WATER QUALITY OF THE FINGER LAKES, NEW YORK: 2005 – 2008.

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3/2/2009

INTRODUCTION

The Finger Lakes of western and central New York are critical to the health, well-being and economy of the region. The eleven Finger Lakes, Conesus, Hemlock, Canadice, Honeoye, Canandaigua, Keuka, Seneca, Cayuga, Owasco, Skaneateles, and Otisco, contain 8.1 trillion gallons of water (30.8 km^3), and their watersheds occupy a 2,630 square mile (4,970 km^2), 14-county region (Fig. 1). These lakes are a source of Class AA drinking water to the 1.5 million residents in the surrounding communities. For example, Skaneateles and Otisco Lakes provide drinking water for the City of Syracuse; and, Hemlock and Canadice Lakes provide drinking water for the City of Rochester. Total withdrawals are approximately 190 million gallons of water per day from all the Finger Lakes, except Honeoye (Callinan, 2001).

The natural beauty of the Finger Lakes region attracts approximately 22 million tourists each year. The tourism generates over $2 billion annually with significant growth projected for the immediate future. Water-based recreation, sport fisheries, wildlife habitat, and a diverse industrial and agricultural sector, that includes a renowned wine and grape industry, comprise the important economic, social, ecological and occasionally competing environmental attributes of the Finger Lakes Region. Thus, these lakes must be protected from numerous threats to water quality.

A preliminary water quality survey, conducted in 2005 and published in 2006 under the direction of Dr. John Halfman, Finger Lakes Institute at Hobart and William Smith Colleges, ranked water quality parameters for Skaneateles, Owasco, Cayuga, Seneca, Keuka, Canandaigua and Honeoye Lakes (Fig. 2, Halfman and Bush, 2006). These lakes were selected because they span the diversity of land use activities and bedrock geologies in the region, they contain 98% of the water in the Finger Lakes, and they are closest to the Colleges in Geneva, NY. The ranking was based on monthly surface water samples, CTD profiles and secchi disk depths from at least two mid-lake, deep-water sites in each lake. Water samples were analyzed for total coliform and *E. coli* bacteria, algae concentrations (chlorophyll-a), nutrient concentrations (dissolved phosphates, nitrates and silica), and suspended sediment concentrations. The data indicated that Seneca,

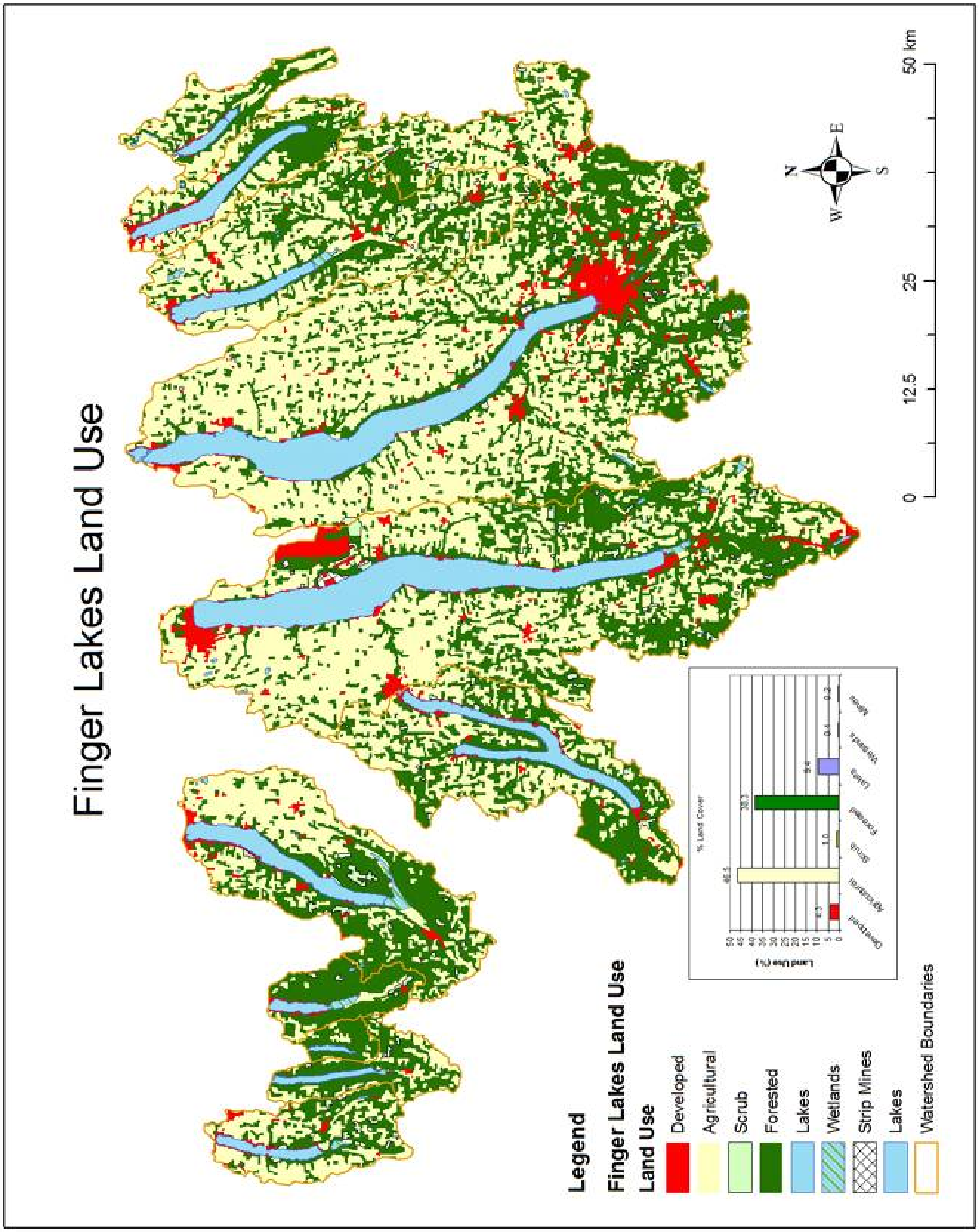

Fig. 1. Land use in the Finger Lake Watershed.

Owasco, and Honeoye Lakes had the worst water quality, whereas Skaneateles, Canandaigua and Keuka Lakes had the best water quality. Cayuga Lake fell in between the end-members. The 2005 preliminary report also noted a correlation between the water quality ranking and a first-order, qualitative assessment of water quality protection legislation. Water quality was better in lakes with more stringent and more importantly more active water quality protection activities.

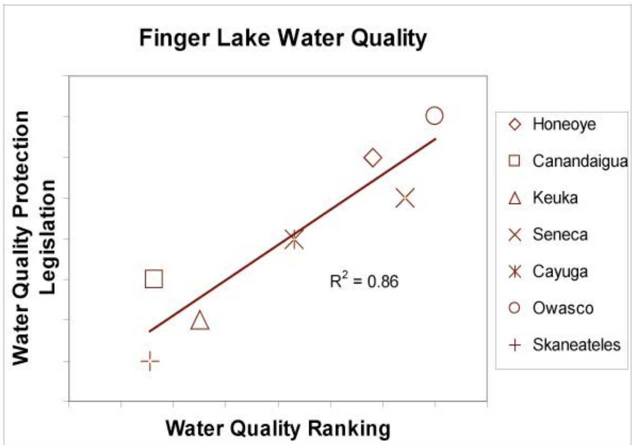

Fig. 2. The 2005 water quality ranking of 7 Finger Lakes.

The 2005 results spearheaded continued research on these seven Finger Lakes. We dovetailed two types of studies: (1) continued comparison between the Finger Lakes to investigate year to year changes in water quality, and (2) more detailed investigations in selected watersheds to more fully understand the source of nutrients and other water quality impairments to these lakes. In this report, we summarize our current understanding of the limnology and water quality of these lakes, investigate year to year changes in water quality in each basin, and summarize detailed investigations in the Seneca, Owasco and Cayuga watersheds. This report also includes an initial water quality evaluation of Otisco Lake, added to our Finger Lakes comparison program in 2008. Our goal is to explain the science so that state, county and local policy makers, residents, farmers, engineers, and all the other stakeholders understand the current situation and probable water quality trends into the future because everyone has to work together to preserve, protect and in some cases improve water quality in the Finger Lakes.

WATER QUALITY INDICATORS

The rural landscape and agricultural land use activities dominate the Finger Lake watersheds with agriculture covering 46.5% of the region, forests 38.3%, lakes 9.4%, and urban areas 4.3%. The land use suggests that the primary water quality threat to these lakes is nutrient loading from the decomposition of organic wastes and agricultural runoff. The reasons are simple. Excess nutrients stimulate algal and nearshore plant productivity, which in turn progressively reduces water quality and water clarity in a lake until the lake becomes eutrophic and impaired.

Nutrients, dissolved phosphates (PO_4^{-3}), nitrates (NO_3^-) and silica ($H_2SiO_4^{-2}$), are essential for life because they are required for critical building blocks of life including amino acids, proteins, cell tissue, RNA and DNA. In a basic aquatic nutrient cycle (Fig. 3), dissolved nutrients enter the food chain by their assimilation and incorporation by plants, phytoplankton (algae, microscopic aquatic plants) and macrophytes (nearshore rooted vegetation). When the algae and other plants are eaten, these nutrients are passed up the food chain to the other organisms in the lake like zooplankton and lake trout. When any of these organisms die, bacteria complete the final step of the nutrient cycle by decomposing the organic material and releasing the nutrients back into the water column to be assimilated by algae and other plants once again. Due to the scarcity of nutrients in lakes, lake ecosystems are very proficient at recycling nutrients. Thus nutrient concentrations are fundamental indicators of algal productivity, the trophic status and eutrophication in lakes.

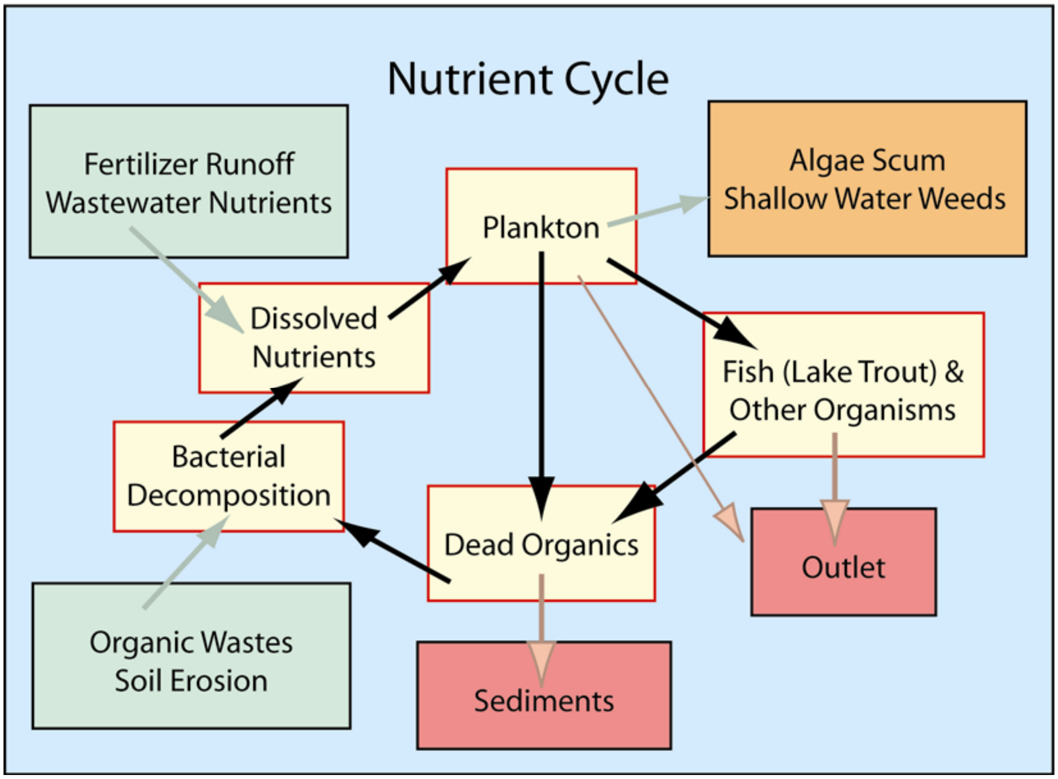

Fig. 3. A typical nutrient cycle for lake ecosystems (yellow boxes). Typical natural and human-induced additions (green boxes), their impact (orange box), and natural sinks (red boxes) from the nutrient cycle are also shown.

Nutrient loading from a variety of sources, can potentially transform an oligotrophic (poorly productive) lake to a eutrophic (highly productive) lake, because the extra nutrients stimulate additional algal and macrophyte growth, and increase the amount of biomass in each box of the nutrient cycle over time. Other, typically undesirable but related impacts occur. For example, a foul smelling/tasting scum of blue-green algae typically dominates the algal community and covers the surface of the lake with a green slime in eutrophic systems. The increase in algae decreases water clarity (e.g., transparency), as the extra algae impede the transmission of light through water. The increased algal concentrations also increase the cost of water filtration for municipal water supplies.

When the algae die (algae live for only a few days), bacteria naturally decompose the organic material. The bacteria consume dissolved oxygen, release carbon dioxide, and recycle nutrients back into the environment. If the removal of oxygen from the summer-time hypolimnion (water depths below the thermocline) is severe enough, respiratory stress is placed on all aquatic animals like lake trout, crawfish and worms, because dissolved oxygen is required for survival. The threshold concentration for induced stress is somewhere below 6 mg/L, each species has its own level of tolerance. Complete de-oxygenation of the bottom waters happens in eutrophic lakes and induces fish kills. However, other strains of bacteria continue the recycling process, using other compounds beside dissolved oxygen to decompose the organic matter and releasing methane instead or carbon dioxide. If sulfur is available, the bacteria release a "rotten egg" odor caused by the bacterial formation of hydrogen sulfide. Unfortunately, once nutrients enter a lake, the ecosystem typically remains enriched in nutrients because nutrients are continually and efficiently recycled within the lake. Thus, the excess nutrients continue to "fertilize" plant growth at enhanced levels. Only a small fraction of the nutrients are permanently lost from the lake out the outlet or buried into the sediments. Burial is only significant in oxygenated systems because anoxic bottom waters allow phosphates, previously buried in the sediments as particles (oxides) in oxygen-rich oligotrophic systems, to subsequently dissolve and re-enter the water column.

