 4 and Table 4). Total phosphorus concentration in the surface water was also lower than in the north basin, and averaged 9.0 µg/L in 2014 (Table 5), with the highest concentration of 14.3 µg/L detected on May 15th. In the hypolimnion average total phosphorus concentration was slightly higher, with the highest concentration of 25.5 µg/L occurring on

August 18th. 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 0.16 µg/L/year (P=0.002, Figure 4 and Table 4). Despite the downward trend in surface water phosphorus, hypolimnetic phosphorus concentrations in the south basin exhibited no significant positive or negative trend (Figure 5, Table 4), and has been elevated and highly variable. Chlorophyll-a concentration in 2014 ranged from below laboratory detection in June to a maximum of 7.7 µg/L on September 29th and averaged 4.2 µg/L (Table 5). 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=0.190, Figure 4, Table 4) Carlson's trophic status calculated from total phosphorus (32.4) indicates an oligotrophic condition for the south basin, while the TSI value based on transparency (42.8) and chlorophyll-a (50) both indicate a mesotrophic condition (Figure 5).

The apparent color of the surface water of the north basin ranged from 13.3 to 35.7 PtCo units and averaged 23.6 in 2014. Color intensity was similar in the bottom water samples with a range from 13.3 to 44.5 PtCo units, and averaged 29.4 (Table 5).

The acidity of the south basin was circumneutral throughout the sampling season. The pH values in 2014 ranged averaged 6.7 pH units in the surface water and 6.6 units in the bottom water (Table 5). The pH of the surface and bottom strata of the north basin has exhibited a significant positive trend (less acidic) at a rate of 0.02 pH units/year (P= 0.0.04 and 0.02 respectively, Figure 4 and 5). The alkalinity in 2014 was similar to the north basin and averaged 11.2 mg/L in the surface water and 11.6 mg/L in the bottom water (Table 5). Alkalinity has also significantly increased since 1993 at a rate of 0.17 mg/L/year in the surface water and 0.14mg/L/year in the hypolimnion (P=0.004 and 0.01 respectively, Figures 4 and 5).

Specific conductance in the south basin surface water was similar to the north and averaged 52.2 µS/cm. The conductivity in the hypolimnion did not substantially vary from the surface water (Table 5). Like the north basin, surface water conductivity exhibited a significant positive trend since 1993 at a rate of 0.75 µS/cm/year (P=0.002, Figure 4), however no trend was detected in the conductivity of the bottom water (P=0.18, Figure 5). Chloride concentration in the south basin was the same as the north and exhibited the same trend (Tables 4, Figure 4). Sodium and calcium concentrations in the south basin were nearly identical to the north basin (Table 5).

Table 5. Water quality indicator values in the epilimnion (surface water) and hypolimnion (bottom water) of the south basin of Upper Saranac Lake in 2014. BDL = below laboratory detection level, ± indicates an estimated value.

Water Quality Indicator South Basin	Sampling Date							Average
	5/15	6/2	6/26	7/24	8/18	9/17	9/29	
	Surface water (0-2 meter integrated)							
Transparency (m)	4.0	ND	2.8	3.4	3.9	3.0	3.3	3.4
Total Phosphorus (µg/L)	14.3	5.5	9.8	8.2	10.3	8.2	7.1	9.0
Chlorophyll-*a* (µg/L)	0.3	BDL	5.6	4.1	5.9	6.6	7.7	±4.2
Laboratory pH	6.8	6.6	6.6	6.8	6.7	6.4	7.2	6.7
Sp. Conductance (µS/cm)	54.0	51.4	51.3	56.8	52.6	48.6	50.4	52.2
Color (Pt-Co)	28.9	19.6	35.1	22.7	22.7	13.3	22.7	23.6
Alkalinity (mg/L)	11.6	10.8	10.1	11.3	10.2	12.0	12.1	11.2
Nitrate-Nitrogen (µg/L)	58.8	6.5	BDL	1.6	18.5	0.3	BDL	±11.7
Chloride (mg/L)	7.0	6.8	5.9	7.5	8.5	8.9	9.1	7.7
Calcium (mg/L)	4.1	4.0	3.8	4.2	4.5	4.2	4.0	4.1
Sodium (mg/L)	4.7	4.5	4.5	5.0	4.9	4.8	4.8	4.8
	Bottom Water (~26 meters)							
Total Phosphorus (µg/L)	11.9	14.8	10.2	24.5	25.0	15.1	9.2	15.8
Laboratory pH	6.8	6.6	6.5	6.5	6.6	6.4	7.1	6.6
Sp. Conductance (µS/cm)	53.0	55.2	54.4	58.1	53.9	48.4	49.9	53.3
Color (Pt-Co)	28.9	32.0	35.1	28.9	44.5	13.3	22.7	29.4
Alkalinity (mg/L)	11.5	11.6	11.2	13.3	9.6	12.0	12.0	11.6
Nitrate-Nitrogen (µg/L)	70.8	62.0	114.0	150.0	185.0	126.0	2.7	101.5
Chloride (mg/L)	7.0	7.1	6.4	7.6	8.5	8.6	9.1	7.8
Calcium (mg/L)	4.1	4.1	4.0	4.3	4.6	4.1	4.0	4.2
Sodium (mg/L)	4.7	4.7	4.7	5.0	5.0	4.7	4.6	4.8

