Decade-Scale Water Quality Variability in the Eastern Finger Lakes, New York

by John D. Halfman

Introduction

The Finger Lakes of central New York are critical to the health, well-being and economy of the region. The 11 lakes – Conesus, Hemlock, Canadice, Honeoye, Canandaigua, Keuka, Seneca, Cayuga, Owasco, Skaneateles and Otisco – hold a combined 8.1 trillion gallons of water (30.8 cubic kilometers), and their watersheds occupy a 2,630 square-mile (4,970 square-kilometer), 14-county region ***(Figure 1)***. These lakes are a source of Class AA drinking water to 1.5 million residents in the surrounding communities. For example, Skaneateles and Otisco lakes provide drinking water to the City of Syracuse, while Hemlock and Canadice lakes provide drinking water to the City of Rochester. In the late 1990s, total municipal withdrawals from Finger Lakes sources were approximately 190 million gallons of water per day *(Callinan, 2001)*.

Since 2005, the eight easternmost Finger Lakes of central New York – Honeoye, Canandaigua, Keuka, Seneca, Cayuga, Owasco, Skaneateles and Otisco – have been monitored monthly during the summer field season by the Finger Lakes Institute. The surveys collected conductivity-temperature-depth (CTD) profiles, plankton tows and Secchi disk depths at a minimum of two deep-water, mid-lake sites at each lake. Surface and bottom water samples were analyzed for major nutrients, major ions, total suspended sediment (TSS) and chlorophyll-a concentrations. Furthermore, analyses of selected streams in the Seneca and Owasco watersheds augmented the data collected in Seneca and Owasco lakes.

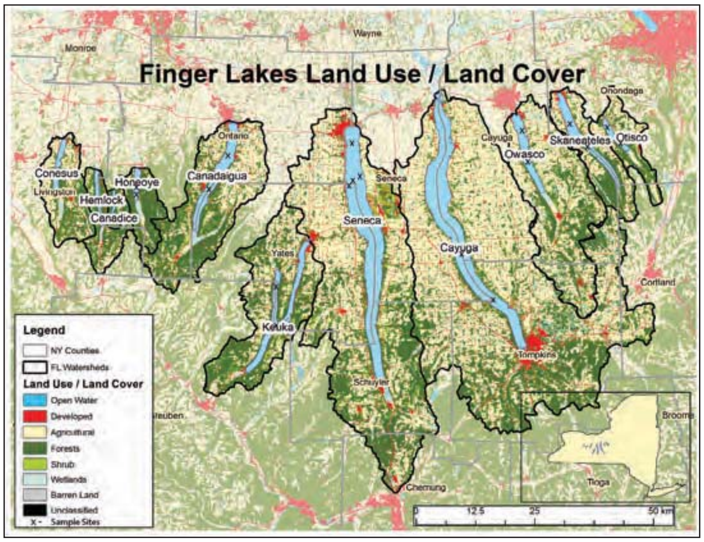

Figure 1. The Finger Lakes, site locations, and land use activities of central New York

Updated from Halfman, 2016

Characteristics of Trophic States

Oligotrophic lakes have low nutrient concentrations, resulting in low algal growth and clear water; Secchi disk depth measurements are high. Dissolved oxygen is also abundant. Such lakes may be used as sources of drinking water with minimal filtration.

Mesotrophic lakes have a moderate concentration of nutrients, moderate algal growth, and moderate water clarity. May still be used as drinking water source, but filtration is required. Conditions usually suitable for contact recreation.

Eutrophic lakes are enriched in dissolved nutrients (such as phosphates) that stimulate the growth of algae. The algae cloud the water, resulting in shallow Secchi disk depth measurements. Dissolved oxygen is depleted in these lakes. Low water clarity, scums of algae and odors make recreational use unpleasant. Harmful blue-green algal blooms are more likely to occur.

The 2005 survey results indicated that Otisco and Honeoye lakes were eutrophic systems, while Skaneateles, Canandaigua and Keuka lakes were oligotrophic systems, and Cayuga, Seneca and Owasco lakes fell in-between as mesotrophic *(Halfman and Bush, 2006; Halfman and O'Neill, 2009)*. In this report, we present an update of our understanding of water quality parameters of the Finger Lakes. This update includes a summary of the monitoring results for these eight Finger Lakes since 2005 to assess the long-term changes in water quality in these lakes. Stream segment and event vs. base flow analyses are used to highlight the nutrient loading issue in the Finger Lakes region. This report focuses on nutrient loading issues, a potential trigger for the recent rise in blue-green algal blooms in several Finger Lakes.

Methods

Field Methods

Water quality was routinely monitored at Honeoye, Canandaigua, Keuka, Seneca, Cayuga, Owasco, Skaneateles and Otisco lakes at a minimum of two deep-water, mid-lake sites on at least a monthly basis during the May to September field season ***(Figure 1)***. Otisco Lake was added to the monitoring program in 2008. CTD (SeaBird SBE-25) water quality profiles, Secchi disk depth, vertical plankton tow, and surface (less than 1-meter depth) and bottom (within a few meters of the lake floor) water samples were collected at each site.

The CTD electronically measured temperature, specific conductance (salinity), dissolved oxygen, pH, turbidity, photosynthetic active radiation intensities (PAR) and fluorescence every 0.2 meters along the surface-to-lake-floor profile. The plankton net (20-centimeter diameter opening, 80-micrometer mesh) integrated the plankton community within the upper 20 meters of water, and each sample was preserved in an alcohol-formalin solution. Water samples were analyzed on-site for temperature, specific conductance, pH, dissolved oxygen, and alkalinity (HCO_3^-) using hand-held probes and field titration kits. Laboratory analyses were performed for major nutrients [total phosphorus (TP), soluble reactive phosphorus (SRP), nitrate (NO_3) and silica (Si)], chlorophyll-a, major ions and TSS concentrations.

Laboratory Methods

Nutrient, chlorophyll-a, and TSS concentrations were analyzed following standard limnological techniques *(Wetzel & Likens, 2000)*. These are summarized in ***Table 1***.

Results

The results over time for the eight monitored Finger Lakes for selected parameters are summarized in ***Table 2.*** Additional data are presented in these graphics with accompanying text:

Table 1. Summary of Laboratory Analytical Methods and Precision for Selected Parameters

Parameter	Analytical Method	Laboratory Precision*
TP	Samples digested in hot (100ºC) persulfate for 1 hour. Analyzed by spectrophotometer.	±0.1 µg/L (both TP and SRP)
TSS	Water samples were filtered through oven-dried (100ºC), pre-weighed, 0.45 micrometer (µm) glass-fiber filters. Concentrations were determined by weight gain volume filtered.	±0.2 mg/L
Chlorophyll-a	Water samples were also filtered through a Gelman HA 0.45-µm membrane filter, and the filtered residue was kept frozen until analysis. Acetone extraction was performed, then analyzed by spectrophotometer at a suite of wavelengths.	±0.5 µg/L
SRP, NO_3, Si	The filtrate was stored at 4ºC until colorimetric analysis of dissolved phosphate (SRP), nitrate (NO_3) and silica (Si) by spectrophotometer.	SRP (see TP) NO_3 ±0.1 mg/L Si ±5 µg/L
Major ions: sodium (Na^+) potassium (K^+) calcium (Ca^{2+}) magnesium (Mg^{2+}) chloride (Cl^-) sulfate (SO_4^{2-})	Analyzed by Ion Chromatograph	±0.5µg/L
Plankton	At least 100 plankton (colonies were counted as one individual) from each tow were enumerated, typically to species level, under a microscope and reported as relative abundance (percentage of the population sampled).	±20%