Excess nitrates also induce health risks to humans, specifically methemoglobinemia or blue-baby syndrome, and the EPA sets a maximum contaminant level (MCL) for nitrate concentrations at 10 mg/L for safe drinking water. Phosphates and silica at natural concentrations do not pose health risks but contribute to the fertilization and eutrophication of waterways. Phosphate is critical for the eutrophication of lakes because it is typically the limiting nutrient for algal growth. Thus its concentration is typically very close to zero, and almost all of the available phosphorus is incorporated into organic matter. Occasionally nitrate is the limiting nutrient, especially in eutrophic lakes. If this is the case, a few groups of algae circumvent the scarcity of nitrogen by "fixing" nitrogen (N_2) from the atmosphere into a useful organic form. Blue-green algae are nitrogen fixers, they dominate nitrate poor systems, and typically dominate eutrophic aquatic systems. We include dissolved silica in the list of nutrients because silica is required by diatoms, a form of algae found in most lakes, to form their frustules (shells). The presence or absence of silica does not impact the trophic status. Instead its presence allows diatoms to dominate an ecosystem, whereas its scarcity favors other forms of algae.

Algal concentrations are another indicator of lake productivity and the ecological health of a lake. Algal concentrations are measured directly by the concentration of chlorophyll, and indirectly by fluorometer, total suspended solids and secchi disk depths. The secchi disk is a weighted disk, 20 cm in diameter, and painted with two black and two white quadrants. It is slowly lowered into the water until it disappears, and this water depth is noted. The disk is lowered some more, and then slowly pulled up until it reappears, and this second depth is noted. The secchi disk depth is the average of these two depths. In very ultra-oligotrophic (low productivity) systems thus very transparent waters, secchi disk depths can be 100 feet (30 m) or more. In eutrophic (highly productive) lakes and ponds, secchi disk depths can be as shallow as a few centimeters.

Thus, nutrient, algal and dissolved oxygen concentrations are useful trophic status indicators. Typically, a combination of nutrient, algal, dissolved oxygen concentrations, and secchi disk depths are utilized to document the degree of productivity, or trophic status, in aquatic systems (Table 1).

Table 1. Typical concentrations for oligotrophic (low productivity) and eutrophic (high productivity) lakes (EPA).

Trophic Status	**Secchi Depth (m)**	**Total Nitrogen (N, mg/L, ppm)**	**Total Phosphate (P, μg/L, ppb)**	**Chlorophyll a (μg/L, ppb)**	**Oxygen (% saturation)**
Oligotrophic	> 4	< 2	< 10	< 4	> 80
Mesotrophic	2 to 4	2 to 5	10 to 20	4 to 10	10 to 80
Eutrophic	< 2	> 5	> 20 (> 30)	> 10	< 10

METHODS

Water quality measurements were routinely collected from selected Finger Lakes at two deep water sites on a monthly basis during the 2005 through 2008 field seasons (Fig. 4.). Honeoye, Canandaigua, Keuka, Seneca, Cayuga, Owasco, and Skaneateles Lakes were sampled through out the survey. Otisco Lake was added to the survey in the 2008 field season. Sampling at Seneca during 2005 through 2008, Cayuga during 2007 and 2008, and Owasco during 2006 and 2007, was more frequent, sampled additional sites and analyzed tributary inputs to Seneca and Owasco Lake to investigate water quality impairment sources in these watersheds.

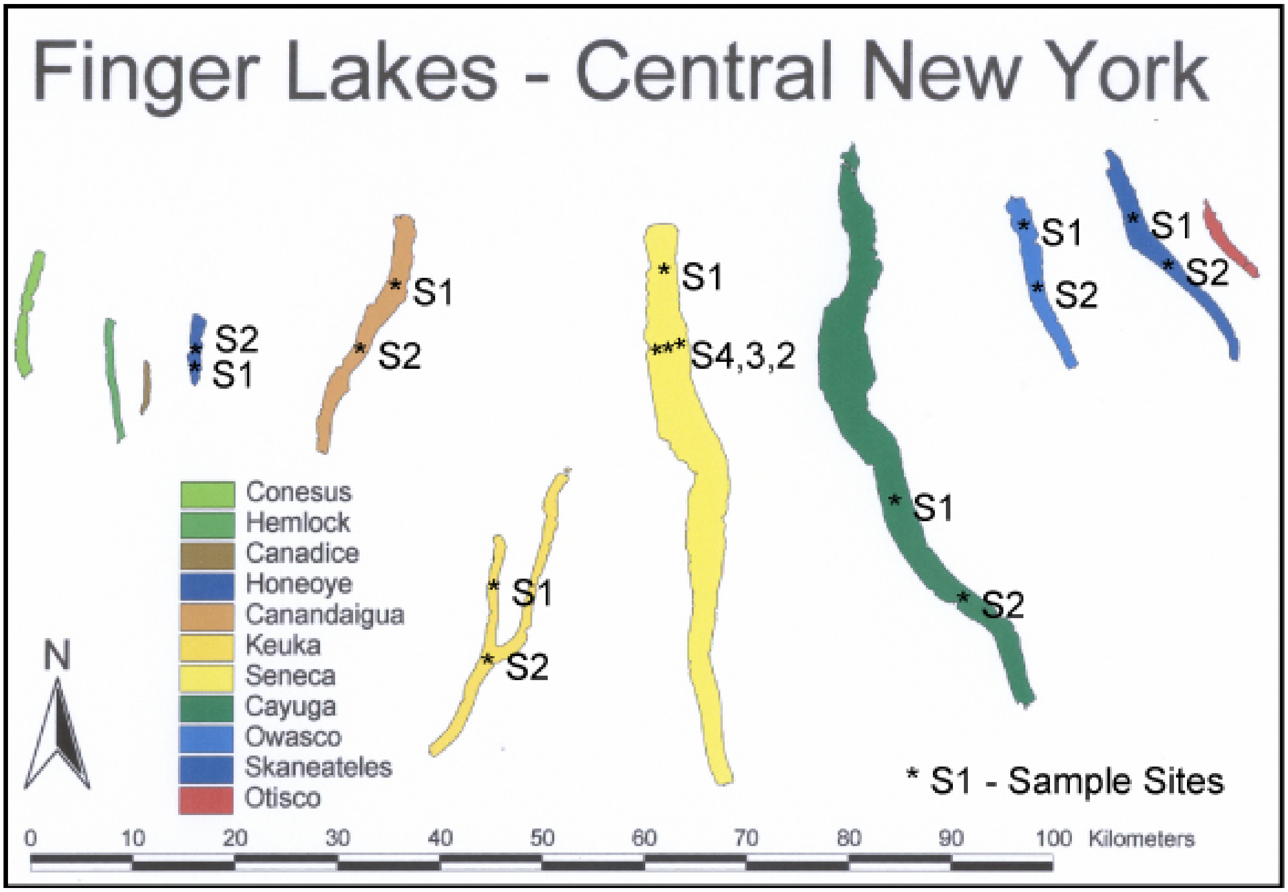

Fig. 4. Sample site locations.

At each site, surface (< 1 m depth) and bottom water (within a few meters of the lake floor) samples were collected for bacterial (only in 2005), nutrient, total suspended sediment and chlorophyll assays with analysis back in the laboratory. In addition, secchi disk depth, plankton tows and a water column CTD profile were collected from each site. We used a SeaBird SBE-19 CTD during 2005 and 2006. The CTD was upgraded to a SeaBird SBE-25 CTD during the 2007 and 2008 field seasons (Fig. 5). Both CTDs were lowered from the surface to approximately 1m above the lake floor. A 10L niskin bottle was attached just above the CTD to collect bottom water. The SBE-19 collected continuous water column profiles of temperature (°C), conductivity (specific conductance, μS/cm), light transmission (proportional to water clarity, %), dissolved oxygen (ml/L) and pH. The SBE-25 collected profiles of temperature (°C), conductivity (specific conductance, uS/cm), dissolved oxygen (ml/L), pH, turbidity, algal biomass (WetLabs ECO-FLU fluorometer), and light intensity (Biospherical PAR).

Fig. 5. The SBE-25 CTD.

Nutrient, chlorophyll-a, and total suspended solids analyses followed standard limnological techniques (Wetzel and Likens, 2000). Typically four liters of lake water was filtered through a pre-weighed 0.45 μm glass-fiber filter. The filter and residue were dried at 90°C overnight. The weight gain and filtered water volume determined the total suspended sediment concentration. Typically one liter of lake water was filtered through a Gelman HA 0.45 μm membrane filter. The filtered residue was kept frozen until chlorophyll analysis, where the chlorophyll pigments were extracted in acetone and analyzed by the trichromic method using a 1-cm cell in a spectrophotometer. The filtrate was analyzed for subsequent soluble reactive (dissolved) phosphate (SRP), nitrate and silica colorimetric analyses by spectrophotometer. Samples were treated in an acidic molybdate reagent and analyzed by spectrophotometer using a 10-cm cell at 885 for phosphates and in a 1-cm cell at 810 nm for silica. Nitrates were prepared with a Hach Low Range Nitrate Kit (Model NI-14) and concentrations were colorimetrically detected by spectrophotometer using a 1-cm cell at 540 nm in the laboratory.

A third unfiltered water sample was analyzed for total phosphates. This sample was in potassium persulfate at 100ºC for 1 hour to release all phosphates into solution and subsequently analyzed by colorimetric analysis by spectrophotometer using the SRP procedure (Fig. 6). Laboratory precision was determined annually by analyzing replicate tests on the same water sample, and typically was 0.2 mg/L for total suspended solids, 0.1 μg/L for phosphate, 0.1 mg/L for nitrate, and 5 μg/L for silica. All water samples were kept at 4°C until analysis and typically analyzed within a week of collection.

For quality control, over 100 randomly selected sample splits were analyzed by Life Science Laboratories, a commercial laboratory, for total phosphate, dissolved phosphate and nitrates within a few weeks of sample collection in 2007. The comparison indicates that our results are statistically equivalent to the Life Science data (r^2 = 0.84 for nitrate, r^2 = 0.93 for dissolved phosphate (SRP) and r^2 = 0.76 for total phosphate (TP)). The correlations were hampered by the time delay between sample date and lab analysis, a few TP outliers, and most importantly, the analytical detection limits at each lab. Life Science Laboratory has a much higher detection limit for all three nutrients and could not detect nitrate concentrations below 0.2 mg/L compared to the 0.1 mg/L at HWS, or phosphate concentrations below 3 μg/L for TP and SRP compared to 1 μg/L at HWS. Thus, Life

Fig. 6. Total phosphate lab analyses.

Sciences could not provide data for 15% of the nitrate, 70% of the SRP, and 40% of the TP sample splits in 2007. Due to the expense, unsatisfactory detection limits and similarity of results, analysis of sample splits was discontinued, and only analyzed at HWS.

Other analyses were performed during the survey but not elaborated on in this report. Surface and depth integrative (20 m) horizontal and vertical plankton tows were collected using 85 μm mesh, 0.2m diameter opening, plankton nets, preserved in a formalin/alcohol solution. Over 100 individuals were identified to species level under a microscope for relative species enumerations. Major ions concentrations were measured on filtered (0.45 μm) water samples by Dionex DX-120 ion chromatograph with a precision of 1.0 mg/L, and alkalinity measured by field titration using a phenolphthalein and bromocresol green/methal red indicator with a precision of 5 mg/L (LaMotte WAT-MP-DR). In 2005 only, water samples for total coliform and *E. coli* bacteria analyses were collected in sterile bags at the stream and lake sites, kept at 4ºC until analysis in the lab using Hach's m-ColiBlue24 broth filtration technique, and reported as colony forming units per 100 mL of water (CFU/100mL). The precision calculated from the difference between replicate analyses was 260 for total coliform and 33 CFUs/100 mL for *E. coli* bacteria.

RESULTS

CTD Temperature Profiles: The temperature profiles were typical for a temperate lake (Fig. 7). Surface waters warmed from ~ 4º C (39º F) in the early spring to nearly 25º C (~75º F) by mid-summer. Surface waters would then cool by the end of the survey (early October) and presumably to isothermal conditions (4º C) by the end of the fall. Bottom waters in the deeper lakes remained near 4º C throughout the survey. The depth of the largest temperature change from warm surface waters to cold bottom waters defines the thermocline. The depth interval where the temperature changes from the uniform warmer epilimnion (surface waters) above from the colder, near 4º C, hypolimnion (bottom waters) below defines the metalimnion. The thermocline was typically at a depth of 10 to 20 m in the surveyed lakes. However, its depth oscillates vertically in response to internal seiche activity, deepening by large surface waves generated by intense storms and frontal systems, and seasonal warming and cooling of the epilimnion. A thermocline was typically not observed in the profiles from Honeoye Lake. Presumably, wind stress and mixing by waves is sufficient to maintain isothermal conditions throughout the entire water column in Honeoye where the deepest survey site is only 7m deep, whereas mixing only encompasses the epilimnion in the other deeper lakes. In Otisco Lake, a thermocline was observed but bottom waters were uniformly warmer than 4º C over the summer season, approximately 9º C. Presumably, wind stress over the relatively shallow lake (22 m depth at the survey sites) maintained isothermal conditions in the lake during the early spring warming before surface waters warmed sufficiently to stratify the water column, as the profiles do not reveal bottom water warming through the summer.