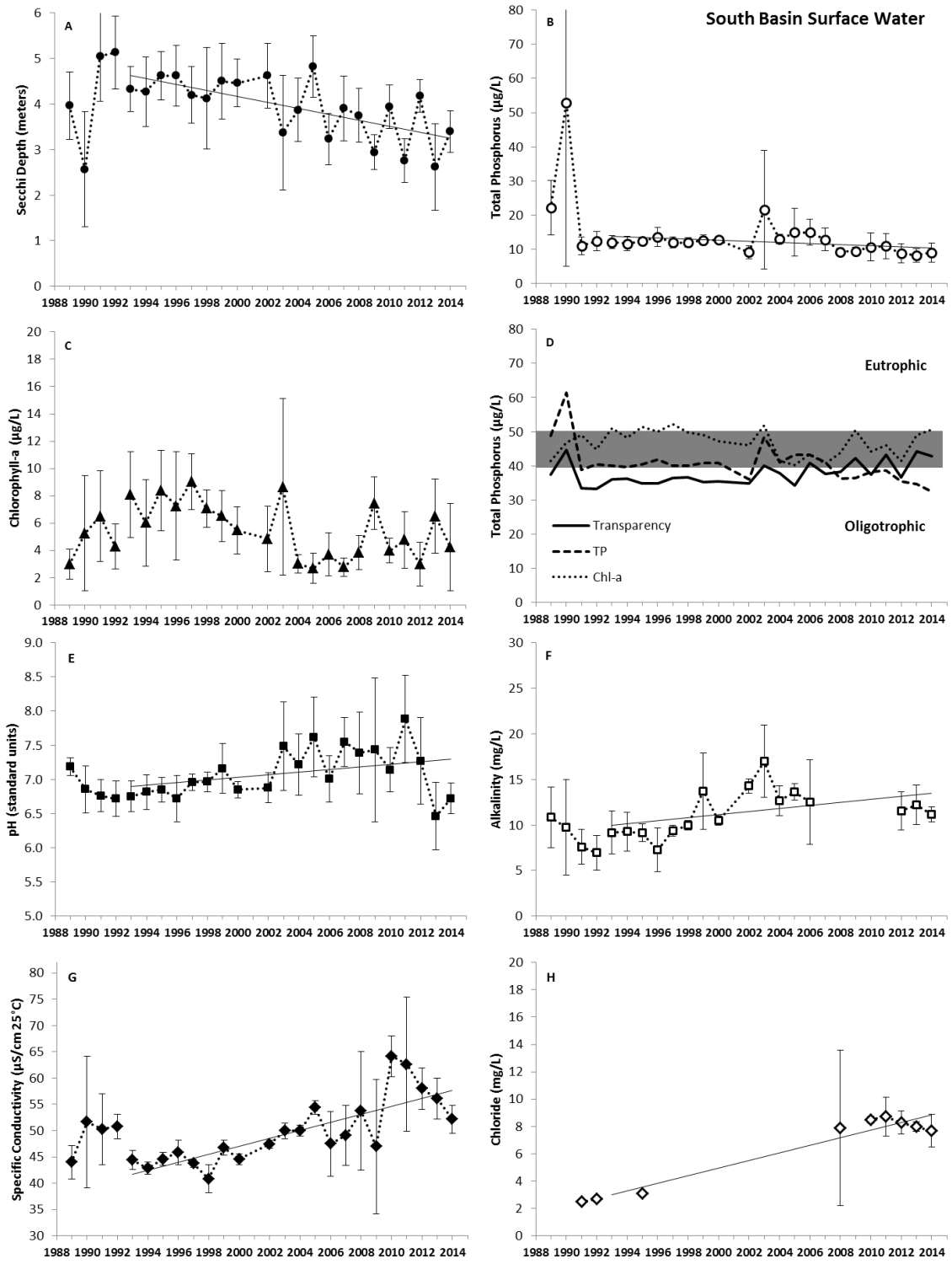

Figure 4. Time series of the average annual trophic and water quality indicators for the surface water of the south basin of Upper Saranac Lake. Significant trends (P<0.05) are indicated with a trend line. Vertical bars represent one standard deviation of the mean.

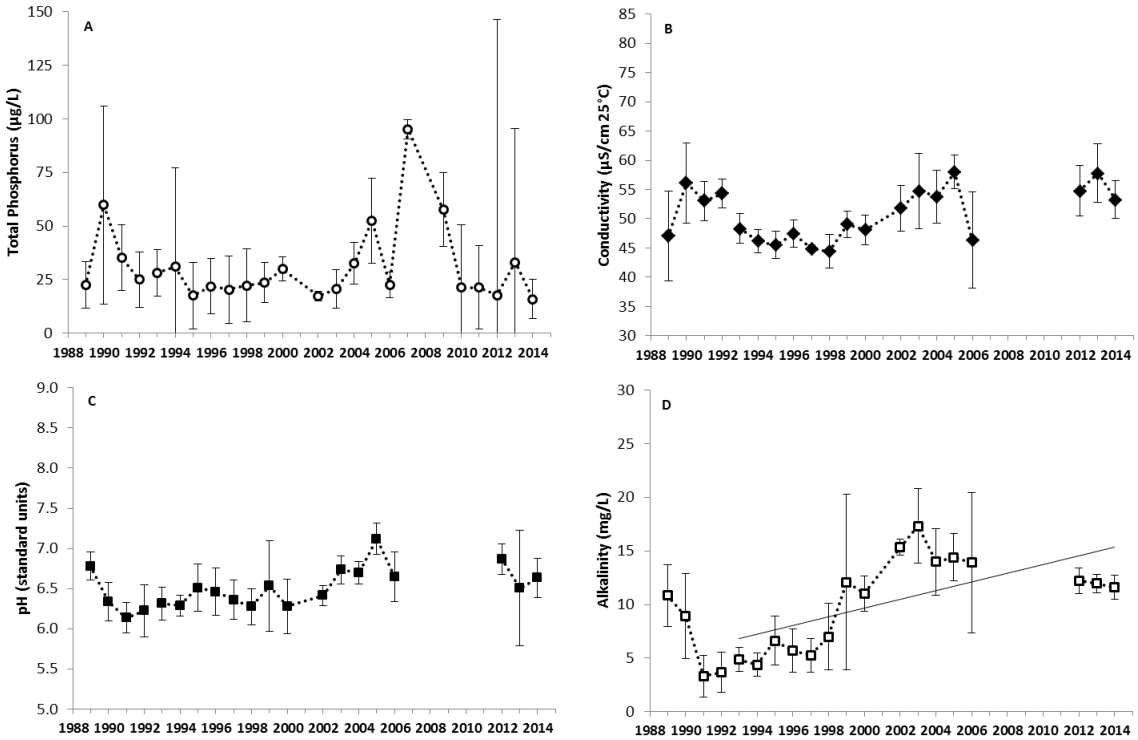

Figure 5. . Time series of the average annual trophic and water quality indicators for the bottom water of the south basin of Upper Saranac Lake. Significant trends (P<0.05) are indicated with a trend line. Vertical bars represent one standard deviation of the mean.

Hypolimnetic Dissolved Oxygen Dynamics

During the 2014 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. In the north basin the bottom meter of water became hypoxic (DO<1.0 mg/L) by mid-June. By the middle of August nearly half of the water column had a dissolved oxygen concentration less than 1.0 mg/L. By the end of September the bottom two meters of the north basin were devoid of oxygen completely. The pattern in the south basin was similar in 2014, but not nearly as extreme. Hypolimnetic dissolved oxygen in the south basin ranged from 3-5 mg/L, with a minimum of 2.7 mg/L near the bottom during the month of September only (Figure 6).