**Note: mg/L = milligrams per liter; µg/L = micrograms per liter*

Table 2. Mean, Maximum and Minimum of Annual Mean Data – 2005-2016*

	Honeoye	Canandaigua	Keuka	Seneca	Cayuga	Owasco	Skaneateles	Otisco
Secchi Mean (m)	3.0	6.2	5.6	4.3	3.8	4.1	8.0	2.8
Max	4.6	7.7	7.3	5.3	4.5	5.6	9.7	3.8
Min	1.6	4.2	3.7	3.1	3.0	3.2	6.9	2.1
N of means (years)	12	12	12	12	12	12	12	9
Chlorophyll-a Mean (µg/L)	15.6	2.0	1.7	3.4	3.3	3.0	0.9	4.1
Max	37.9	4.2	2.7	4.7	5.4	4.1	1.4	5.7
Min	2.7	1.2	0.8	2.4	2.0	1.9	0.6	2.8
N of means (years)	12	12	12	12	12	12	12	9
TSS Mean (mg/L)	4.3	1.3	1.3	1.7	1.7	1.8	0.8	3.1
Max	8.3	2.2	4.5	2.3	2.6	3.5	1.2	5.9
Min	1.4	0.8	0.7	1.3	1.2	1.2	0.5	1.5
N of means (years)	12	12	12	12	12	12	12	9
TP Mean (µg/L, P)	33.8	9.8	8.5	12.4	13.0	11.0	7.1	18.2
Max	52.4	18.0	14.4	19.6	23.9	17.7	15.5	36.1
Min	16.0	5.2	4.3	6.5	6.8	7.4	2.7	8.6
N of means (years)	11	11	11	11	11	11	11	9
SRP Mean (µg/L, P)	5.8	0.8	0.9	0.9	1.3	1.1	1.1	2.5
Max	16.9	3.0	4.1	3.1	4.4	5.8	5.3	15.7
Min	0.5	0.3	0.2	0.4	0.4	0.4	0.0	0.3
N of means (years)	12	12	12	12	12	12	12	9
NO_3 Mean (mg/L, N)	0.3	0.5	0.4	0.6	1.0	0.9	1.0	0.4
Max	2.8	5.3	4.0	3.8	3.3	3.7	7.3	2.1
Min	0.0	0.0	0.0	0.1	0.6	0.4	0.3	0.2
N of means (years)	12	12	12	12	12	12	12	9
**P:N Ratio (TP:NO_3)	7.6	54.9	46.8	45.5	79.8	78.0	141.8	24.6

**Note: Otisco results represent the 2008 through 2016 annual means.*

***Note: The P:N Ratio is presented as the average of the ratios calculated for each sample date.*

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- ***Figure 2a:*** CTD profiles, Seneca Lake 2015.
- ***Figure 2b:*** CTD surface and bottom water average data, Seneca and Owasco lakes, 2005 through 2016.
- ***Figure 3:*** CTD turbidity profiles, Keuka, Canandaigua, Seneca and Skaneateles lakes.
- ***Figure 4:*** Annual precipitation totals at the Ithaca Airport.
- ***Figure 5:*** Box and whisker plot of Secchi disk depths.
- ***Figure 6:*** Box and whisker plot of chlorophyll-a concentrations.
- ***Figure 7:*** Box and whisker plot of TSS concentrations.
- ***Figure 8:*** Box and whisker plot of surface TP concentrations.

Nitrate, dissolved silica, major ions, additional CTD profiles and other data, as well as numerous annual reports and various data summaries, are available elsewhere *(Halfman, 2016; http://people.hws.edu/halfman/).*

Selected Highlights

Temperature Profiles and Stratification

The CTD temperature profiles revealed the expected onset and decay of the summer-season stratification ***(Figure 2a;*** *Halfman 2016)*. For example, in Seneca Lake the epilimnion (warmer surface waters) warmed from about 4ºC (39ºF) in the early spring survey to nearly 25ºC (about 75ºF) by mid-summer, cooling again by the last survey date in late September ***(Figure 2b)***. Surface water temperatures warmed quicker in the smaller lakes such as Owasco ***(Figure 2b)***. The hypolimnion (colder bottom waters) remained at or slightly above 4ºC throughout the survey, especially in the deeper lakes.

A few lakes revealed different thermal responses. Persistent summer stratification was not observed in Honeoye Lake. Mixing by wind-driven waves was apparently sufficient to maintain polymictic conditions in this shallow lake (5.0 meters average depth, 11 meters maximum depth). The same wind events established and mixed the epilimnion to depths of 10 to 20 meters in the deeper lakes. In Otisco Lake, and occasionally other shallower lakes, the hypolimnion was typically warmer than 4ºC in the summer. Presumably, wind stress in these relatively shallow lakes maintained isothermal conditions throughout the entire water column as it warmed above 4°C (in some cases up to 10°C) in the early spring, until thermal stratification commenced sometime later in the spring. The hypolimnion temperatures remained constant throughout summer.

Specific Conductance and Salinity

Specific conductance CTD data ranged from 230 micro-siemens per centimeter (μS/cm) (approximately 110 mg/L) in Honeoye Lake to 730 μS/cm (approximately 350 mg/L) in the hypolimnion of Seneca Lake ***(Figure 2b)***. None of the salinities measured preclude these lakes from being viable drinking water supplies (USEPA's Maximum Contaminant Limit is 500 mg/L for total dissolved solids). The differences observed in specific conductance between lakes can be attributed to differences in bedrock geology. Limestones weather more easily, and thus watersheds overlying limestones contribute more dissolved ions (calcium and bicarbonate) to their lakes than do other bedrock in the region *(Halfman, 2014)*. For example, Honeoye and Keuka lakes revealed a smaller specific conductance and both lakes have much less limestone underlying their watersheds than the other lakes. The extensive de-icing salt use in the watersheds is another major source of dissolved ions to the Finger Lakes *(Wing et al., 1995; Halfman et al., 2006)*.

Seneca Lake, and to a lesser degree Cayuga Lake, have the largest salinities among the Finger Lakes. The source of extra sodium and chloride to Seneca Lake was previously hypothesized to originate from the influx of saline groundwater due to the lake floor's connection to the rock-salt Salina Formation *(Wing et al.,*

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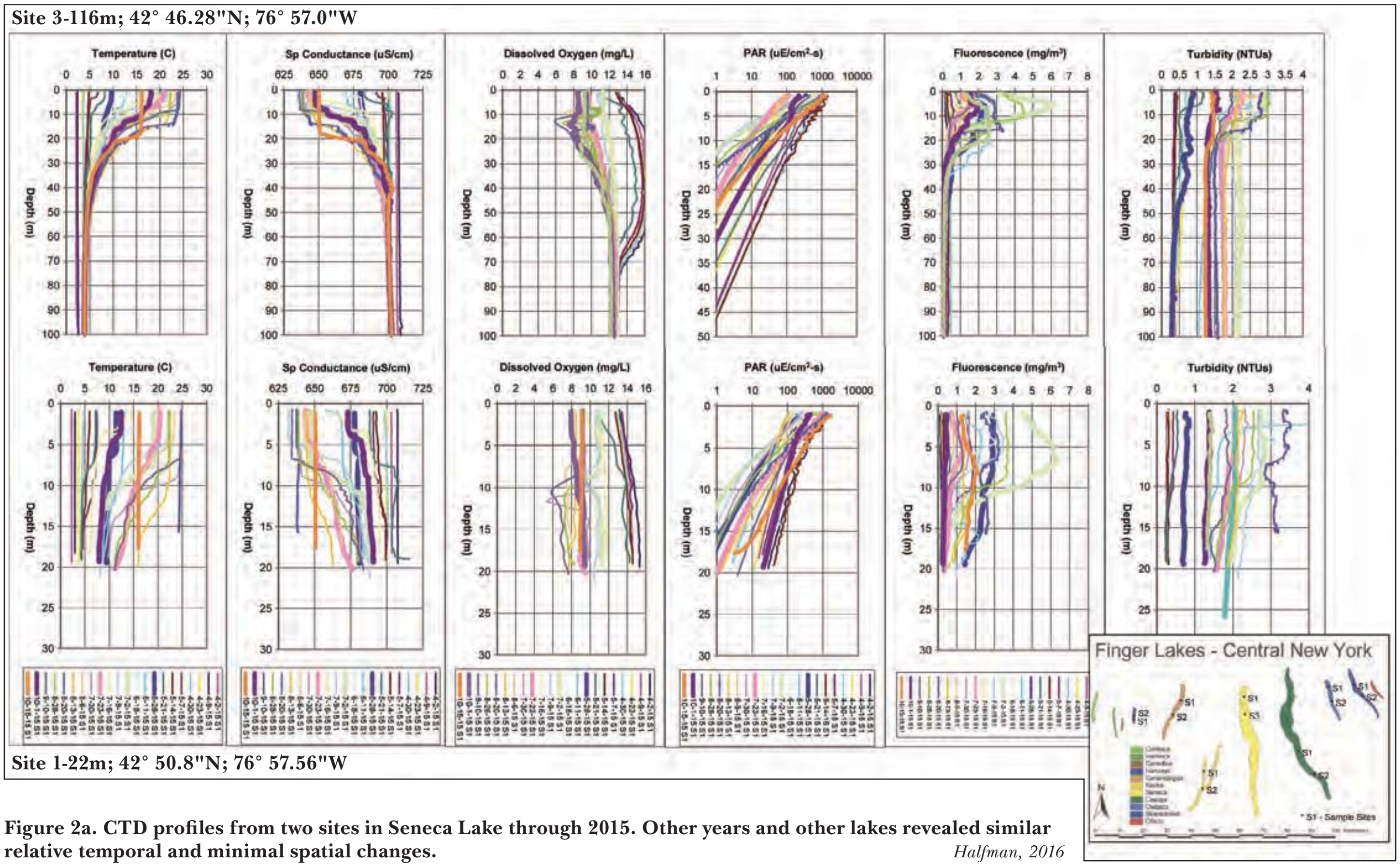