The separation of the epilimnion from the hypolimnion is fundamental to lake processes because the vertical stratification typically isolates the hypolimnion from sunlight and atmospheric oxygen. Thus, it also typically separates the nutrient depleted, turbid, and algal-enriched epilimnion from the oxygen depleted, nutrient enriched and slightly more saline hypolimnion. The extent of these differences intensifies through the summer season, especially in more productive lakes. During fall and spring overturn, these differences are eliminated as the lake vertically mixed during overturn, and these parameters become uniform throughout the entire water column.

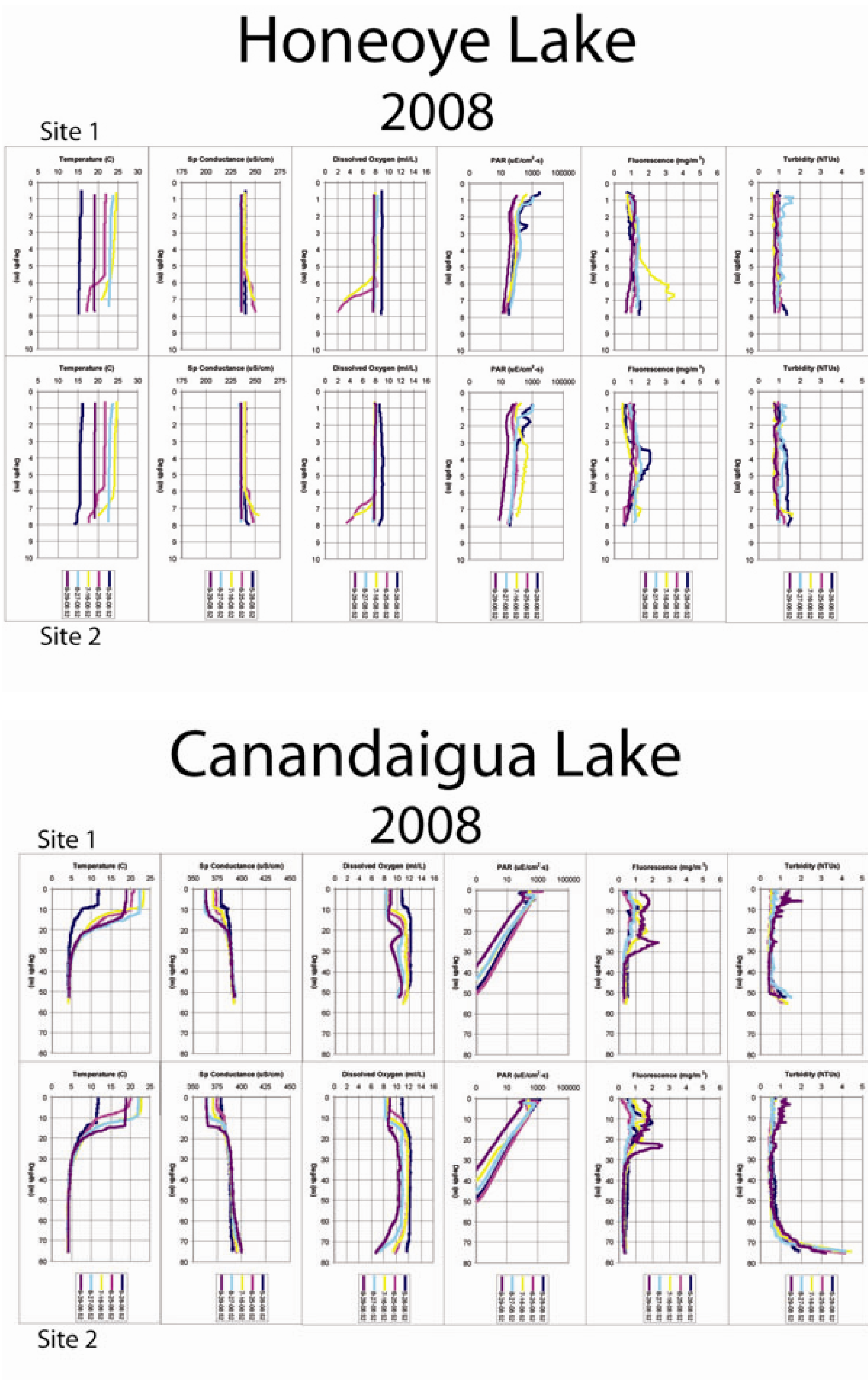

Fig. 7. CTD Profiles from Honeoye and Canandaigua Lakes.

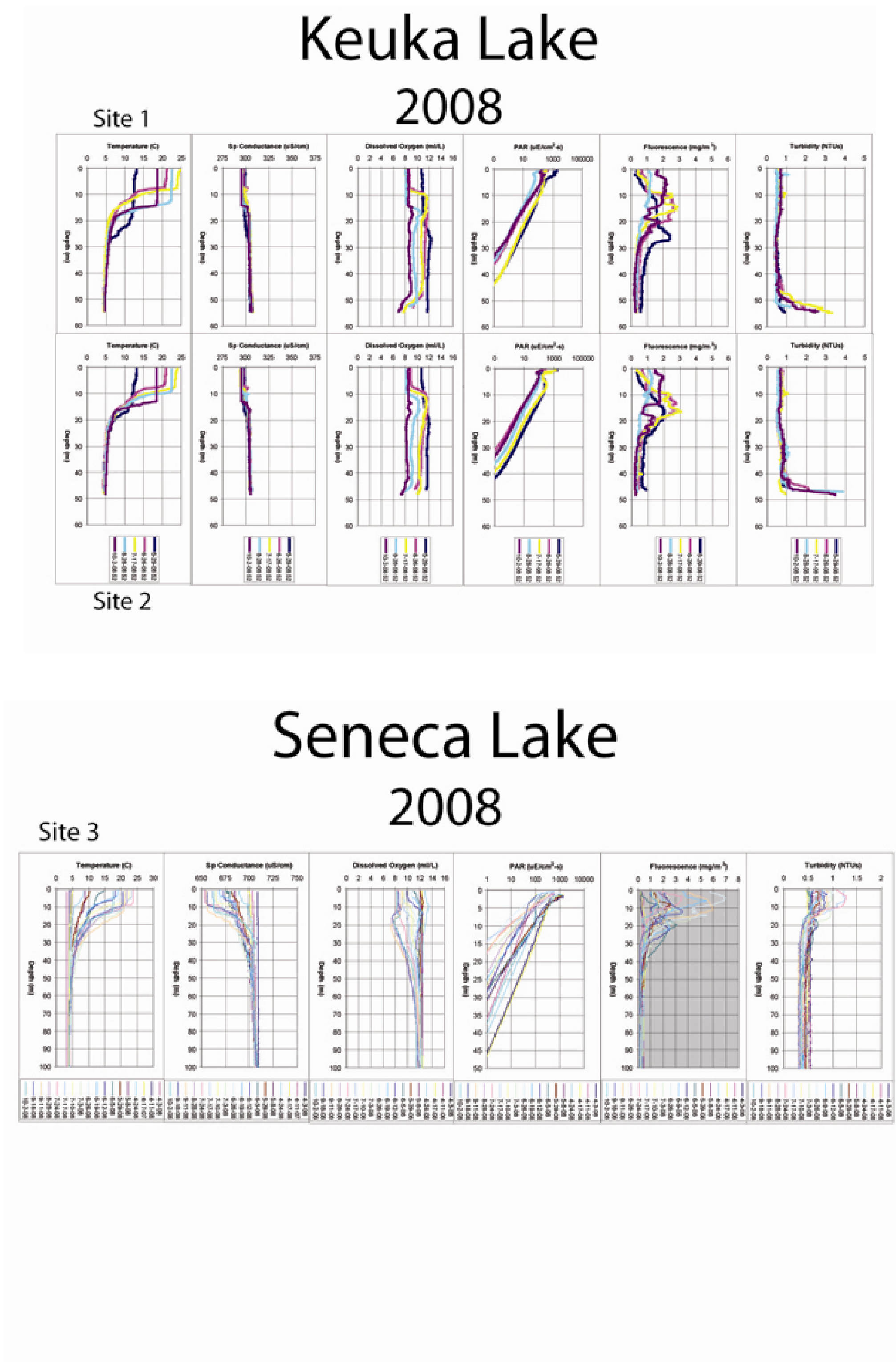

Fig. 7. CTD Profiles from Keuka and Seneca Lakes.

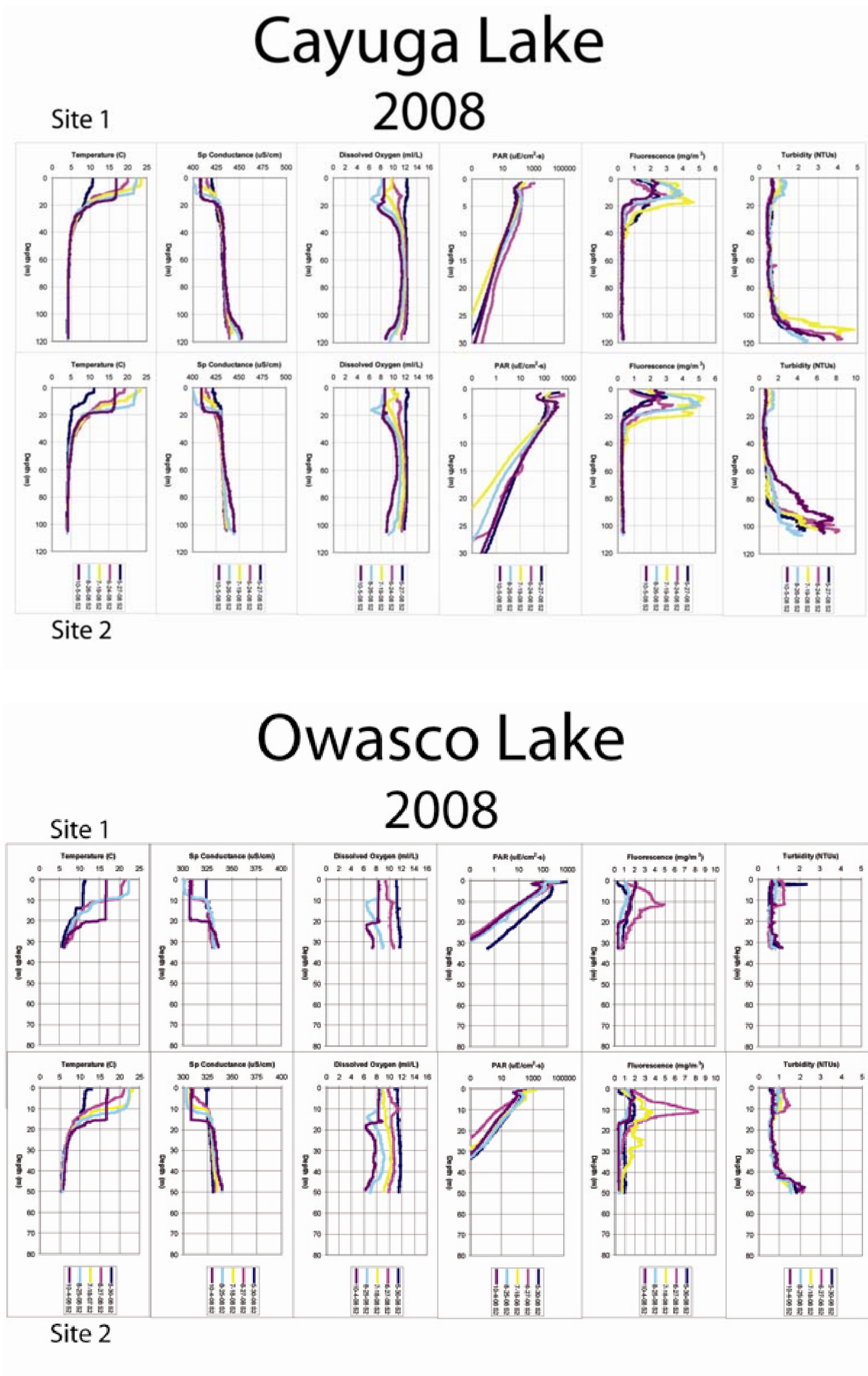

Fig. 7. CTD Profiles from Cayuga and Owasco Lakes.