Historically, the zone of oxygen depletion was greatest in the early 1990's. In the summer of 1990 the greatest extent of the hypoxic zone covered a region of approximately 6.6 km^2. 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 (Figure 7). The vast majority of the reduction in hypoxic area was observed in the south basin, 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-squared = 0.40, Slope = -0.06).

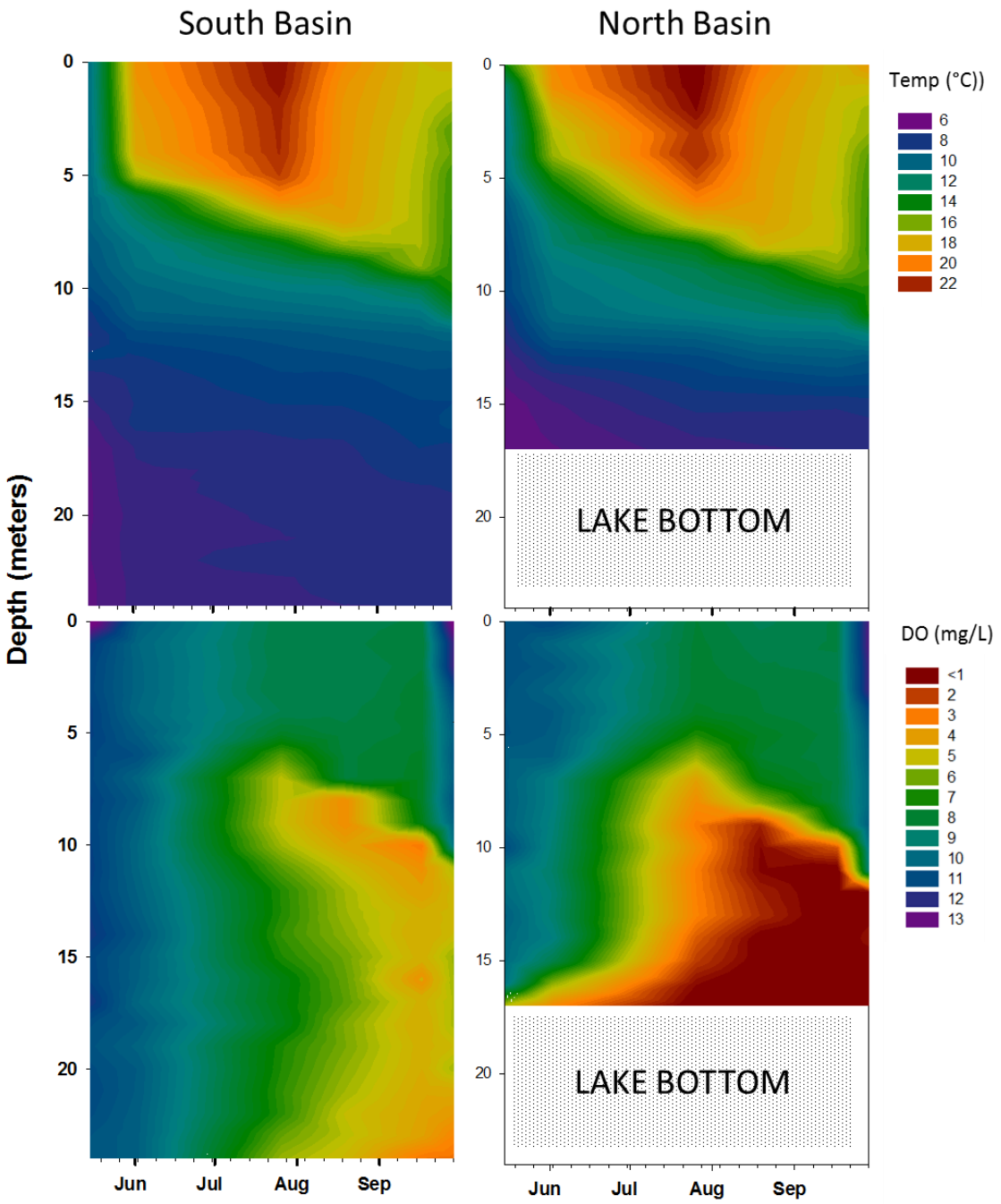

Figure 6. Time series isopleth graphs of temperature (upper panels) and dissolved oxygen (lower panels) for the north (right column) and south left column) of Upper Saranac Lake for the 2014 field season.