Figure 2a. CTD profiles from two sites in Seneca Lake through 2015. Other years and other lakes revealed similar relative temporal and minimal spatial changes.

Halfman, 2016

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1995; Halfman et al., 2006). However recent data from Seneca Lake, along with modeling efforts in Cayuga Lake, refute this groundwater source theory *(Effler et al., 1989; Halfman, 2014)*. In summary, the specific conductance of Seneca Lake has steadily decreased, from a high of 730 µS/cm in 2005 to a low of 635 µS/cm in the fall of 2015 ***(Figure 2b)***. This decrease is consistent with the lake's overall decrease in salinity, from a high in the 1960s to 1970s of about 200 mg/L Cl^-. This decrease over several decades is likely due to the regulation by the NYSDEC and USEPA of previously unregulated probable discharge of salt mine wastes (mostly sodium chloride) *(Halfman, 2014)*. More importantly, since the hypolimnetic (deep water) salinity has been relatively uniform each stratified season since the early 1990s, a lake floor (groundwater) source of excess sodium and chloride ions appears to be lacking in Seneca Lake.

Overall, in the Finger Lakes epilimnetic specific conductance gradually decreased by 10 to 50 µS/cm (approximately 5 to 25 mg/L) through the stratified season ***(Figure 2b)***. It suggests that the epilimnion was increasingly diluted by less saline precipitation directly onto the lake and runoff to the lakes. In support of this hypothesis, a large decrease in epilimnetic conductivities was detected between two surveys that straddled heavy rains. The tail end of Hurricane Katrina, in 2005, dropped three inches of rain in Geneva, New York, over a 48-hour period. Katrina's impact was especially pronounced in Owasco Lake, probably because this watershed has the largest watershed-area-to-lake-surface-area ratio of the eight lakes in the survey. Thus, Owasco Lake received a relatively larger volume of fresh water to its relatively smaller epilimnion from the same amount of rainfall. Over longer time scales, the largest epilimnetic decreases in Seneca and Owasco lakes occurred in 2011, 2014 and 2015; these three years had the most spring through fall rainfall measured *(Halfman et al., 2016)*.

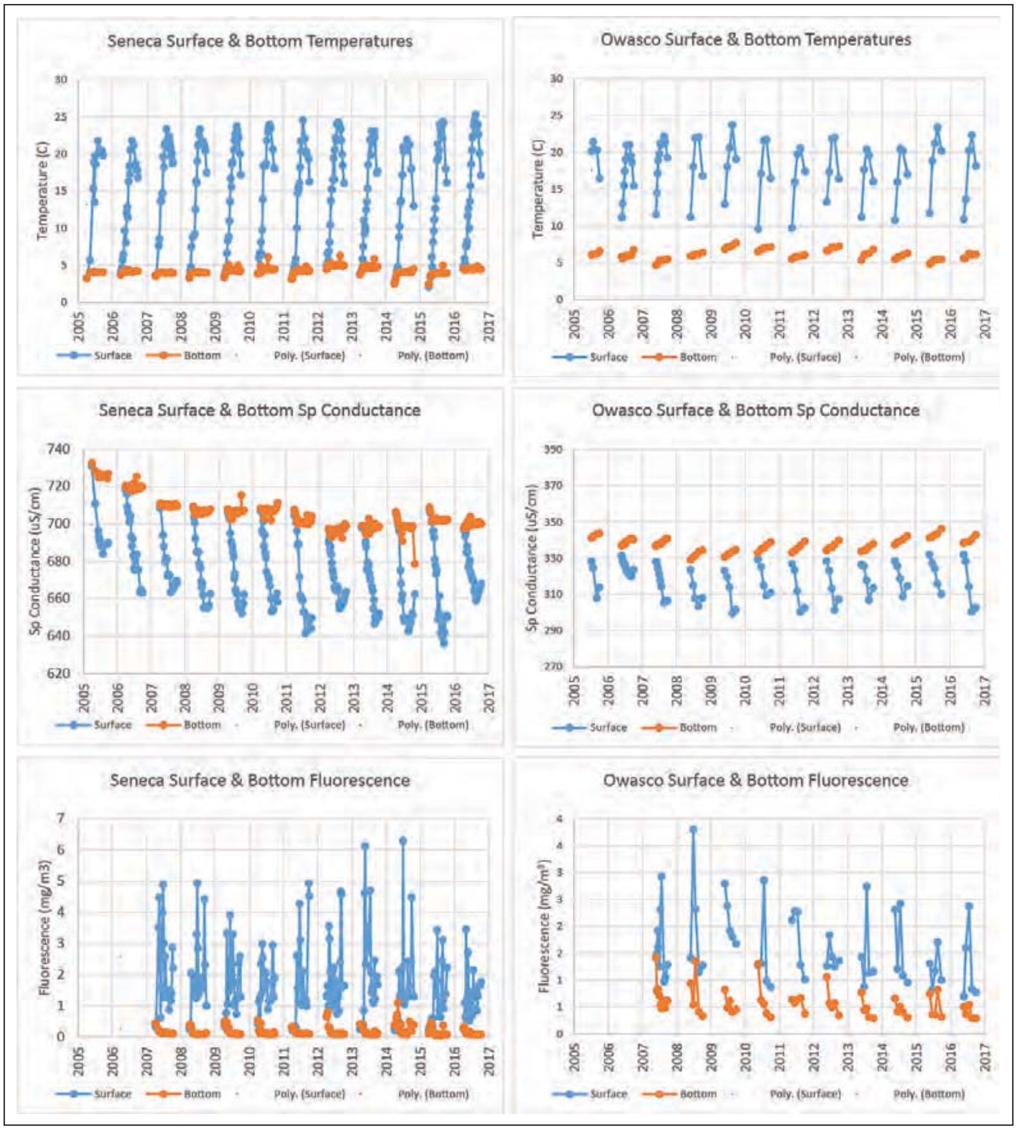
Seneca Surface & Bottom Temperatures
Owasco Surface & Bottom Temperatures
Seneca Surface & Bottom Sp Conductance
Owasco Surface & Bottom Sp Conductance
Seneca Surface & Bottom Fluorescence
Owasco Surface & Bottom Fluorescence

Figure 2b. Surface and bottom water averaged CTD temperature, specific conductance (salinity) and fluorescence (algae) data integrating over a 10-meter thickness from two representative lakes: Seneca (left) and Owasco (right).

Updated from Halfman, 2014

Turbidity

Surface water zones of increased turbidity were observed in the CTD profiles from many of the Finger Lakes ***(Figure 3)***. Parallel increases were observed in the epilimnetic fluorometer data, which indicates that the epilimnetic turbidity was primarily due to algae blooms. Algal peaks of 3 to 10 µg/L were detected in the epilimnion of Seneca, Cayuga, Owasco and Otisco lakes. Smaller peak concentrations were detected in the metalimnion of Keuka and Canandaigua, and into the upper hypolimnion of Skaneateles.