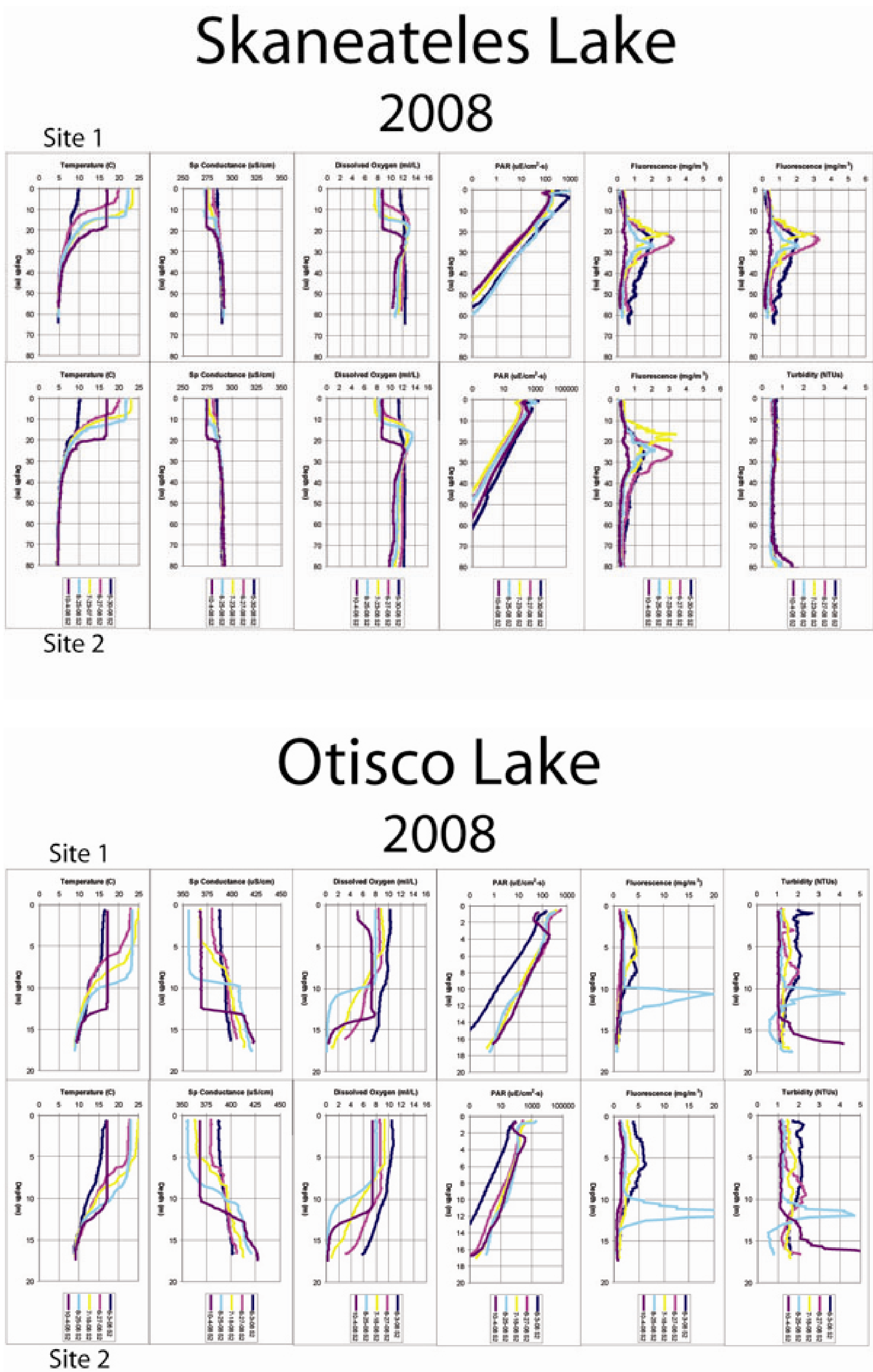

Fig. 7. CTD Profiles from Skaneateles and Otisco Lakes.

Specific Conductance Profiles: Specific conductance is proportional to the salinity of the water. In general, the salinity reflects the input of salt from surface runoff, including road salt and weathering reactions, and loss of salt through the outlet and burial in the sediments. Specific ions like calcium are also lost through the formation of water column precipitates (whiting events of calcium carbonate) or incorporation into the shells of organisms (zebra and quagga mussel calcium carbonate shells) and in both cases eventual burial in the sediments.

In the Finger Lakes, specific conductance data ranged from a low of 230 μS/cm in Honeoye Lake to 730 μS/cm in the hypolimnion of Seneca Lake in 2005 (Fig. 7). The change between basins can be attributed to differences in bedrock geology, as limestones weather more easily and thus provide more salts than other bedrock in the region, and hypothesized access to saline groundwater from the rock-salt bearing Salina Formation and/or salt wastes in Seneca and to a lesser degree Cayuga Lakes. Honeoye typically revealed well mixed profiles.

Typically conductivities were 15 to 20 μS/cm smaller in the epilimnion than the hypolimnion in most lakes. This difference becomes larger through the stratified season. The largest difference was up to 50 μS/cm and consistently observed in Seneca Lake. Two hypotheses may account for this difference. It may reflect the input of saline groundwater to the hypolimnion as hypothesized by Wing et al. (1995) or the input of dilute surface runoff to the epilimnion as discussed by Halfman and Franklin (2008). The CTD data from all the lakes support the second hypothesis as the conductivity typically remained constant in the hypolimnion each season, whereas the conductivity decreased through the summer in the epilimnion. Temporally, the largest decrease in epilimnion conductivities occurred just after the heavy rains (3” in Geneva) during the aftermath of Hurricane Katrina in 2005. This decrease was especially pronounced in Owasco Lake, which is expected as it has the largest watershed area to lake surface area ratio of the lakes in the survey. Over longer time scales, the specific conductance of Seneca Lake has steadily decreased over the past four years from a high of 730 μS/cm in 2005 to a low of 655 μS/cm in the fall of 2008. Each year the lower salinity epilimnion would mix with the more saline hypolimnion during overturn, and as a result the entire water column would become slightly fresher.

Dissolved Oxygen: Temperature, photosynthesis and respiration influenced dissolved oxygen concentrations in these lakes. Water temperature is inversely related to the saturation concentration of oxygen, i.e., warmer water holds less dissolved oxygen than colder water at saturation (the maximum concentration). Photosynthesis by algae and macrophytes release oxygen to the water and respiration by all living things in the lake, especially bacteria, consumed oxygen dissolved in the water.

Most of the lakes in the survey revealed saturated dissolved oxygen profiles with summer epilimnion concentrations slowly decreasing as the surface waters warmed through the spring to summer season (Fig. 7). Cayuga, Owasco, and to a lesser degree Canandaigua and Keuka Lakes, revealed below saturation concentrations in the hypolimnion and was probably due to respiration by bacteria. Occasionally oxygen enrichments (Skaneateles & Canandaigua) or deficits (Owasco, Seneca, & Cayuga) were observed above or below the thermocline. The variability can be attributed to the depth of the oxygen producers (algae) and consumers (all organisms especially bacteria and zooplankton) in relation to the thermocline. Anoxic bottom waters were detected by mid-summer in Otisco Lake, and most likely due to the respiration of the large concentrations of algae by bacteria in this eutrophic lake. Honeoye typically revealed well mixed profiles.

PAR – Photosynthetic Active Radiation Profiles: Light is critical to photosynthesis, and this instrument measures the intensity of light critical to photosynthesis. The quantity of light decays exponentially with water depth as it is absorbed and scattered by the water, dissolved compounds and suspended matter in the water column. The attenuation of light is intensified and its penetration is limited to shallower depths as the concentration of suspended matter (both organic and inorganic) increases in the water column. The loss of light with water depth is critical to aquatic life. As it falls below 1% of surface light concentrations, algae and attached plants can not photosynthesize enough organic matter to survive and net productivity falls below zero. In deep lakes, the epilimnion is pitch black.

Light exponentially decreases with water depth in all the Finger Lakes (Fig. 7). Please note: the plots use an exponential scale. Only Honeoye and on a few occasions Otisco have measurable light at the lake floor at the mid-lake survey sites due to their shallow maximum depths. In the other deeper lakes, light declined from a few 1,000 $\mu E/cm^2$-s at the surface (the amount of light at the surface depends on the cloud cover, time of day and time of year) to ~ 1 $\mu E/cm^2$-s anywhere from 15 to 40 meters below the surface. The lakes with more algae correlated with shallower light penetration. The frequent decline in light beyond the exponential decay at the upper few meters of the water column was due to the passage of the sensor through the shadow of the field vessel.

Light Transmission, Turbidity & Fluorescence Data: Suspended sediments are composed of inorganic (fluvial muds) and organic (algae) fractions. The sources to the lake include tributary inputs, erosion by large waves resuspending bottom sediments, and the creation of algae. Suspended sediments are lost from a lake by transport out the outlet, and settling to the lake floor as suspended sediments are denser than water. The inorganic fraction is denser thus settle faster than the organic fraction.

CTD profiles from 2005 and 2006 utilized the attenuation of light measured by a transmissometer to detect the presence and concentrations of all suspended particles. Light transmission data are inversely and logarithmically related to suspended solids concentrations. In 2007, this instrument was replaced with two sensors, a fluorometer that detects the concentration of algae suspended in the water using algae's light induced fluorescent properties, and a nephelometer which detects the concentration of suspended particles using light backscattering technologies. The new profiles thus can differentiate between suspended sediments with organic and inorganic origins.

Surface, near surface and/or bottom water zones of increased turbidity were observed in the Finger Lakes (Fig. 7). Typically turbid layers were observed throughout the entire epilimnion in Cayuga, Canandaigua, Keuka, Owasco, and Seneca. These epilimnetic layers were best developed in Cayuga and Seneca, and least developed and only occasionally observed in Canandaigua Lake. Turbid zones were observed in the lower metalimnion through the upper hypolimnion of Skaneateles Lake. We previously speculated that the source and magnitude of the surface and near surface turbid zones are autochthonous and the extent of the turbidity is proportional to plankton (algae + zooplankton) biomass (Halfman and Bush, 2006). These interpretations were consistent with TSS and chlorophyll-a data. The new fluorometer data confirmed this hypothesis. Algal peaks were best developed in the epilimnion for Seneca, Cayuga, Owasco and Otisco Lakes. The peak in algal abundance deepened to the metalimnion and upper hypolimnion in Skaneateles, Keuka and Canandaigua Lakes. In all lakes the amount of algae peaked in the middle of the summer. Maximum algal concentrations were near 3 mg/m^3 in Keuka, Canandaigua, and Skaneateles Lakes, between 3 and 10 mg/m^3 in Seneca, Cayuga, and Owasco Lakes, and was typically near 5 mg/m^3 in Otisco Lake. The largest peak was above 25 mg/m^3 on 8/25 just below the thermocline in Otisco Lake. The water column in Honeoye was typically well mixed.

Benthic nepheloid layers were observed in all but Honeoye and Seneca Lakes. The nepheloid layers persisted throughout the field season but their extent varied from lake to lake. Honeoye is probably too well mixed to reveal anything but uniform turbidity profiles. The absence of benthic nepheloid layers in Seneca requires further investigation as it may reflect sample sites that do not occupy the deepest part of the lake where the nepheloid development is typically more pronounced. The nepheloid layers were best developed in Cayuga Lake where light transmission values started to decrease from background values of 60% ~20 m above the lake floor to 30% (maximum turbidities) just above the lake floor. We previously speculated that the bottom water nepheloid layers are accumulations of resuspended fine-grained sediments and/or allochthonous material that are transported to the lake floor by density currents (Halfman and Bush, 2006). The 2007 & 2008 fluorometer and nephelometer profiles confirmed this hypothesis because the material is primarily non-fluorescing materials, and therefore are composed of accumulating dead algae and settling sediments.

Secchi Disk, Chlorophyll-a, TSS Data: Annual average secchi disk depths were deeper in Canandaigua and Skaneateles Lakes (6.5 and 7.5 m, respectively), and shallower in Cayuga, Owasco, Honeoye and Seneca Lakes (~4 m) and Otisco Lakes (~3 m, Fig. 8). The depths inversely correlated to annual average chlorophyll-a concentration (an annual average 10 $\mu g/L$ (mg/m^3) in Honeoye to < 1 $\mu g/L$ in Skaneateles Lake) and TSS data (an average of 2.5 mg/L in Honeoye to < 1 mg/L in Skaneateles Lake, Figs. 9 & 10). Annual average chlorophyll-a concentrations were larger in epilimnion than the hypolimnion for all the lakes except for the well-mixed Honeoye. Thus algae are concentrated in the epilimnion. Annual average TSS concentrations were larger in the hypolimnion of Cayuga, by 1.5 mg/L, and to a lesser extent in Canandaigua and Keuka Lakes by 1 mg/L, and is discussed below. Honeoye Lake revealed the largest variability in these parameters, and reflects the presence or absence of an algae bloom on the sample date.

Georgian and Halfman (2008) investigated the correlation of secchi disk, chlorophyll-a, TSS, Fluorometer and nephelometer data. The largest correlations were observed between chlorophyll and fluorescence data and between total suspended solids and nephelometer data with correlation coefficients, r^2, above 0.60. The lowest correlations were between fluorometer and nephelometer data, and between total suspended sediments and fluorometer data with coefficients, r^2, below 0.25. The associations indicate that each parameter measures a subset of water clarity. Chlorophyll and fluorescence measures the organic component; the nephelometer and total suspended solids measure the inorganic fraction; whereas, secchi disk depths measure a combination of both fractions. Thus, monitoring protocols should include as many water clarity parameters as possible to most fully characterize the water quality in a lake.

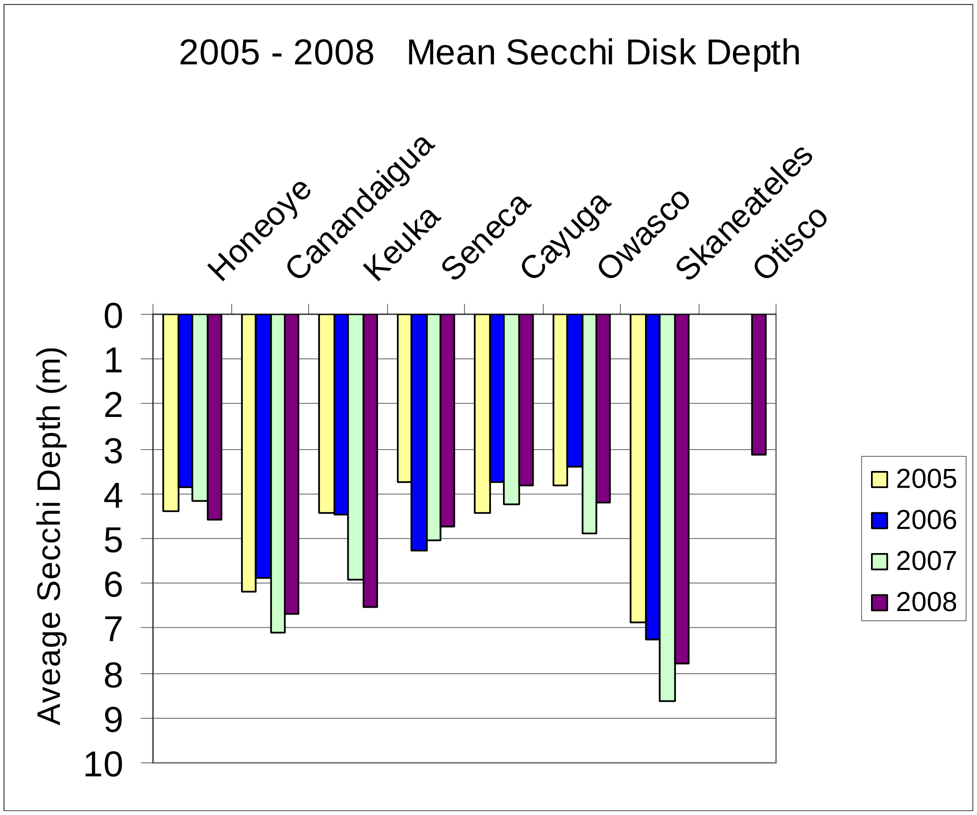

Fig. 8. Annual mean secchi disk depths from the Finger Lakes.