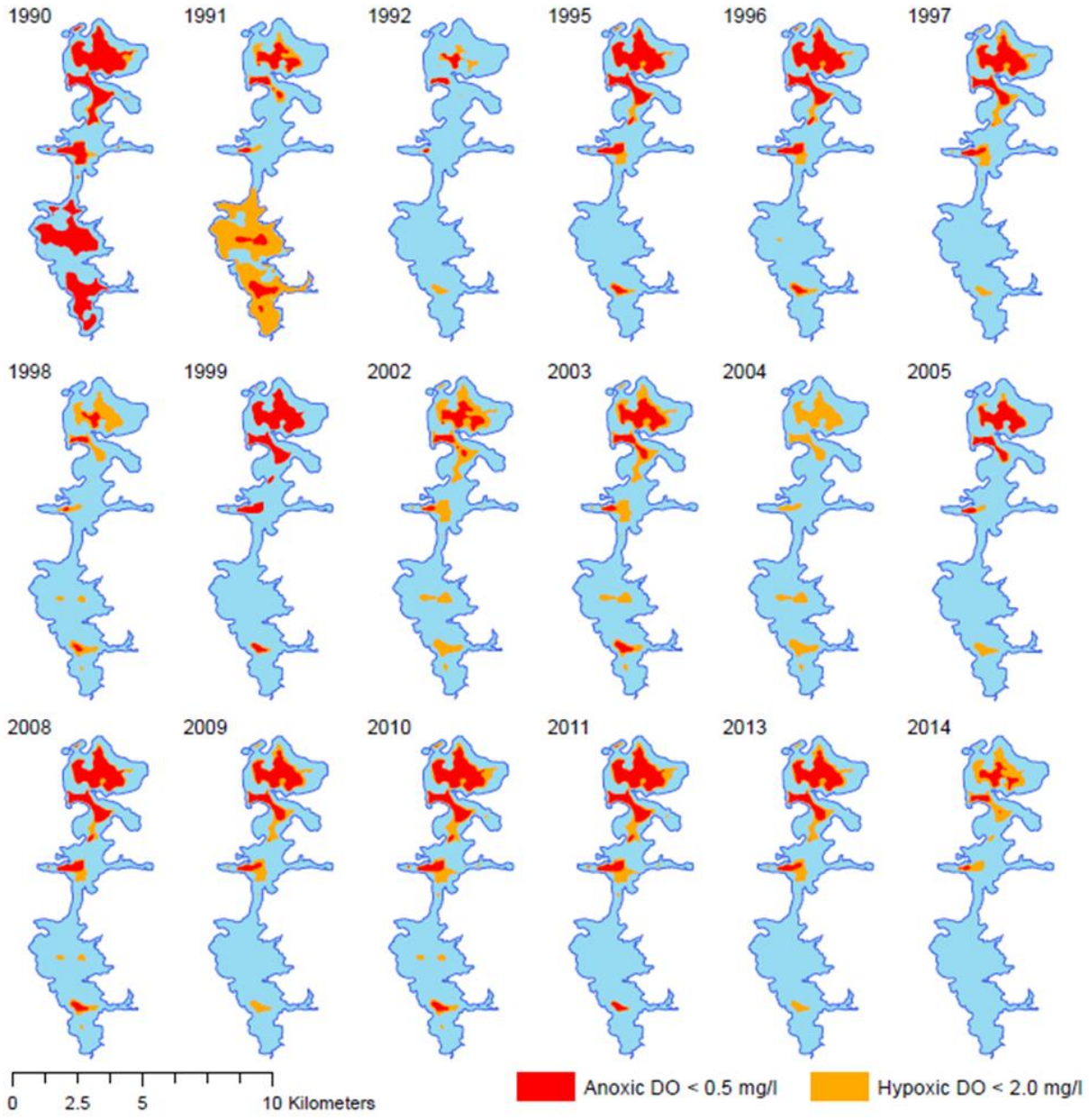

Figure 7. Time series maps of the areal extent of anoxic (DO < 0.5 mg/L)and hypoxic (DO < 2.0 mg/L) regions of Upper Saranac Lake, 1990 – 2014.