Benthic (lake floor) nepheloid layers were observed in all the surveyed Finger Lakes, except for Honeoye and Seneca. Years with larger benthic nepheloid turbidities typically corresponded to years with more precipitation, thus presumably more sediment laden runoff. The benthic nepheloid layers were best developed in Cayuga Lake, where hypolimnetic turbidities increased from 1 to 2 nephelometric turbidity units (NTUs) to 10 or more NTUs near the lake floor. Higher lake floor turbidities were detected at the southern monitoring site, where the largest subwatersheds empty into the lake. In contrast, Honeoye mixed too frequently for persistent nepheloid layers. The absence of benthic nepheloid layers in Seneca, even in the occasional profile from the deepest and southern locations, is perplexing but may reflect the presence of smaller tributaries in proportion to the lake's larger size as compared with Cayuga Lake.

Two years, 2014 and 2015, revealed larger turbidities throughout the entire water column for many of the lakes, as compared to the other years in the survey, especially during the early portion of the field season ***(Figure 3)***. Turbidities were typically larger than 2 NTUs in a few profiles in 2014 and 2015, while in other years turbidities were smaller in the same lakes. These larger turbidities were coincident with years with the largest precipitation totals, especially

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precipitation during the early spring *(Figure 4)*. Spring rains supply proportionally more runoff and suspended sediments because fields are bare. Agricultural fields have just been tilled for planting, and thus the soils are loosened and exposed, maximizing the potential for soil erosion by runoff. The ratios of runoff to infiltration and evapotranspiration are also larger in the spring, due to more saturated soils and inactive plant growth. Both factors increase the percentage of rainfall diverted to runoff. The change in turbidity is not consistent across all the surveyed lakes, most likely because rainfall totals and intensities are not uniform over the 14-county region, and the watershed-area-to-lake-volume ratios vary across the region.

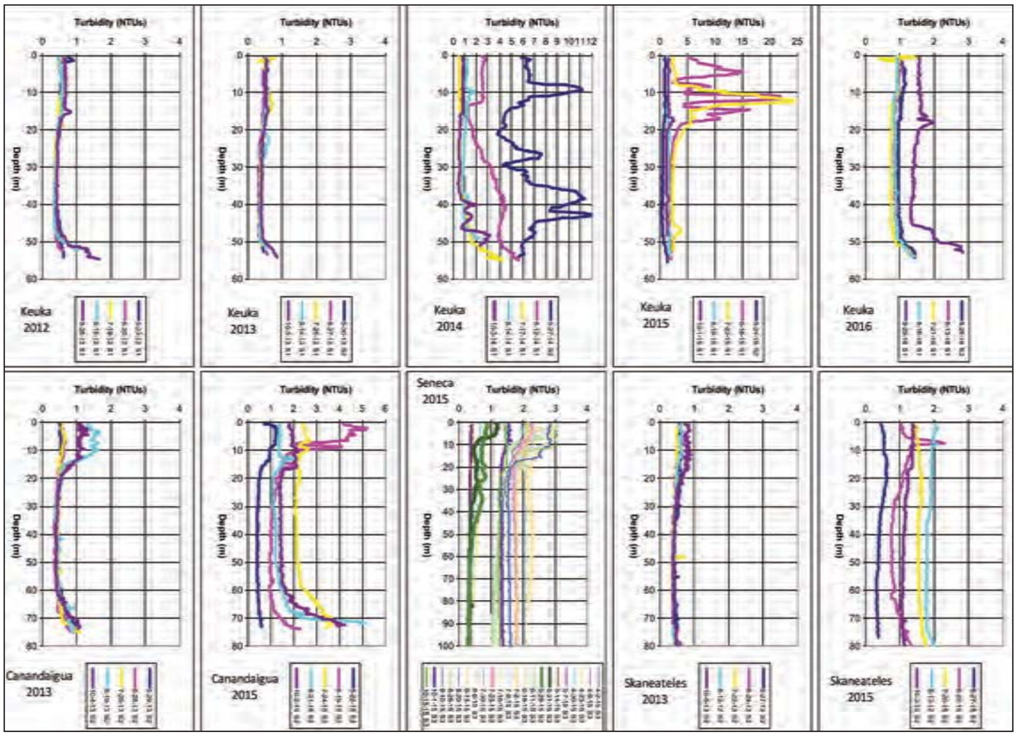

Figure 3. Turbidity profiles from 2012 through 2016 at Site 1 in Keuka Lake; 2013 and 2015 at Site 2 in Canandaigua Lake; 2015 at Site 3 in Seneca Lake; and 2013 and 2015 at Site 2 in Skaneateles Lake. Profiles reveal the changes in water column turbitity between survey dates and from one year to the next.

Updated from Halfman, 2016

Secchi Disk Depths

Annual mean Secchi disk depths ranged from 1.6 to 9.7 meters, and were deepest (least turbid) in Skaneateles Lake, and shallowest (most turbid) in Honeoye, Cayuga, Owasco and Otisco lakes *(Table 2, Figure 5)*. Annual mean Secchi disk depths in Seneca Lake revealed the largest multi-year change, of about 4.5 meters, as compared to the other lakes. The transition to deeper Secchi disk depths from 1992 to 1998 was due to the invasion and establishment of the filter feeding zebra (dreissenid) mussels. Zebra mussels came into the lake starting in 1992, and the population expanded until their first population crash in 1998 (*Halfman et al., 2012)*. Since 1998, Secchi disk depths have slowly declined back to 1992 levels, reflecting increasing concentrations of algae despite the addition of another dreissenid species, quagga mussels, to the filter-feeding mussel community in the early 2000s. The other seven lakes were not sampled until 2005; therefore, this survey could not detect the impact of the 1990s zebra mussel invasion on their water clarity.

Honeoye Lake has also experienced a significant shift from deeper to shallower Secchi disk depths starting in 2009; the reason is unknown. More recently, Honeoye, Canandaigua, Keuka, Seneca, Cayuga and Otisco monitoring revealed shallower Secchi disk depths – thus more turbid water – in 2014 and 2015, the two years with more spring precipitation as compared to other years in the survey.

Chlorophyll-a

Annual mean surface chlorophyll-a concentrations ranged from less than 1 µg/L in Skaneateles Lake to about 10 µg/L in Honeoye Lake *(Table 2, Figure 6)*. Cayuga, Owasco and Otisco revealed the second largest chlorophyll-a concentrations, while Canandaigua and Keuka showed the second smallest chlorophyll-a concentrations. Some of the variability between surface chlorophyll-a concentrations reflect the variable depth of the algal peaks in these lakes and the coincidence (or lack thereof) between the survey dates and algal blooms.

Annual average chlorophyll-a concentrations were larger in the epilimnion than the hypolimnion for all the lakes except for the well-mixed Honeoye, as algae thrive in the sunlit epilimnion. Surface chlorophyll-a concentrations in Seneca Lake declined from 1993 through 1998, and paralleled deeper (clearer water) Secchi disk depths during this time due to grazing pressures by zebra mussels. Since then, chlorophyll-a concentrations have increased and paralleled the decrease (cloudier water) in Secchi disk depths. Of note, surface chlorophyll-a concentrations were larger in Honeoye, Canandaigua, Keuka, Seneca, Cayuga, Owasco, and Skaneateles in 2014 and 2015 than in other years, consistent with the spike in turbidity data and rainfall totals.

Total Suspended Solids

Annual mean surface total suspended solids (TSS) concentrations were proportional to the chlorophyll-a concentrations and inversely

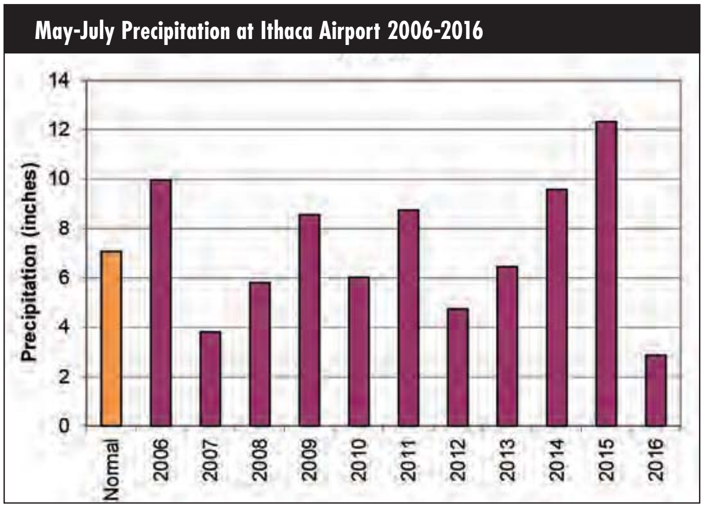

Figure 4. Annual precipitation totals from the Ithaca Airport during the 3-month, May through July, spring season, from 2006 to 2016

Updated from Halfman et. al., 2016

proportional to the Secchi disk data ***(Table 2, Figure 7)***. The largest concentrations were detected in Honeoye Lake and the smallest in Skaneateles Lake. Honeoye Lake revealed the largest date-to-date and year-to-year variability in TSS, most likely reflecting the presence or absence of algal blooms on the dates sampled. Surface TSS concentrations were relatively larger in 2014 – and to a lesser extent in 2015 – than other years in Honeoye, Canandaigua, Keuka, Seneca, Cayuga, Owasco and Skaneateles lakes.