Nutrient Data: Mean annual nitrate concentrations were largest in Cayuga, Owasco, and Skaneateles Lakes from 0.4 to 1.6 mg/L, N (ppm), and smallest in Canandaigua, Keuka and Honeoye Lakes from 0 to 0.2 mg/L (Fig. 11). Bottom water mean annual results typically revealed more, up to 0.5 mg/L more nitrates than surface water, especially in Keuka and Cayuga. Annual mean nitrate concentrations are near or below Redfield 7:1 (N:P) ratios, using annual mean nitrate and total phosphate data, in Honeoye and Keuka Lakes. They were significantly above Redfield ratios, from 40:1 up to 140:1, in Seneca, Cayuga, Owasco and Skaneateles Lakes. The calculated ratios indicate that nitrogen was the limiting nutrient in Honeoye and occasionally Keuka Lakes but phosphorus was clearly the limiting nutrient for algal growth in the other lakes in the survey. Typical sources of nitrate are from agricultural activities, municipal wastewater treatment facilities, septic systems, and atmospheric fallout (acid rain). The US EPA assigned 10 mg/L as a maximum contaminate level (MCL) for safe drinking water. All of the nitrate concentrations in these lakes were below this limit.

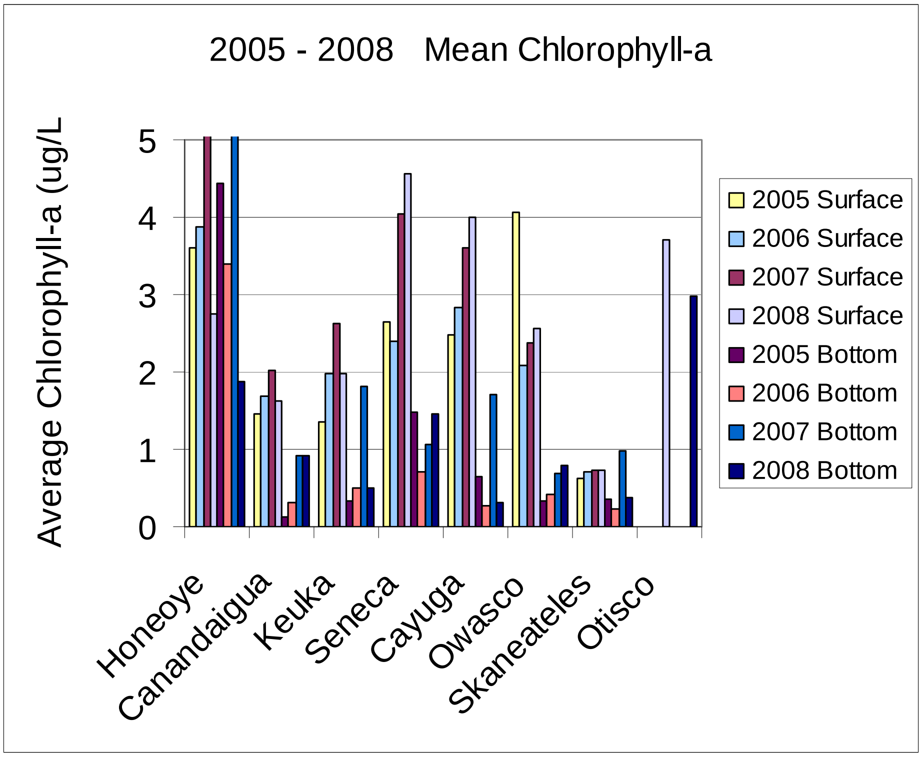

Fig. 9. Annual mean chlorophyll-a concentrations from the Finger Lakes.

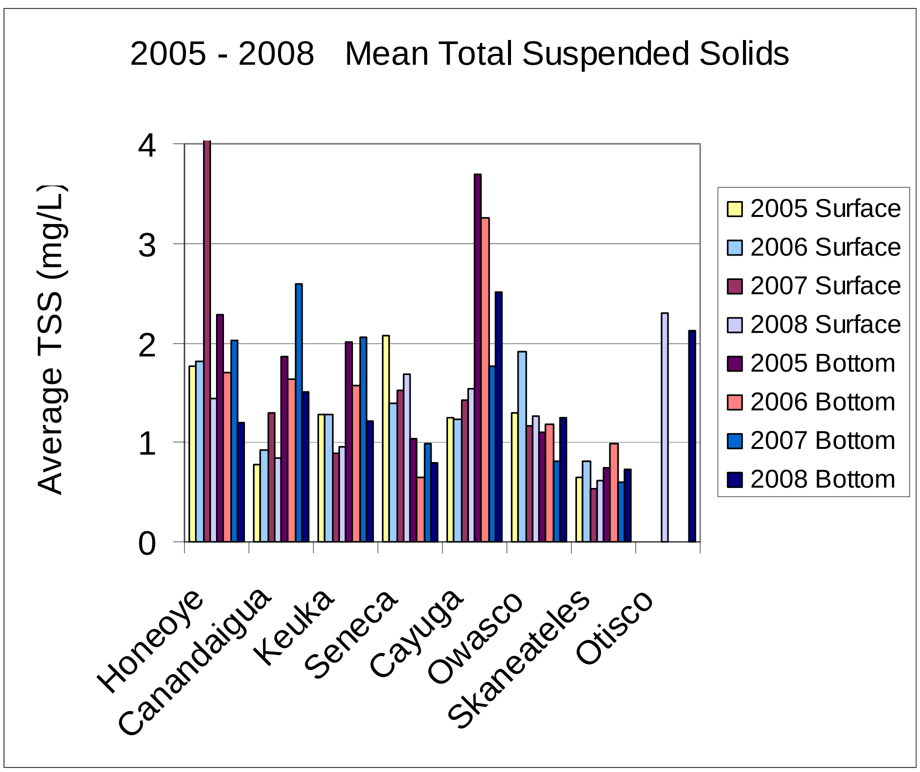

Fig. 10. Annual mean total suspended solids concentrations from the Finger Lakes.

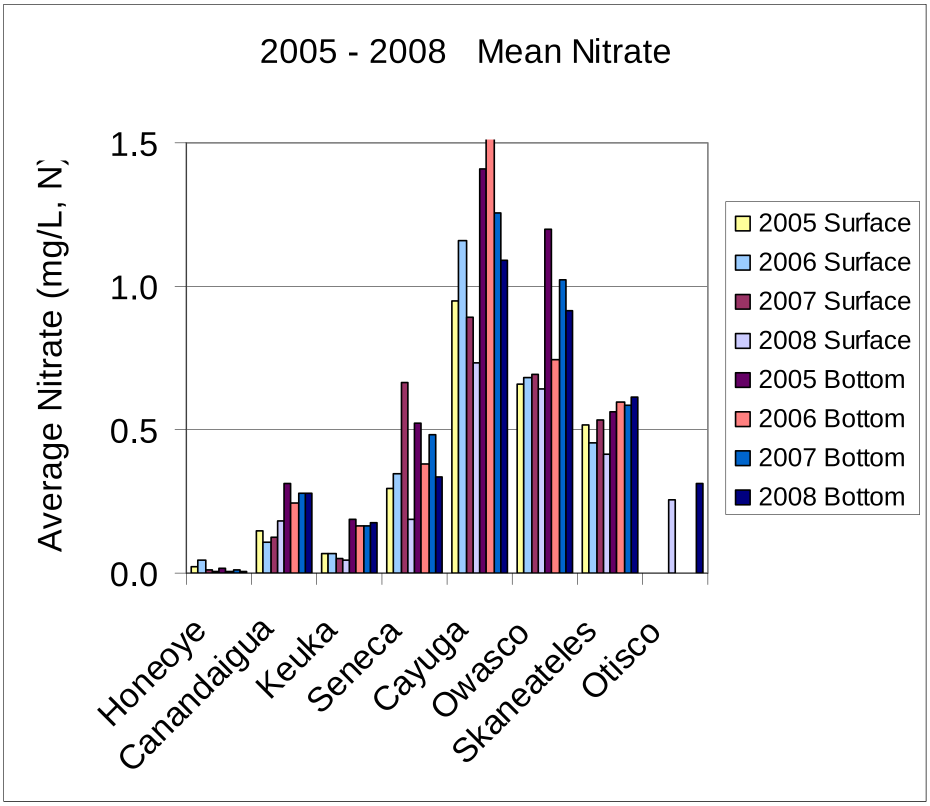

Fig. 11. Annual mean nitrate concentrations from the Finger Lakes.

Annual mean soluble reactive (dissolved) phosphate (SRP) concentrations were largest in Honeoye Lake and the hypolimnion of Cayuga Lake, from 3 to 10 μg/L, P (ppb, Fig. 12). Annual mean phosphate concentrations were below 1 μg/L in the epilimnion and below 2 μg/L in the hypolimnion of the other lakes. Larger concentrations were commonly found in the hypolimnion, typically increasing through the summer season, and were interpreted to reflect the steady release of nutrients by bacterial activity through the summer season. The abundant phosphate in Honeoye Lake suggested that phosphate was the limiting nutrient in all but Honeoye Lake. The abundant phosphate in the hypolimnion of Cayuga Lake is a concern. Internal waves, other upwelling events, fall and spring overturn, and Cornell's Lake Source Cooling project, mechanisms that bring hypolimnion waters to the surface will fertilize algal growth in the epilimnion and will degrade water quality. Cayuga's hypolimnion phosphate enrichment will be discussed more fully later in this report.

Annual mean total phosphate (TP) concentrations were largest in Honeoye Lake with annual mean concentrations from 15 μg/L to above 25 μg/L, P (ppb, Fig. 13). Otisco Lake revealed the next largest concentrations between 10 and 15 μg/L. TP concentrations were smallest in Skaneateles Lake below 5 μg/L. Concentrations in the other lakes were between 5 and 12 μg/L, with Seneca and Cayuga Lakes with slightly more TP than Canandaigua, Keuka and Owasco Lakes. Minimal change was observed between the epilimnion and hypolimnion in each lake. The New York Department of Environmental Conservation (NYS-DEC) designates 20 μg/L as the concentration threshold for impaired water bodies. Thus, Honeoye was impaired by this definition, and Otisco Lake is very close to impairment.

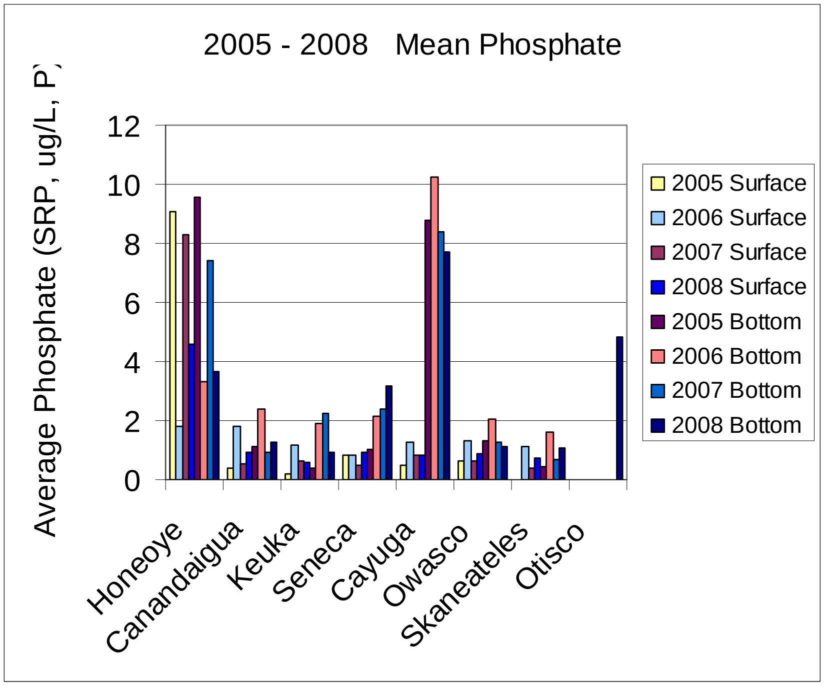

Fig. 12. Annual mean soluble reactive phosphate concentrations from the Finger Lakes.