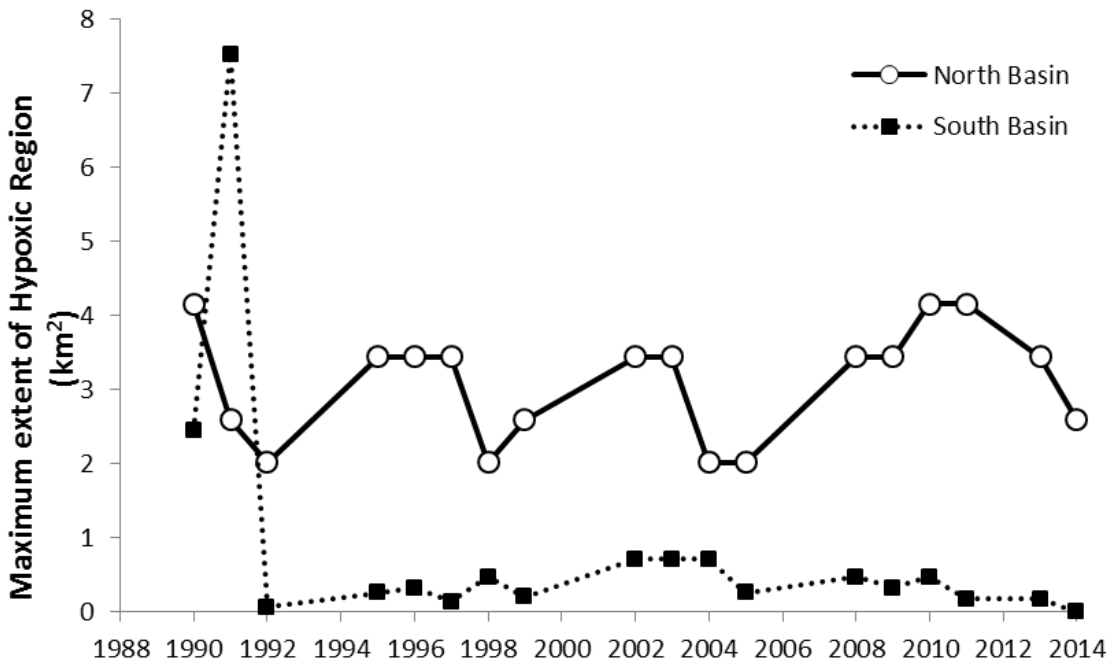

Figure 8. Maximum areal extent of the hypoxic region of Upper Saranac Lake by basin, 1989-2014

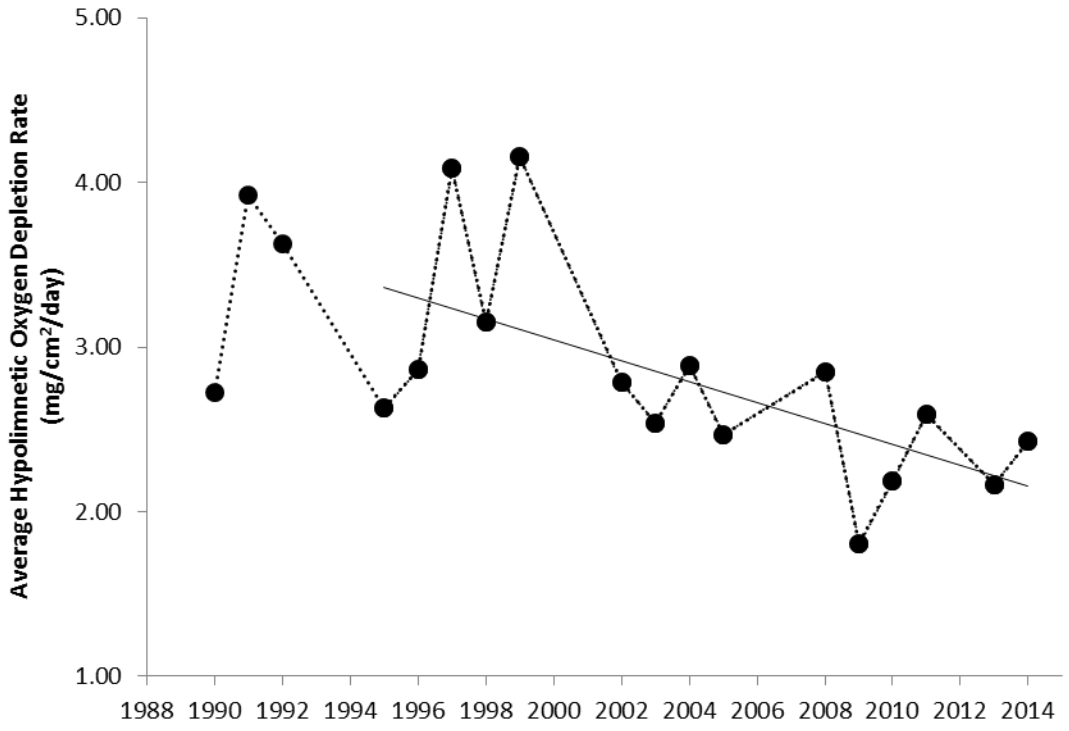

Figure 9. Average hypolimnetic oxygen depletion rate of the south basin of Upper Saranac Lake. Solid line denotes significant trend (P = 0.01).