Total Phosphorus

Surface total phosphorus (TP) concentrations were largest in Honeoye Lake, with annual means up to 52 µg/L as P ***(Table 2, Figure 8)***. Honeoye continues to be impaired based on NYSDEC's 20 µg/L TP numeric guidance threshold. Otisco Lake revealed the next largest TP concentrations, with annual means between 10 and 35 µg/L and thus was occasionally above the 20 µg/L impairment threshold. TP concentrations were smallest in Skaneateles, Canandaigua and Keuka lakes, with annual means ranging from 5 µg/L to 15 µg/L. Concentrations in Seneca and Cayuga lakes were between these high and low ranges. The largest TP concentrations in each lake were detected in 2014. The mean concentration in 2014 was typically twice the mean from the preceding year in each lake.

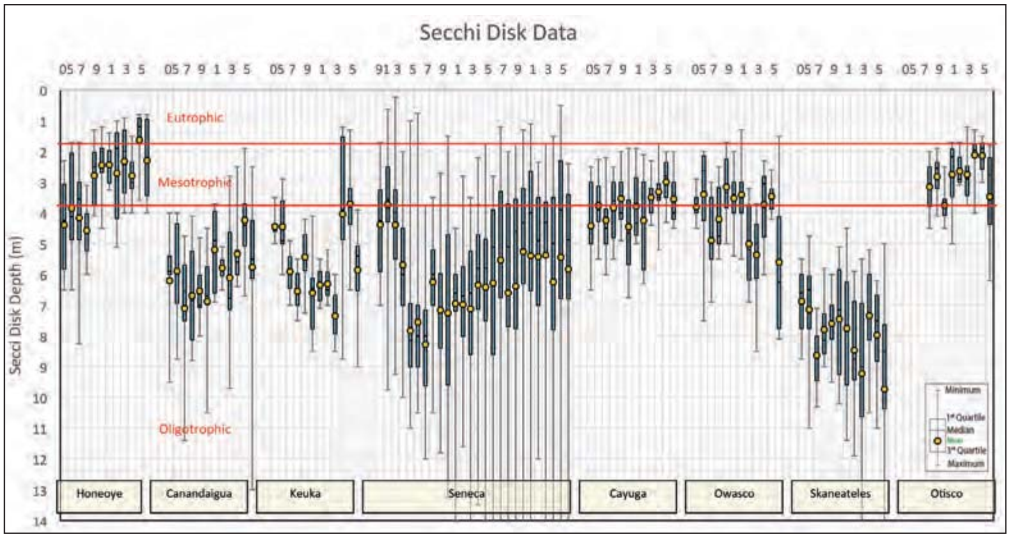

Figure 5. Box and whisker plot of Secchi disk depths. The numbers on the x-axis identify the year, e.g., 05 is 2005 and 91 is 1991. *Halfman, 2016*

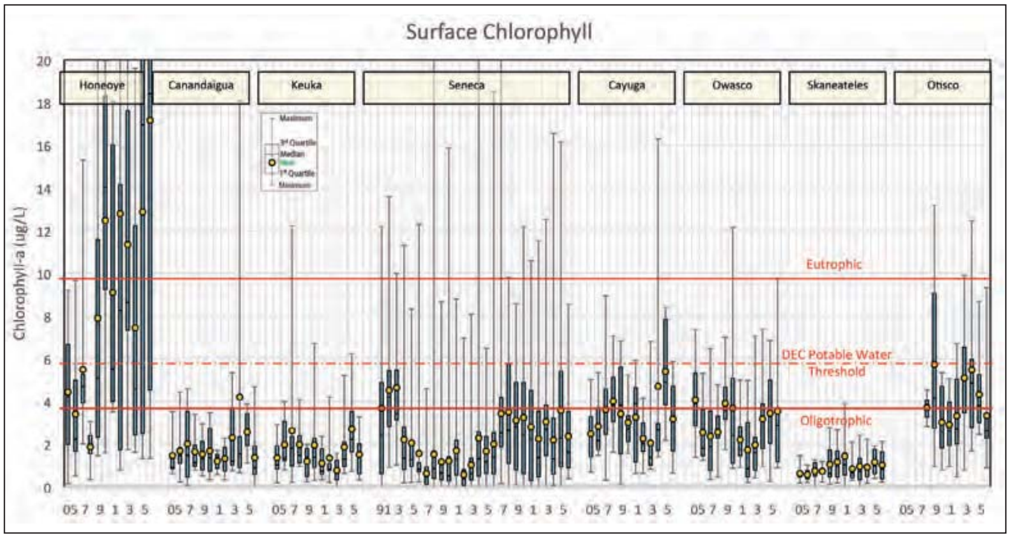

Figure 6. Box and whisker plot of surface water chlorophyll-a concentrations. The numbers on the x-axis identify the year, e.g., 05 is 2005 and 91 is 1991. *Halfman, 2016*

P:N ratios using the TP and NO_3 data indicate that, except for Honeoye Lake, the surveyed lakes are phosphorus-limited, meaning that the ratios are above the 1:7 Redfield Ratio *(Halfman, 2016)*.

Plankton and Algal Communities

Plankton populations were dominated by diatoms in all the eight Finger Lakes monitored ***(Figure 9)***. Seneca, Cayuga and Keuka consistently had the largest percentages of diatoms (50 percent to 80 percent of the taxa) whereas Otisco and Skaneateles had the least (20 percent to 30 percent). Dinoflagellates and blue-green algae were the next common plankton groups with annual percentages ranging from 5 percent to 20 percent. Of dinoflagellates, Canandaigua, Keuka, Owasco and Otisco had the largest percentages (greater than 10 percent), while Cayuga and Seneca had the least (less than 5 percent); Skaneateles was in-between. More green algae were detected in Honeoye, Cayuga, Skaneateles and Otisco lakes, up to 5 percent of the plankton community; Canandaigua, Keuka, Seneca and Owasco had the least, at only a few percent of the plankton community.

Definition: Redfield Ratio

Redfield measured the ratio of P:N in algae across the globe and always got the same answer, 1:7. The implication is simple: algal photosynthesis requires phosphorus and nitrogen in a fixed ratio, 1:7. If the supply of these two nutrients in the water column is skewed above or below this ratio, then the skew direction highlights which nutrient limits algal growth, because when the lake runs out of the under-supplied nutrient, photosynthesis stops.

The plankton net mesh (80 µm) was too large to trap significant quantities of cryptophytes. Recent Finger Lakes Institute Fluoroprobe data revealed that cryptophytes are major parts of the plankton community in Skaneateles, Keuka, Canandaigua and Cayuga *(Halfman, 2016)*. Specifically, the genera *Fragilaria, Tabellaria, Diatoma, Asterionella, Synedra, Melosira, Rhizosolenia* and *Cymbella* dominated the diatom taxa. *Dinobryon* and *Ceratium* dominated the dinoflagellate taxa. *Closteriopsis* and *Closterium* dominated the green taxa. *Anabaena, Stichosiphon, Gomphosphaeria* and *Microcystis* dominated the blue-green taxa.