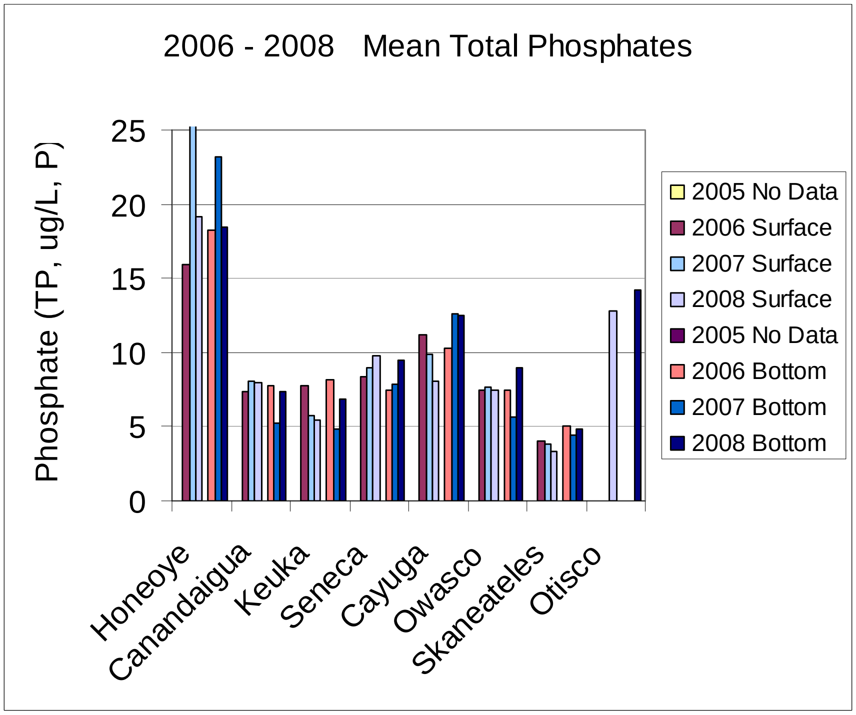

Fig. 13. Annual mean total phosphate concentrations from the Finger Lakes.

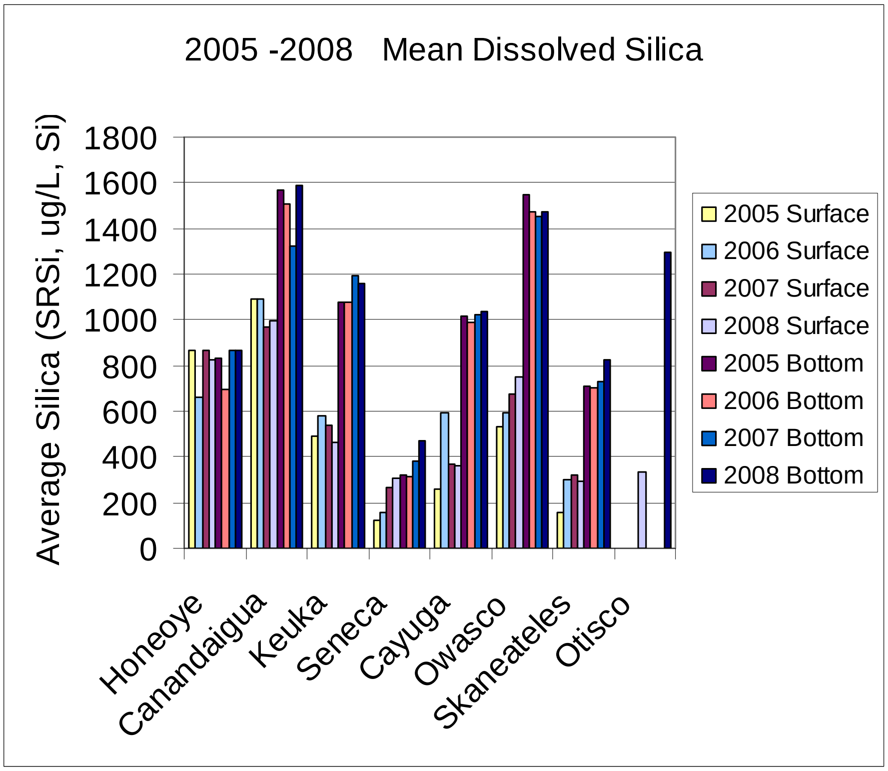

Fig. 14. Annual mean silica concentrations from the Finger Lakes.

Mean annual epilimnetic soluble reactive silica (SRSi) concentrations were largest in Canandaigua (1,100 μg/L, Si, ppb), Honeoye (800 μg/L) and Keuka Lakes (~450 μg/L), and smallest in Seneca (100 to 200 μg/L) and Skaneateles (150 to 250 μg/L) Lakes (Fig. 14). Dissolved silica concentrations were typically larger than the hypolimnion than the epilimnion, and Owasco and Otisco Lakes revealed the largest increase (~600 to 1,500 μg/L and 300 to 1,300 μg/L, respectively).

DISCUSSION – FINGER LAKES WATER QUALITY

These eight Finger Lakes revealed a range of water quality but none of them revealed significant health threats (Appendix, Fig. 15). To investigate the range and reasons for the range, water quality for each lake was numerically ranked based on parameters fundamental to water quality and water clarity. Here we utilized the annual average surface water concentrations of total phosphates, dissolved phosphates, nitrates, chlorophyll-a, total suspended solids, and secchi disk depths. The previous ranking by Halfman and Bush (2006) also included *E. coli* and total coliform bacteria concentrations but these analyses were discontinued after 2005, and replaced with measurements for total phosphate concentrations.

Data Analysis: A separate rank was calculated for the water quality in each lake during each year of the survey. The process starts by calculating an annual average of each water quality parameter for each lake from the available surface water data. Then the annual average was ranked by normalizing the average to a scale of 1 to 29 by proportionally adjusting the rank to the observed full range of annual averages for each parameter. A rank of one represents the best water quality observed in any lake over the four years of study, and a rank of 29 the worst water quality. Twenty nine corresponds to seven lakes that were surveyed for four years 2005 – 2008 for 28 annual averages, plus one more for the one year of data from Otisco. Finally, the annual ranks for each parameter at each lake were averaged to establish an annual average rank for each lake. These ranks were normalized to a 1 to 29 scale and are shown in Figure 15.

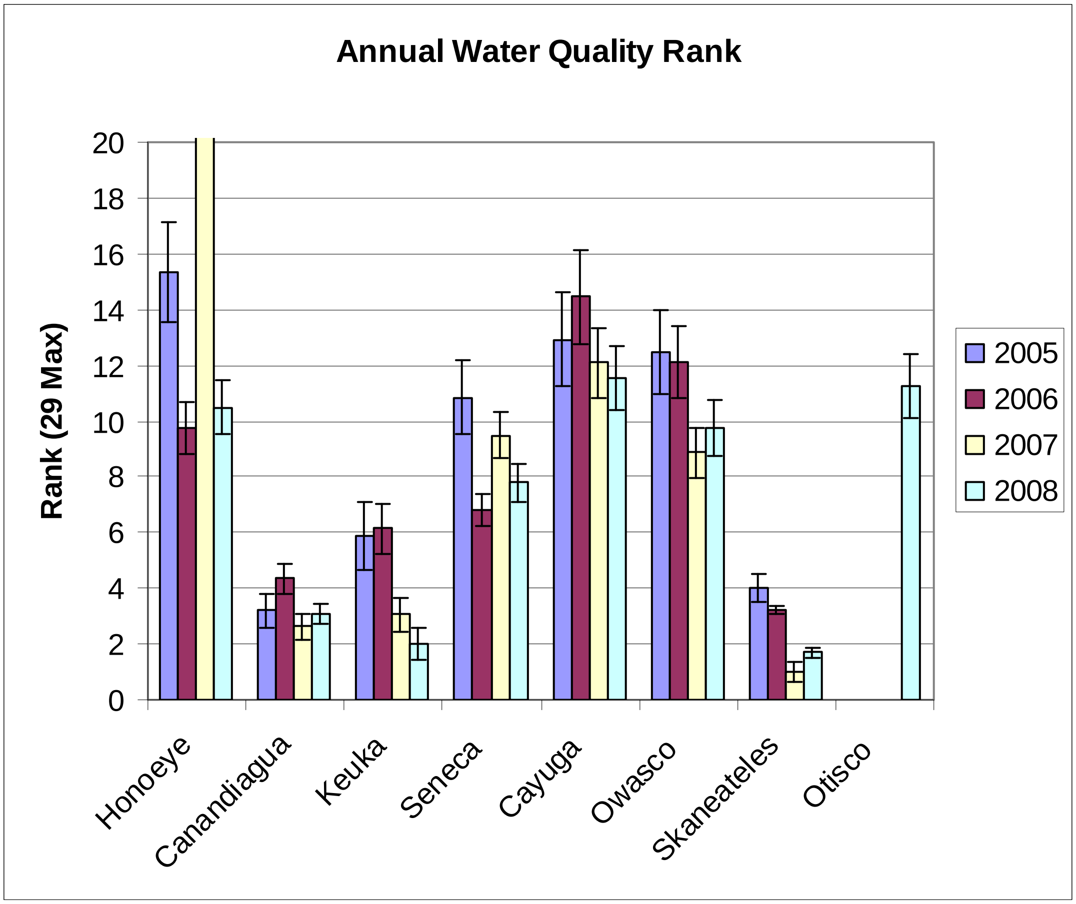

Fig. 15. Annual Water Quality Ranks..

These annual ranks range from 1, the lake with the best water quality over the four years, to 29, the lake with the worst water quality over the four years. The other ranks were proportionally distributed between 1 and 29. Thus, lakes with a water quality similar to the best lake, got a rank close to one, other lakes with a water quality close to the worst lake got a rank close to 29. Simply put, a rank of 1 corresponds to the smallest combination of nutrient (TP, SRP, nitrate), suspended sediment, and chlorophyll-a concentrations, and deepest secchi disk depths; whereas, a rank of 29 corresponds to the largest combination of nutrient (TP, SRP, nitrate), suspended sediment, and chlorophyll-a concentrations, and shallowest secchi disk depths. The other ranks fall proportionally between 1 and 29.

Several tests were performed to examine the robustness of the calculations. First, we tested the variability introduced into the results due to the parameters selected for this study. To do this, we eliminated one parameter from the calculations, and recalculated the annual ranks. This was repeated for each remaining parameter, each calculated rank removed only one of the parameters until a new rank was calculated for every parameter. The new ranks were then averaged and the 1σ standard deviation of these averages is displayed as error bars on Fig. 15. The results indicate that this variability may slightly modify the actual rank but does not alter the relative ranking between lakes.

Second, does the monthly sampling of two sites adequately characterize water quality in these lakes? Cayuga, Seneca and Owasco Lakes have additional sites and additional sample dates over two or more years through the four year study. The ranks calculated above only used two sites from each lake and the sample dates consistent with the monthly sampling of the other lakes in the survey. New annual ranks were calculated after averaging all of the available surface water data from every deep-water site in each lake. The resulting variability is smaller than the previous test, and indicates that the data from two sites taken at monthly intervals provides a robust water quality comparison.

Finally, bacteria counts for *E. coli* and total coliform bacteria were excluded from these ranks presented in this report but were included in the preliminary report (Halfman & Bush, 2006). In the preliminary report, water quality in Cayuga Lake was better than Seneca Lake. When bacteria counts are excluded from the ranking, the difference decreases significantly, and water quality in Cayuga Lake gets worse while Seneca Lake gets slightly better. The other lakes did not significantly change due to the exclusion or inclusion of the bacterial counts and provides additional evidence that these ranks are useful for comparison between lakes and from year to year.

Ranks: The ranks indicated that the best water quality was in Skaneateles, Canandaigua and Keuka Lakes (Fig. 15). In limnological terms, these lakes were oligotrophic. The same plot revealed that the worst water quality was in Honeoye, Owasco, Cayuga, Otisco and Seneca Lakes. Limnologically, these lakes were either mesotrophic or eutrophic. The larger lakes, Seneca, Cayuga and Owasco, were mesotrophic, the smaller lakes, Honeoye and Otisco, were eutrophic, the most productive aquatic ecosystems, if bottom water anoxia is the sole determinant between mesotrophic and eutrophic lakes.

The relatively poor water quality in Honeoye, Otisco, Seneca, Cayuga and Owasco Lakes is a concern, even though Seneca, Cayuga and Owasco did not experience bottom water anoxia. Water quality degradation in both Honeoye, Cayuga and Owasco Lakes have stimulated local and state agency concern due to changing plankton communities and the impact, for example, drinking water, macrophyte growth, and fish populations. Debate and implementation of initial action items are currently underway on how best to improve the water quality. Water quality degradation has been noticed by concerned citizens in the Seneca watershed, but it has not stimulated as much concern at the regulatory level. For example, the periodic inspection and pump out of on-site systems is still lacking in this watershed. This lack of concern is disturbing because Seneca Lake contains 50% of the water in the Finger Lakes, and has the longest water residence time of the Finger Lakes (20 years vs. a few years). If nothing is done to improve water quality, then Seneca Lake may become eutrophic for generations.

Significant year to year changes in rank are observed in Honeoye, Keuka, Owasco and Skaneateles Lakes (Fig. 15). The variability in annual ranks was largest in Honeoye Lake ranging from a low of ~10 in 2006 to the highest rank of 29 (worst water quality lake over the four year study) in 2007. Honeoye's shallow depth and small size sets this lake apart from the other lakes in the survey. The shallow depth allows the entire water column to mix in only this lake during windy days. Mixing breaks down any stratification and bottom water anoxia that established during calm days. Anoxia events are important because they allow the release of phosphates from the sediments, providing a significant internal source of nutrients. Oxygenated bottom waters precipitate and lock phosphates as particles in the sediments. Thus, any phosphates buried in the mud as organic matter or attached to sediment particles in oxygenated lakes typically are lost from the aquatic ecosystem; whereas, phosphates are instead liberated from the sediments and recycled back to the water column in anoxic systems. When recycled, a significant bloom of algae typically occurs stimulated by the sudden release of nutrients.

Honeoye's annual average chlorophyll-a concentrations have varied from a low of 2.7 ± 1.9 in 2008 to 28.2 ± 52.8 μg/L in 2007. The difference between years and large standard deviation in 2007 reflected sampling a bloom of blue-green algae on 7/24/07 and not sampling major blooms during the other sample dates. Ignoring the 7/24/07 chlorophyll-a results reduces the 2007 annual average from 28 ± 52.8 to 3.3 ± 1.5 μg/L, a concentration very similar to the other annual average concentrations at Honeoye Lake. Even though the annual chlorophyll-a concentration decreased significantly after ignoring the bloom event, the 2007 rank still remained at 29. Interestingly, ranks for the other impaired lakes increased proportionally, typically from the low teens to the low 20s (Fig. 16). The relative order of ranks from lake to lake did not change. Honeoye sought and was recently granted permission to spread alum in the deep sediments of the lake. Alum binds phosphates and locks them into the sediment column. It is imperative to follow future water quality changes in Honeoye to see if the treatment improves water quality in the future, once the internal sediment loading of phosphates is significantly reduced.