Discussion

An emerging issue for freshwater habitats across the northeast, including Upper Saranac Lake, is the influence wide spread use of road deicers has on lake chemistry. The New York State Department of Transportation applies an average of 28 tons of road salt per kilometer of State and Federal roads annually (NYSDOT, 2006). Given that there are 27 km of state roads within the Upper Saranac Lake watershed, we can estimate an annual salt load of approximately 756 tons of NaCl. The influence deicers have had on the chemistry of the lake is clear. Non-impacted lakes in the Adirondacks have naturally low concentrations of sodium and chloride, with average background concentrations of 0.5 mg/L and 0.24 mg/L respectively. The concentration of sodium and chloride in Upper Saranac currently average around 5 mg/L for sodium and 8 mg/L for chloride. The chloride concentration and the electrical conductivity of the water (a surrogate for ion concentration) have both exhibited a significant positive trend over time (Table 4). This trend is consistent across the region. Kelting et al. (2012) found state and federal road densities explained 86 percent of the variation in sodium and chloride concentration in 138 Adirondack lakes.

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 1980's and early 1990's. The two most pronounced indicators of the recovery is the concentrations of total phosphorus and chlorophyll-a in the surface water. In both lake basins the phosphorus concentration has decreased in the last 20 years, and is currently within the target concentration of 12 mg/L outlined in the Upper Saranac Lake Management Plan (Martin 1998). The observed decrease in phosphorus concentration is due to numerous improvements made on 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 1990's. Phosphorus discharge from the hatchery has been greatly reduced over time, and the facility currently operates well below its permitted discharge rate of 0.45 lbs/day (Figure 10). The extensive cyanobacterial blooms that plagued the lake have not been observed since 1991 and the algal productivity (based on chlorophyll-a concentration) has decreased in both basins. Although some trophic indicators of the lake have exhibited improvement, the transparency of the lake has significantly decreased in recent decades (Figures 2 and 4).

The decrease in transparency of Upper Saranac seems paradoxical given the reductions observed in both phosphorus and chlorophyll. However, in recent decades decreasing transparency related to increase

concentration of dissolved organic carbon (DOC) has been one of the strongest signals of change in aquatic systems (Williamson et al. 2014, Montieth et al. 2007). DOC has a strong ability to absorb light, thus when lakes become enriched with DOC, the transparency of the water decreases and the color of the water becomes more stained in appearance (Wetzel 2001). The primary source of DOC is from the terrestrial landscape (although aquatic plants and phytoplankton also produce DOC). Many researchers believe that observed increases in DOC are related to climate change and its effect on terrestrial decomposition rate (Tranvik et al. 2009), as well as recovery from acid deposition (Montieth et al 2007). Unfortunately long term data on DOC does not exist for Upper Saranac Lake, and is scarce for many lakes in the region. Despite the paucity of DOC data, we know other lakes in the Adirondacks are experiencing similar decreases in transparency. Of the 70 lakes study monitored in the Adirondack Lake Assessment Program in 2014, 11% exhibited a significant decrease in transparency (AWI, unpublished data). Lakes with decreasing transparency ranged from impacted lakes, such as Lower Saranac, to lakes with virtually no human impact, such as Brandreth Lake (Laxson et al. 2015a and 2015b).