Honeoye, Canandaigua, Keuka and Skaneateles had the largest percentage of blue-green algae (cyanobacteria) taxa (greater than 20 percent), and Seneca and Cayuga the least (less than 5 percent, ***Figure 9***). *Microcystis* was the most common form of cyanobacteria. It is surprising that three oligotrophic lakes had the largest relative

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abundance of blue-green taxa, as these cyanobacteria were thought to only impact eutrophic systems. Please note, relative abundances reported here do not dictate large concentrations of algae, just dominance of the taxa as a percent of the overall algal population. Cyanobacteria have been detected at the same relative abundance in these lakes since the start of the Finger Lakes Institute survey in 2005. In fact, blue-green species were detected in the Finger Lakes as long ago as 1914 *(Bloomfield, 1978)*. Only some of these Finger Lakes experienced significant nearshore blooms of cyanobacteria. It suggests that localized perturbation(s) must have triggered the recent and large nearshore blooms in selected lakes.

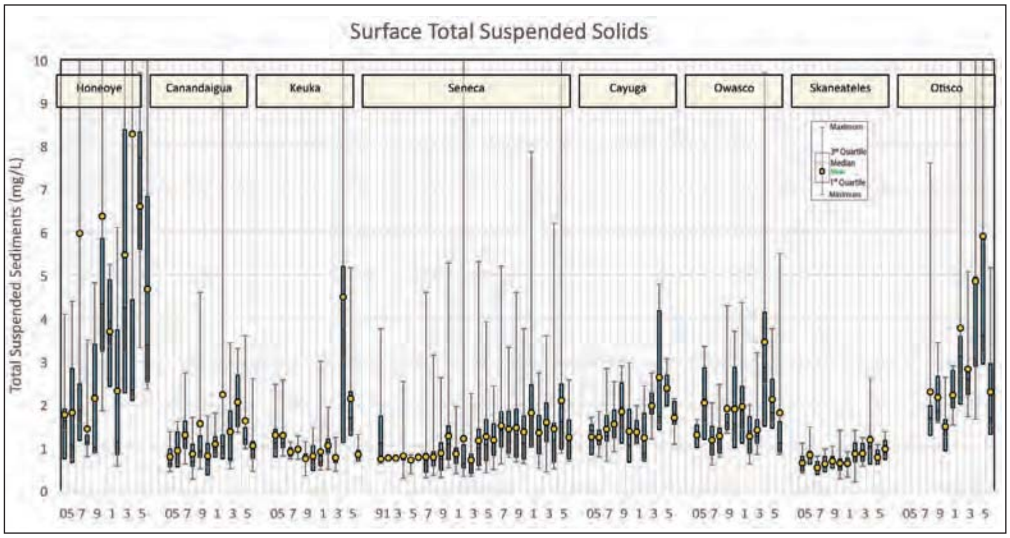

Figure 7. Box and whisker plot of surface water total suspended solids concentrations. The numbers on the x-axis identify the year, e.g., 05 is 2005 and 91 is 1991. *Halfman, 2016*

Finger Lakes Trophic State and Water Quality

The eight surveyed Finger Lakes ranged from oligotrophic to eutrophic systems ***(Table 2)***. Since Callinan's water quality survey of the Finger Lakes in the late 1990s *(Callinan, 2001)*, the trophic states of Keuka and Otisco lakes improved. Keuka's trophic state changed from mesotrophic to oligotrophic, while Otisco shifted from eutrophic to mesotrophic. The trophic status declined in Cayuga, Seneca and Owasco lakes, from borderline oligotrophic to mesotrophic. The trophic states of Skaneateles and Honeoye remained the same: oligotrophic and eutrophic, respectively.

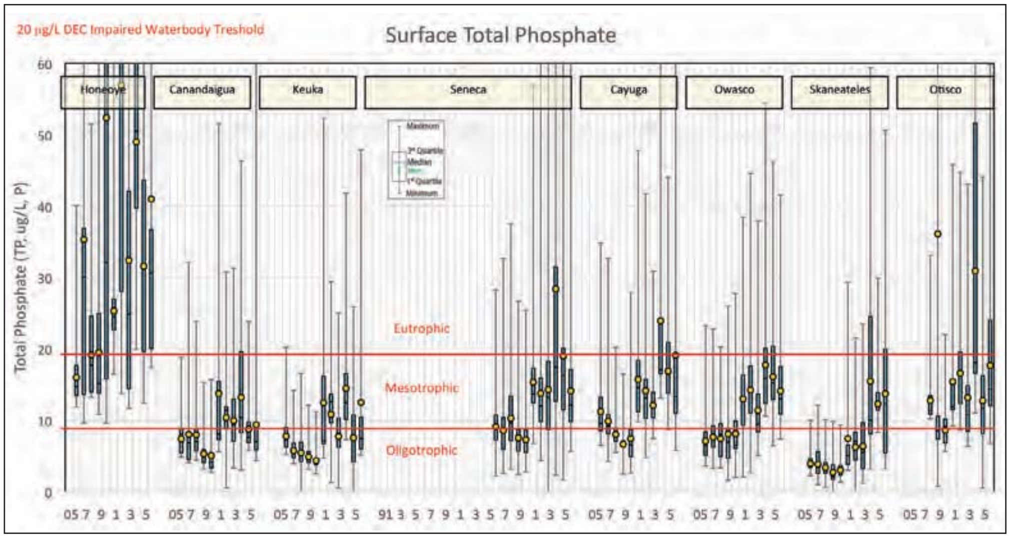

Figure 8. Box and whisker plot of surface water total phosphorus concentrations. The numbers on the x-axis identify the year, e.g., 05 is 2005 and 91 is 1991. *Halfman, 2016*

To increase the sensitivity of the water quality analysis, an independent annual water quality rank was calculated for each lake based on surface water concentrations of TP, SRP, NO_3, chlorophyll-a, TSS and Secchi disk depths *(Halfman and Bush, 2006)*. These independent ranks are consistent with a mean Carlson's Trophic Status Index (TSI) that mathematically manipulates surface concentrations of chlorophyll-a, TP, and Secchi disk depths *(Carlson, 1977)*. ***Figure 10*** plots the average (±1 standard deviation) of the annual mean TSIs. A mean annual TSI for each lake calculated the average of the annual mean Secchi disk (SD), total phosphorus (TP) and chlorophyll-a (Chl) TSIs using the