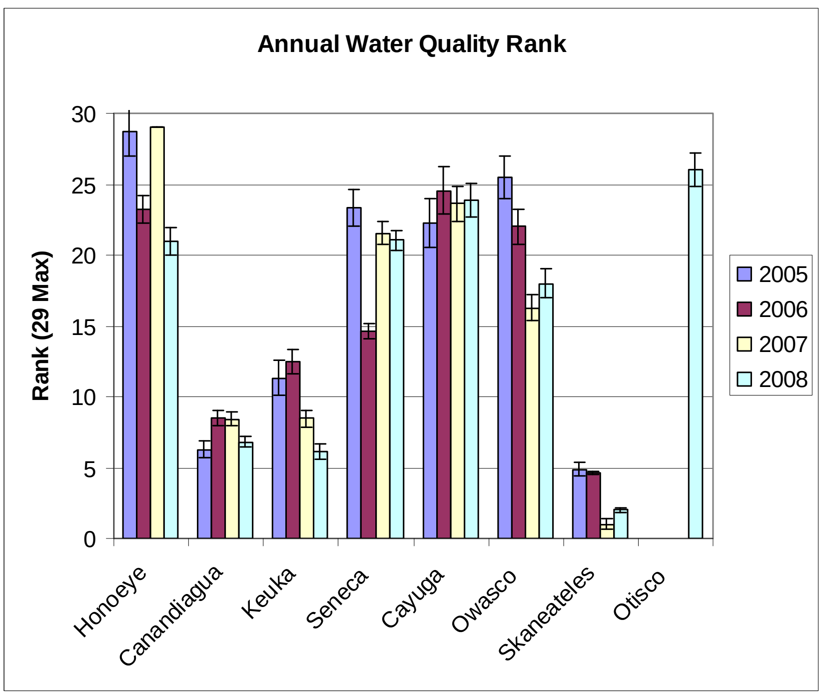

Fig. 16. Annual water quality ranks excluding a bloom at Honeoye.

Ranks for Keuka, Owasco and Skaneateles Lakes decreased from 2006 to 2007, and remained relatively low in 2008 (Fig. 15). Owasco watershed research revealed that the variability in phosphorus loading from the watershed played a critical role in the productivity and water quality of this phosphate limited lake (Halfman et al., 2008). Hydrogeochemical data from the major tributaries flowing into Owasco Lake revealed that phosphorus loading was significantly higher in 2006 than 2007. Mean total phosphorus loading during base flow decreased from 7.2 kg/day in 2006 to 2.9 kg/day in 2007, with significantly fewer precipitation/runoff/storm discharge events in 2007. The difference reflected the decrease in precipitation from 24 inches to 15 inches during the summer season, and a parallel decrease in base-flow runoff from 2.1 to 0.2 m^3/s from the watershed. We suggest that these lakes are all sensitive to changes in phosphorus supply, and thus experienced similar decrease in phosphorus loading and water quality rank as Owasco Lake from 2006 to 2007 and 2008. Consistent changes were not observed in the remaining lakes. Both Seneca and Cayuga Lakes and to a lesser extent Canandaigua Lake are probably large enough to desensitize them from year to year changes in phosphorus loading, but over time, the continued nutrient loading will degrade water quality in these lakes if not significantly reduced at the present time.

Otisco Lake was the only lake in the survey to reveal permanent anoxic conditions in the hypolimnion during the latter half of the summer season. Interestingly, this eutrophic lake ranked lower, i.e., revealed a better surface water quality, than Seneca and Cayuga Lakes. The difference between these lakes is probably related to their relative sizes. All three lakes were very productive during the summer season. Annual average chlorophyll-a concentrations were 3.7 μg/L for Otisco, and larger, over 4 μg/L, in Seneca and Cayuga Lakes, larger than the other large lakes in the survey. Annual average total phosphorus concentrations were 12.8, 9.8 and 8.0 μg/L for Otisco, Seneca and Cayuga Lakes, respectively, larger than the other large lakes in the survey. Yet, the hypolimnion is significantly larger in Seneca and Cayuga Lakes than Otisco Lake with total lake volumes of 15.5, 9.4 and 0.08 km^3, respectively. Thus, Seneca and Cayuga have a larger capacity to respire the supply of epilimnetic algal organic matter without significantly depleting the hypolimnetic dissolved oxygen concentrations. Owasco Lake is another lake with a relatively high rank. It too is larger than Otisco Lake and the bottom waters did not become anoxic at the end of the stratified season. However, Owasco is not as large as Seneca and Cayuga, and Owasco oxygen profiles revealed below saturated and continually decreasing concentrations in the hypolimnion. Thus Owasco appears on the verge of becoming anoxic, especially if nutrient loading persists into the future.

CAUSES OF WATER QUALITY DEGRADATION

Nutrient runoff from agricultural land, improper disposal of organic wastes, stream bank and nearshore/shoreline erosion, and other land use practices can degrade water quality. To test the potential nutrient runoff to water quality relationship, the percentage of agricultural land within each watershed was plotted against the lake's average water quality ranking (Fig. 17). When all of the lakes are taken into account, no correlation ($r^2 = 0.05$) is observed. However, when Honeoye is excluded from the comparison, a positive and strong correlation ($r^2 = 0.98$) is observed. Removing Honeoye Lake is plausible because Honeoye is nitrogen limited and not phosphorus limited as in the other lakes, Honeoye is significantly shallower than the other lakes, and historically its watershed was heavily agricultural until the fields were abandoned and overgrown with forests. Nutrient loading by the earlier agricultural activities has probably remained in Honeoye Lake as nutrients are effectively recycled from the sediments and not lost from the lake's ecosystem.

Other correlations were tested. No or significantly smaller correlations were observed when mean water quality rank was compared to watershed area, lake volume, volume to area ratio, water residence time, and population served with drinking water. Rank versus watershed size revealed a correlation if Honeoye, Otisco and Owasco were excluded from the analysis.

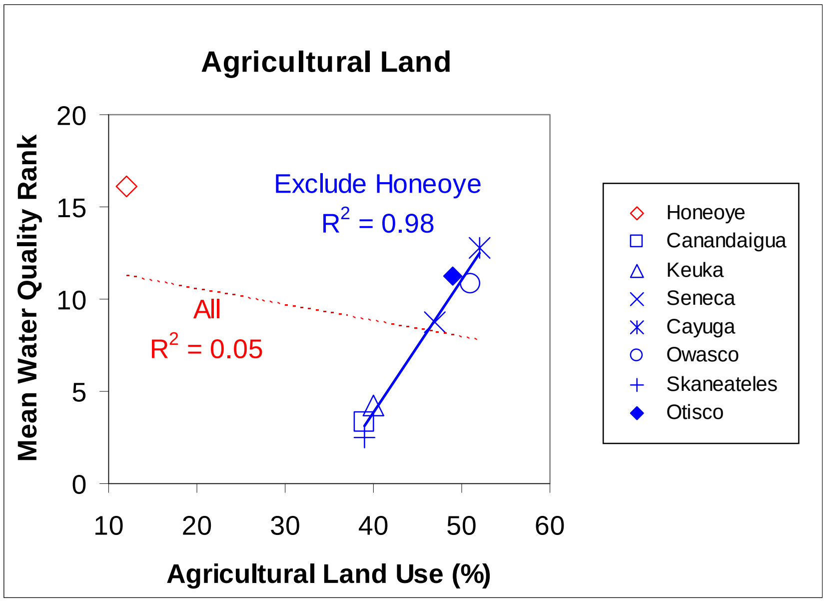

Fig. 17. Mean Rank vs. Agricultural Land Use.

An agricultural correlation does not dictate causation but is supported by nutrient loading studies in the Seneca and Owasco watersheds. Nutrient concentrations are 10 to 100 times larger in tributaries than the respective lake indicating a nutrient loading problem (Halfman et al., 2008; Halfman and Franklin, 2008, Fig. 18). Tributaries draining agricultural land transport more nutrients to the lake than more forested drainages. Field data from Conesus watershed and the watershed surrounding the Catskill reservoirs revealed similar trends (Makarewicz, 2007 Pionke et al., 1999). Computer models utilizing natural average nutrient loading curves confirm our field data (Evans, 2008).

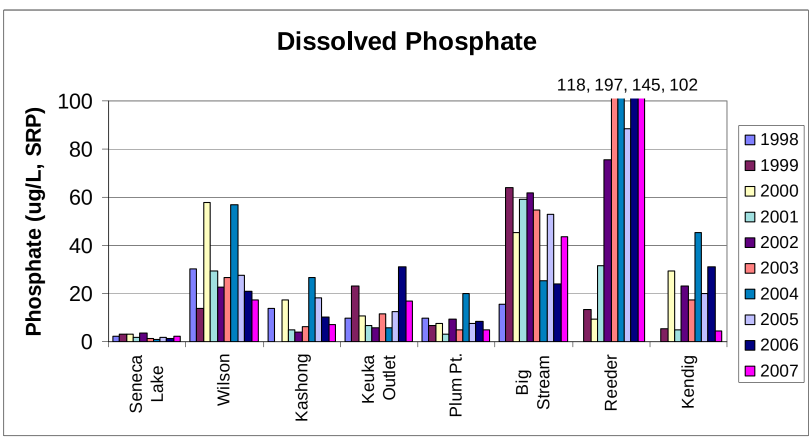

Fig. 18. Nutrient Loading by Seneca Tributaries.

Both nitrates and phosphates are not identical in their delivery. Nitrates are easily and ubiquitously transported in runoff as nitrates are water soluble. Phosphates however, are not easily transported because they attach onto soil particles. Major runoff events that transport eroded soils also transport large quantities of phosphates attached to the particles. Thus their impact is most critical during major runoff events. The correlation is confirmed by preliminary field data in the Owasco and Seneca watersheds, observations from elsewhere, and assumed by the Owasco watershed computer modeling. The relative contribution of phosphorus by base flow and peak flow (major runoff events) requires additional study. Preliminary data from Wilson Creek in the Seneca watershed revealed significant sediment and phosphate loading during a major precipitation / runoff event (Fig. 19).

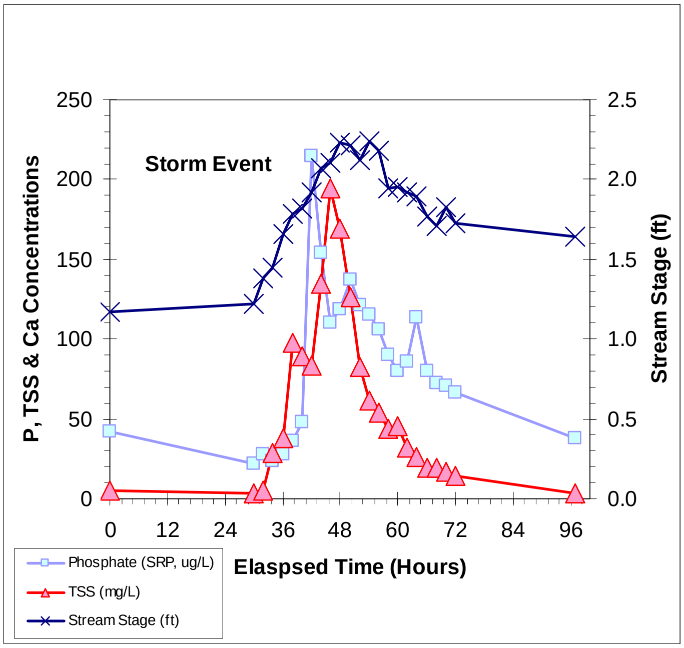

Fig. 19. Total suspended sediments and phosphate concentrations during a peak-flow event in Wilson Creek, Seneca watershed.

The Owasco Lake study outlined additional pertinent water quality issues (Halfman et al., 2008). First, nutrient loading from the Owasco Inlet significantly impacts water clarity and enhances macrophyte growth at the southern end of the lake. The impact is best developed after significant precipitation/runoff events (Halfman et al., 2006 & Gilman et al., 2008). Second, the two year study fortuitously sampled widely different runoff regimes. Rainfall during the 5 month field season decreased almost 70% from 24.3 inches in 2006 to 17.5 inches in 2007. This reduction impacted runoff (measured as stream discharge) as well. Annual mean discharge during the survey decreased from 2.1 to 0.2 m^3/s (Fig.20). This decrease has a profound impact on the delivery of nutrients to Owasco Lake as described above. The decrease in runoff from 2006 to 2007 decreased the flux of total phosphates from 6.2 to 2.9 kg/day, dissolved phosphates from 6.8 to 1.6 kg/day, nitrates from 210 to 88 kg/day and total suspended solids from 17,000 to 465 kg/day past Moravia in Owasco Inlet (Fig. 21). Similar decreases were observed in the other major tributaries and were attributed to the decrease in the delivery of non-point source nutrients, those delivered from the landscape and in particular those delivered from bare ground and agricultural activities. Third, the observed decrease in nutrient loading to the lake also coincided with decreased impairment of the southern end of the lake (Fig. 22). The association indicates that water quality in the Finger Lakes improves if nutrient loading is significantly reduced. The recovery time however can be years to decades and depends on the amount of nutrient reduction, water residence times, and other factors. It was relatively quick in Owasco Lake because the water retention time is approximately a year or two in Owasco Lake (i.e., quick to clean up once source reduced).