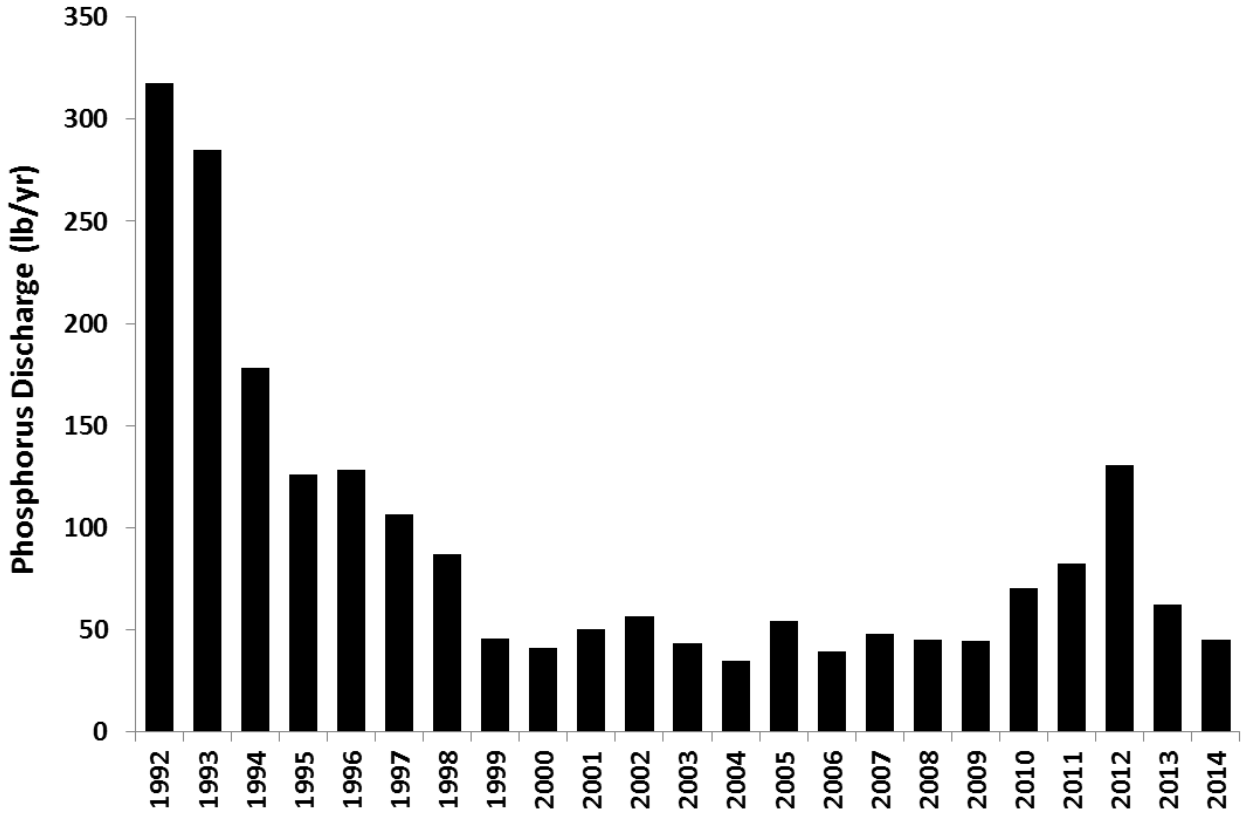

Figure 10. Annual total phosphorus discharge reported for the Adirondack Fish Culture Station.

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 (Figure 6, 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 alone. A second important impact of bottom water hypoxia is that it results in internal loading of phosphorus. Lack of oxygen in the hypolimnion influences the solubility of phosphorus, and allows the release of dissolved reactive phosphorus from the lake sediments. During fall turnover the phosphorus can then get distributed through the entire water column (Wetzel 2001). This pattern is clearly evident in the bottom water of the north basin, where total phosphorus concentrations average three times higher than in the surface water (Table 2).

Various features of the DO regime have showed improvement since the 1990's 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 (Figure 7). 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 (Figure 8). 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. Increased oxygen depletion in the hypolimnion is often a symptom of excessive nutrient loading and an indicator of cultural eutrophication (Hutchinson 1938). In the case of Upper Saranac Lake, the observed progressive decrease in AHOD rate should serve as an indicator of recovery, at least for the south basin.

Conclusion

Lake many developed lakes in the Adirondacks, Upper Saranac Lake is experiencing increased salinization from the wide spread use of road deicers in the watershed. Reductions in point and non-

point source pollution to the lake have resulted in notable improvements to the trophic status of the lake compared to the impaired state of the early 1990's, particularly in terms of nutrient concentration and algal productivity. The transparency of the lake has been decreasing over the years, we hypothesis that this trend is most likely related to regional changes in the amount of dissolved organic carbon. There are indications that the persistent hypoxic conditions of the bottom water has improved, although these improvements seem to be restricted to the south basin.

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