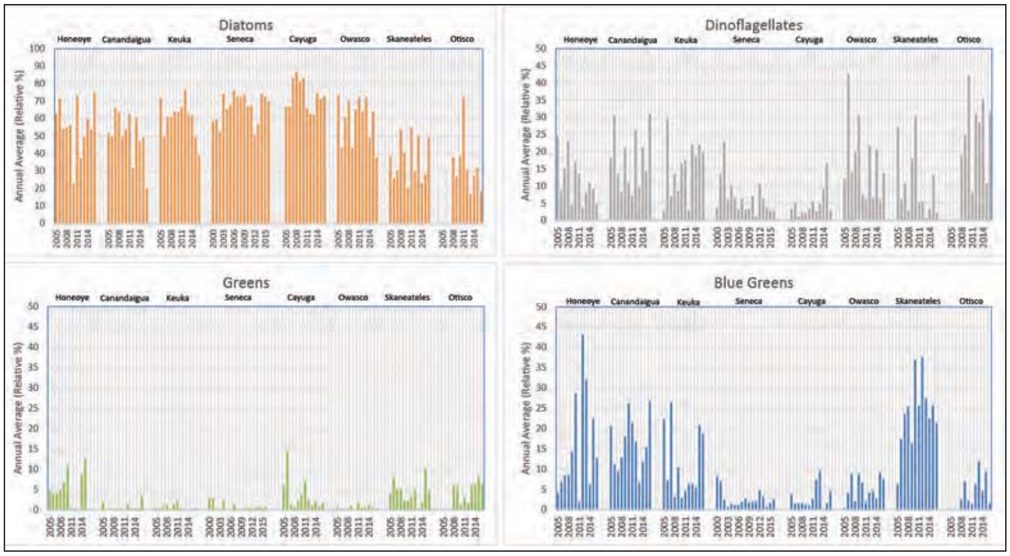

Figure 9. Annual average plankton relative percentages *Halfman, 2016*

Table 3. Trophic status of the Finger Lakes: Late 1990s, 2015 and 2016

Lake	Secchi Depth (m)	TP (µg/L)	Chlorophyll-a (µg/L)	Trophic Status	Callinan's Designation
Trophic Classification Boundaries					
Oligotrophic	> 4	< 10	< 4		
Mesotrophic	2 to 4	10 to 20	4 to 10		
Eutrophic	< 2	> 20	> 10		
Late 1990s *(Callinan, 2001)*					
Honeoye	3.7	24.2	8.4		Eutrophic
Canandaigua	7.7	6.2	1.0		Oligotrophic
Keuka	5.6	8.0	2.8		Mesotrophic
Seneca	6.0	9.8	2.4		Oligotrophic
Cayuga	4.0	9.7	3.5		Oligotrophic
Owasco	2.8	12.0	3.8		Oligotrophic
Skaneateles	7.6	4.0	0.7		Oligotrophic
Otisco	2.0	13.0	5.3		Eutrophic
2015					
Honeoye	1.6	31.6	19.0	Eutrophic	Eutrophic
Canandaigua	4.2	8.7	2.6	Oligotrophic	Oligotrophic
Keuka	3.7	7.6	2.7	Oligotrophic	Mesotrophic
Seneca	3.6	13.8	3.7	Mesotrophic	Oligotrophic
Cayuga	3.0	16.9	5.4	Mesotrophic	Oligotrophic
Owasco	3.3	15.5	3.8	Mesotrophic	Oligotrophic
Skaneateles	8.0	12.3	1.1	Oligotrophic	Oligotrophic
Otisco	2.1	12.7	4.3	Mesotrophic	Eutrophic
2016					
Honeoye	2.3	41	22.7	Eutrophic	Eutrophic
Canandaigua	7.7	18	1.8	Oligotrophic	Oligotrophic
Keuka	5.9	12.5	1.5	Oligotrophic	Mesotrophic
Seneca	4.3	15.1	2.7	Oligotrophic	Oligotrophic
Cayuga	3.5	16.5	3.0	Mesotrophic	Oligotrophic
Owasco	5.6	14.1	3.5	Mesotrophic	Oligotrophic
Skaneateles	9.7	13.7	1.0	Oligotrophic	Oligotrophic
Otisco	3.2	16.1	3.0	Mesotrophic	Eutrophic

Eleven Years of Water Quality Annual Ranks

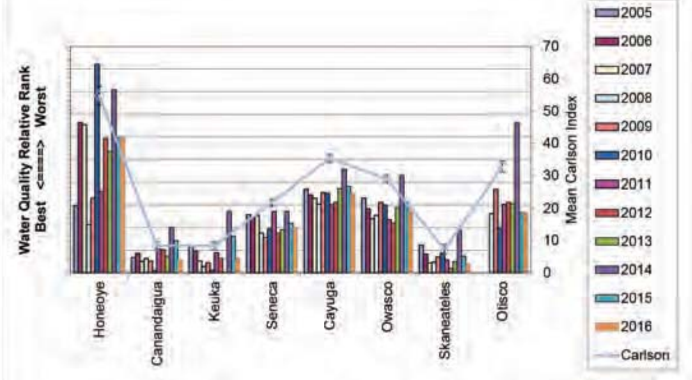

Figure 10. Annual water quality ranks and the mean Carlson's trophic status index *Halfman, 2016*

formulas below:

$$TSI\ (SD) = 10\ [6 - \ln\ (SD)\ /\ \ln 2]$$

$$TSI\ (TP) = 10\ [6 - (\ln\ (48/TP)\ /\ \ln 2)]$$

$$TSI\ (Chl) = 10\ [6 - (2\text{-}04 - 0.68 \ln\ (Chl))\ /\ \ln 2]$$

Two years – 2014 and 2015 – stand out in the year-to-year changes in water quality. Water quality declined in 2014 and 2015 for Canandaigua, Keuka, Cayuga, Owasco, Skaneateles and Otisco compared to other years in the record. These two years correspond to the larger concentrations of suspended sediments, TP, dissolved phosphates and chlorophyll-a mentioned previously, and were also the two rainiest springs in the recent past ***(Figure 4)***.

The mean water quality ranks were compared to the percentage of agricultural land, watershed area, lake volume, lake-volume-to-surface-area ratio, watershed area, water residence time, total population and population served with drinking water *(Halfman and O'Neill, 2009)*. Rank vs. watershed area revealed a correlation when the smallest lakes – Honeoye, Otisco and Owasco – were excluded from the analysis. When all eight of the surveyed lakes were included, none of these variables revealed a correlation ($r^2 <= 0.1$).

The percentage of agricultural land within each watershed revealed a strong correlation to the water quality ranks ($r^2 = 0.92$), but only when Honeoye was excluded from the comparison ***(Figure 11)***. This analysis suggests that runoff from agricultural landscapes is more nutrient-rich, fertilizing the algal populations and thus degrading the receiving lake. Excluding Honeoye Lake from this analysis is reasonable because its watershed history, shallow depth and small size set this lake apart from the other Finger Lakes in this survey. In the 1800s, the timber industry clear-cut the Honeoye watershed, resulting in severe soil erosion and nutrient transport to the lake. The nutrients transported historically exist today in the sediments of the lake. The lake's polymictic status (it is well-mixed from surface to bottom) induces significant internal nutrient

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Mean Rank vs. Agricultural Land Use

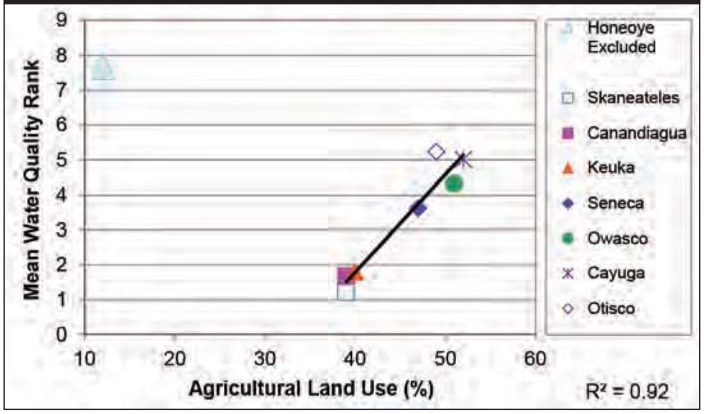

Figure 11. Mean water quality rank vs. agricultural land use. The best-fit correlation excluded Honeoye Lake. *Halfman, 2016*

loading to the water column from the sediments. Honeoye is also unique in that algal growth is limited by nitrogen, not phosphorus, as in other lakes in this survey.

Nutrient Loading Issues

Evidence from several Finger Lakes watersheds studies linked nutrient loading to water quality degradation (refer to *Halfman et al., 2008; Makarewicz et al., 2009; Effler et al. 2010; Halfman et al., 2012; UFI et al., 2014; Halfman et al., 2016;* and *Halfman 2016*). For example, each year's SRP concentrations in the Seneca Lake watershed are consistently 10 to 100 times larger in tributaries draining the watershed than in the lake, indicative of a nutrient loading problem *(**Figure 12;** Halfman et al., 2012)*. The phosphorus sources to Seneca Lake were multifaceted and included:

- Runoff from agricultural land, including both crop and animal farms, especially from Concentrated Animal Feeding Operations (CAFOs).
- Municipal wastewater treatment facilities.
- Soil, road ditch and stream bank erosion.
- Construction activities.
- Lakeshore on-site septic systems.
- Atmospheric deposition.

Another phosphorus source unique to the Reeder Creek tributary of Seneca Lake is residue from exploded munitions at the former Seneca Army Depot. The nutrient loads over time paint a consistent scenario with the decline in water clarity and water quality in Seneca Lake since the late 1990s ***(Figure 5)***.

Research in the Owasco watershed highlights the importance of precipitation events on nutrient loads *(Halfman et al., 2016)*. Event vs. base flow measurements at Dutch Hollow Brook, an agricultural-intense subwatershed of Owasco Lake, revealed that over 90 percent of the nutrient and sediment loads were transported during precipitation-induced runoff events as compared to base flow inputs, especially in the spring season *(Halfman et al., 2016)*. Comparable results were found in other Finger Lakes watersheds. This difference was less staggering in 2016, a relatively "dry" year. Annual nutrient and sediment loads positively correlated to precipitation totals as well, especially precipitation totals during the spring months ($r^2 = 0.81$, *Halfman et al., 2016)*. Thus, rainfall events and runoff from agricultural areas are significant to the delivery of nutrient and sediments to the lake. Other, but quantitatively less important, sources of phosphorus include effluent from municipal wastewater treatment facilities, on-site wastewater systems, stream bank and road ditch erosion, construction activities and atmospheric deposition (*Halfman et al., 2016*).

Estimated annual phosphorus budgets for Seneca and Owasco lakes confirmed a nutrient loading problem *(Halfman et al., 2012; Halfman et al., 2016)*. In Seneca Lake, inputs exceeded outputs by 45 metric tons of phosphorus per year or about one-third of the total amount of phosphorus in the lake *(Halfman et al., 2012)*. This annual load likely underestimated the actual load because most of the stream samples were collected during base flow. Annual phosphorus budgets for Owasco Lake from 2011 through 2016 ***(Figure 13)*** revealed a persistent net addition of phosphorus to the lake as well *(Halfman et al., 2016)*. A positive balance was probably also true for 2009 and 2010; as only base-flow stream data were used in these two years, therefore their phosphorus inputs lacked event contributions. Those years with significantly larger inputs than outputs experienced more spring rainfall.

Nutrient loading is an obvious "bottom up" ecological stressor to aquatic ecosystems by stimulating algal blooms and degrading water quality in the lake. But nutrient loading is not the only stressor controlling water quality in these lakes. "Top down" ecological perturbations can remove algal predators, and thus enhance algal populations and decrease water quality. For example, grazing of herbaceous zooplankton by the carnivorous zooplankton *Cercopagis pengoi* induced a mid-summer algal bloom in Owasco Lake *(Brown and Baulk, 2008)*. In contrast, the filter-feeding zebra and quagga mussels increased water clarity in the 1990s. Thus "top down" alter-

Dissolved Phosphate (SRP) Average (1999-2014) Concentrations

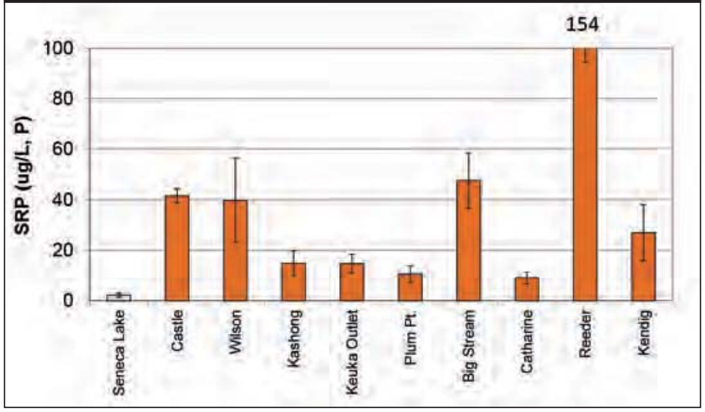

Figure 12. Average dissolved phosphate (SRP) concentrations in the major Seneca Lake subwatersheds (orange) compared to SRP concentrations in the lake (green-left side) *Halfman, 2016*

Phosphate Inputs and Outputs

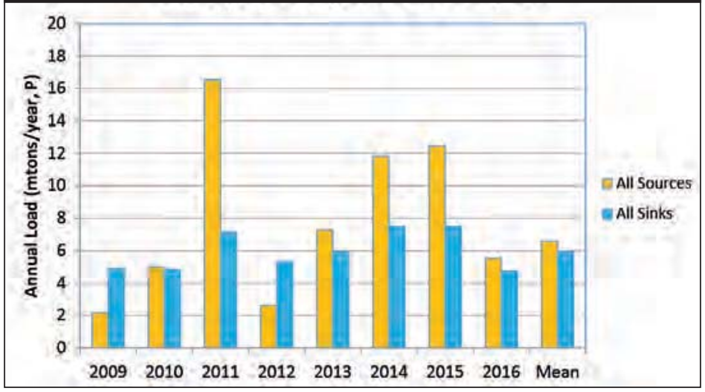

Figure 13. Estimated annual total phosphorus inputs and outputs for Owasco Lake *Halfman et. al., 2016*

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ations probably influenced some of the year-to-year variability in water quality and water clarity, as well.

Implications for Blue-Green Algae (Cyanobacteria)

The recent rise in blue-green algal (cyanobacterial) blooms and their associated toxins, with concentrations occasionally above toxic thresholds in many Finger Lakes, is disturbing *(**Table 4;** R. Gorney and S. Kishbaugh, NYSDEC, personal communication 2016)*. The Finger Lakes were not unique in having more recent cyanobacteria blooms; 95 lakes in New York had confirmed blooms in 2016, and 38 of those also had confirmed high toxin concentrations. The number of impacted lakes throughout the state has grown from 58 lakes in 2012 to 172 lakes in 2016. However, the trend over time may reflect that, in more recent years, there have been an increasing number of people looking for blooms. The most disturbing aspect is that cyanobacterial blooms were detected in some oligotrophic (Canandaigua) and mesotrophic (Cayuga, Owasco, Otisco and Seneca) lakes as well as the expected eutrophic (Honeoye) systems. By the end of 2016, cyanobacterial blooms have not been reported by the NYSDEC for Hemlock, Canadice, Keuka and Skaneateles lakes. Unfortunately, by the end of the summer of 2017, cyanobacterial blooms had been confirmed for all 11 of the Finger Lakes. *(NYSDEC)*.

All of the affected Finger Lakes revealed suspended sediment and nutrient perturbations in 2014 and 2015. Those years paralleled the first detection of cyanobacteria blooms in many of the impacted lakes. Those lakes lacking cyanobacterial blooms have less agricultural land and more forested land in their watersheds, and/or have stricter watershed protection legislation, thus less runoff of nutrients during events. The temporal association suggests that nutrient loading may have provided a trigger for these blooms in the Finger Lakes. It also implies critical remediation strategies must be established now to reduce and hopefully reverse the disturbing trends in water quality.

Table 4. Harmful algal blooms (HABs) reported in the Finger Lakes, 2012-2016
(Source: Gorney and Kishbaugh, personal communication 2016)

Lake	2012	2013	2014	2015	2016
Conesus	–	–	C (7)	C (3)	C (4)
Hemlock	–	–	–	–	–
Canadice	–	–	–	–	–
Honeoye	S (12)	HT (18)	C (8)	HT (7)	C (9)
Canandaigua	–	–	–	HT (4)	C (3)
Keuka	–	–	–	–	–
Seneca	–	–	–	C (6)	HT (2)
Cayuga	–	–	S (3)	–	C (7)
Owasco	HT (1)	C (7)	HT (12)	HT (9)	HT (9)
Skaneateles	–	–	–	–	–
Otisco	–	–	–	S (?)	–

Note: Bloom status key: S = suspicious, C = confirmed, HT = confirmed with high toxins; The value in parentheses is the number of weeks detected in lake. Harmful Algal Blooms (HABs) Archive Page, NYSDEC Website (http://www.dec.ny.gov/chemical/83332.html).

Conclusions

The trophic status ranged from oligotrophic to eutrophic systems across the eight easternmost Finger Lakes. Skaneateles, Canandaigua and Keuka Lakes are the most oligotrophic and exhibit the best water quality. Honeoye is the most eutrophic. The remaining lakes – Seneca, Owasco, Cayuga and Otisco – are in-between, i.e., borderline oligotrophic/mesotrophic to mesotrophic. The trophic status in many lakes has changed since the late 1990s. Nutrient loading can explain the observed degradation in water quality and even some year-to-year variability, especially during 2014 and 2015. This timing coincides with the onset of blue-green algal (cyanobacterial) blooms in many Finger Lakes. It implies remediation efforts to reduce nutrient loading must be established now to reverse the observed water quality degradation of these lakes. Since the sources of nutrients are multifaceted, and everyone contributes in some way to the nutrient loading problem, everyone must also contribute to the nutrient reduction strategies.

The critical roles of the lakes as drinking water supplies and recreational resources are essential to the regional tourism-based economy, so everyone has a stake in protecting and preserving water quality in the Finger Lakes. Therefore, everyone must work together to reduce nutrient sources and cyanobacteria blooms to eventually improve water quality in our lakes.

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