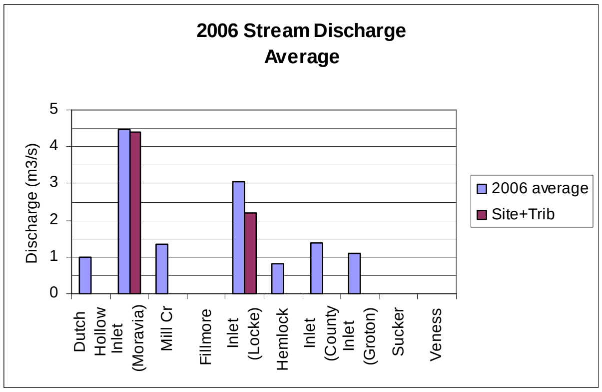

Fig. 20a. Owasco watershed 2006 discharge data.

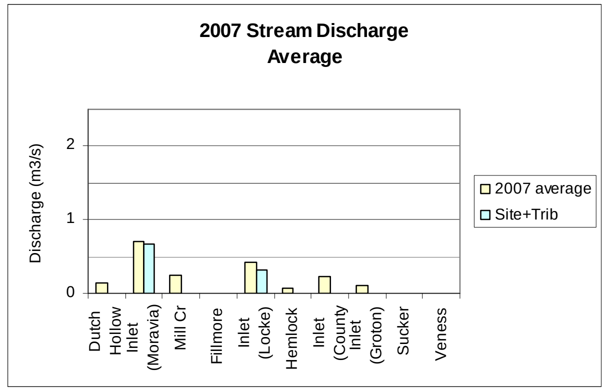

Fig. 20b. Owasco watershed 2007 discharge data.

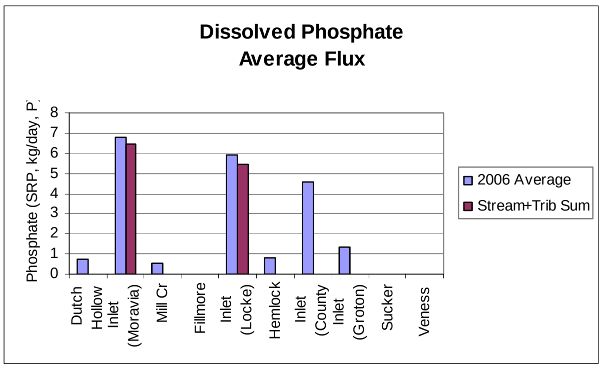

Fig. 21a. Owasco watershed 2006 nutrient flux data.

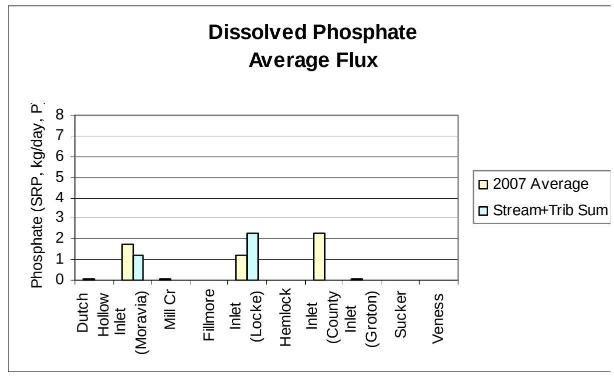

Fig. 21b. Owasco watershed 2007 nutrient flux data.

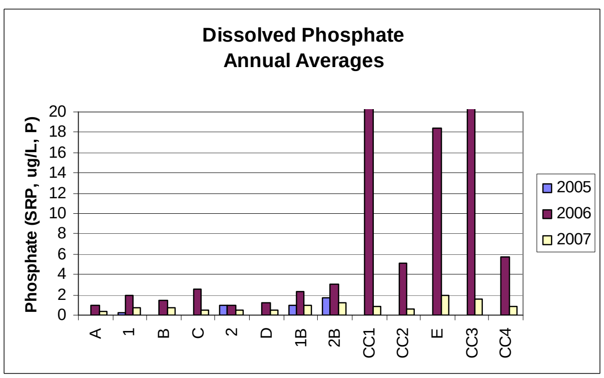

Fig. 22a. Owasco Lake SR phosphate data.

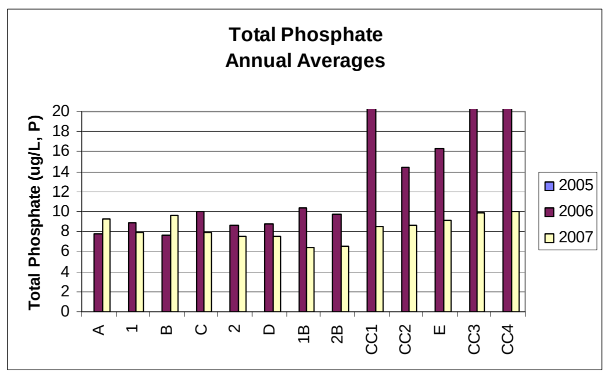

Fig. 22a. Owasco Lake total phosphate data.

Data from the Seneca and Owasco watersheds also confirm the degrading impact of nutrients from the treatment of organic wastes by municipal wastewater treatment plants. Segment analysis of Owasco Inlet in the Owasco watershed and Big Stream in the Seneca watershed revealed that effluent from municipal waste water treatment facilities in Groton and Dundee, respectively, was a major source of nutrients to these streams. The Groton plant delivered 20% in 2006 and over 80% in 2007 of the total phosphorus, 50% in 2006 and 100% in 2007 of the dissolved phosphates and 30% in 2006 and 45% in 2007 of the total nitrates flowing down Owasco Inlet and past Moravia just upstream from Owasco Lake (Halfman et al., 2008). Their contribution is especially noticeable during base flow. Not all wastewater treatment plants release significant quantities of nutrients to the watershed. Those with tertiary treatment specifically designed to remove phosphates from the effluent release significantly less phosphorus to the watershed than those facilities with only secondary treatment. Plans are currently underway to mandate and install tertiary treatment at the Groton facility.

We lack irrevocable field data to link and quantify the leakage of organic wastes from on-site systems (septic systems). However, we suspect and other studies confirm that on-site systems release more nutrients to the environment per pound of organic wastes than municipal facilities. The relationship is complicated though by the type, upkeep and age of the on-site wastewater treatment facility. On-site systems are ubiquitous in the rural region. The relative contribution of human wastes to water quality degradation, especially from on-site systems, requires further study. Data are also insufficient to assess the impact of other activities by lakeside residents. For example, a highly manicured and well fertilized lawn surrounding a year-round, lake-side home probably releases more nutrients to the lake than a rustic, lawn-free, summer cabin. All of these issues require additional study to assess their relative impact.

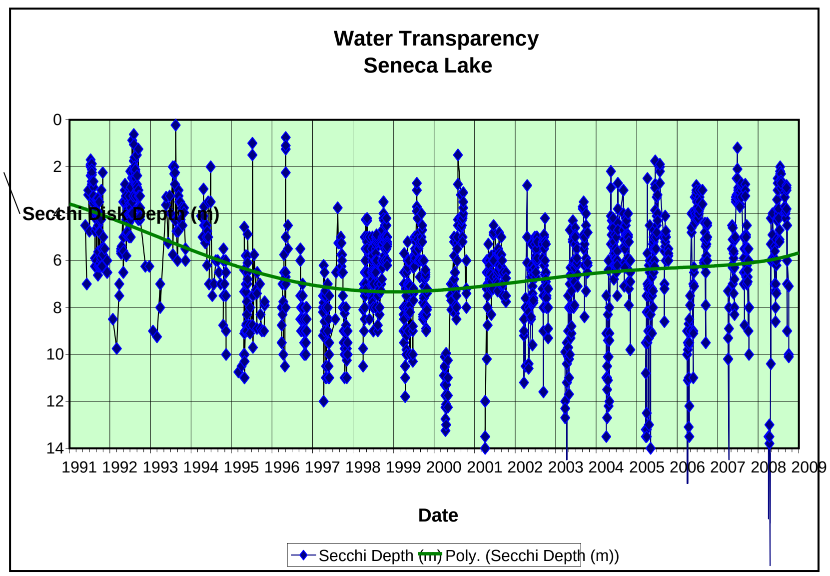

Fig. 23. Seneca Lake secchi disk depths.

Nutrient loading, a "bottom up" stressor to aquatic ecosystems, is not the only factor controlling water quality in these lakes. Zebra mussels and their relative quagga mussels are prolific filter feeders of plankton, each mussel cleansing up to 4 liters of water per day. Mussel populations were sufficient in Seneca Lake during 1998 to effectively filter the entire lake in a few days. Secchi disk data revealed the increase in water transparency from mean annual depths of a few meters before zebra mussels entered the lake in 1991 to depths over 15 meters in 1998 (Fig. 23). During 1998, their populations crashed, and the lake established a zebra/quagga mussel equilibrium with annual mean secchi disk depths close to 5 or 6 meters with significantly deeper early spring depths (below 20 m during the early spring). Deeper early spring depths allow sunlight to penetrate to deeper depths and probably assisted in the enhanced macrophyte (rooted nearshore vegetation) growth and expansion to deeper water over the past few years. The mean secchi disk depths have declined since 2000, and the decline has been attributed to nutrient loading from the watershed (Halfman & Franklin, 2008). The other lakes are experiencing zebra mussel impacts but the timing and the extent of the invasions are not identical.

Other invasive species have influenced water clarity by "top down" mechanisms. "Bottom up" perturbations, like nutrient loading, add nutrients to the base of the ecosystem, and thus enhance algal populations; whereas, "top down" perturbations remove algal predators higher up the food chain in the ecosystem, and thus enhance algal populations. For example, the carnivorous zooplankton *Cercopagus pengoi* feed on herbaceous zooplankton species. If sufficient grazing decimates herbaceous zooplankton populations then zooplankton are incapable of reducing algal blooms. The result is an algae bloom, similar to a bloom in eutrophic lakes, without the nutrient supply to be a eutrophic lake. Preliminary data from Owasco and Seneca Lakes also reveal evidence for a 'top down" impact (Brown and Balk, 2008). Similar results are observed through the introduction of zooplanktivorous fish like alewife. These fish eat the herbaceous zooplankton, and can severely decrease their populations, which in turn are not available to keep the phytoplankton populations in check. Thus evidence exists for "top down" alteration of aquatic ecosystems as well, and perhaps the non uniformity of the year to year ranking is a result of different perturbations impacting different watersheds with different outcomes.

WATER QUALITY PROTECTION LEGISLATION

The United States Environmental Protection Agency (US EPA) sets legislation that regulates and protects the quality of surface water. The Safe Drinking Water Act and subsequent amendments must be upheld or replaced with a more stringent standard by environmental regulatory agencies in the individual states. During the latter part of the 20th century, legislation was passed to control point source pollution. In New York, potential point-source polluters had to apply for permits to discharge wastes into surface waters. More recent legislation has focused on non-point source pollutants including legislation that controls land use options and best management practices, e.g., the reduction of runoff from agricultural land. Additional legislation focused on the repair, maintenance, and upgrades of on-site wastewater treatment. However the application of the more recent regulations is not state-wide.

The Catskill Watershed Cooperative (CWC) is an example where stringent water quality protection legislation protection was adopted for this primary drinking water supply for New York City. The nineteen reservoirs and three controlled lakes in the rural setting located north of the city and just west of the Hudson River supply ~90% of the city's drinking water. The incentive for New York City to establish stringent water quality protection legislation was to avoid the huge construction costs for EPA mandated water filtration plants. City funds supported the rehabilitation and maintenance of on-site wastewater systems. Their funds also support storm-water runoff reduction from agricultural land through best management practices (BMPs), and public education through various outreach efforts. Specifically, their programs focus on rehabilitation and replacement of septic systems, septic system maintenance programs, septic system monitoring programs, community wastewater management systems, stormwater control programs, local technical and economic assistance to encourage growth of environmentally friendly business ventures, and best management practices at agricultural sites.

In the Finger Lakes region, each watershed has a variety of regulations to maintain water quality. The degree of water quality regulation depends on citizen involvement and awareness, and the specificity and degree of implementation of the legislative goals. For example, the land protection, agricultural environmental management, and public outreach programs provide stringent water quality protection controls in the Skaneateles Watershed. The Canandaigua Lake Watershed Council utilizes BMPs and other agricultural programs to control runoff issues. Seneca Lake Pure Waters Association and the Genesee/Finger Lakes Regional Planning Council use public education and other rather vague county programs to offer some protection to Seneca Lake.

The preliminary report calculated a first-order approximation of the degree of legislative "protection" between each watershed from best (most protective) to worst (least protective). We will not describe a similar ranking here because we have since learned that the degree of protection incorporates two variables. Clearly, the degree of watershed protection legislation is important, as assumed before. However, legislation in New York stems from the local communities because New York is home-rule state. Every community is required to follow basic minimum standards set by the Department of Environmental Conservation in New York State (NYS-DEC). Each local entity can increase the degree of protection above the minimums if desired. For example, all new septic systems must follow basic building codes. However local communities may upgrade their standards to also enforce periodic septic system inspections, perk tests and pump outs. For enhanced watershed protection, all local communities within the watershed must utilize the same stringent standards. This is relatively easy when the watershed is in one county and only spans a few towns. When faced with a lake like Seneca Lake where the watershed spans over five counties, and 40+ cities, towns and villages, watershed protection legislation faces significant hurdles. Every community must agree to identical legislation. Thus every stakeholder must feel empowered to improve water quality, if we want to save our lakes.

Many of the regulations/methodologies require money either to hire "protectors" or utilize economic incentives to assist in water quality protection, and not all watersheds have sufficient funds to sponsor a stringent program. For example, funds are used to hire a watershed inspector(s), septic inspector(s), and/or education and provide incentives for homeowners to upgrade on-site wastewater treatment systems along the lakeshore. Skaneateles has financial incentives because the City of Syracuse draws drinking water from the lake, and the city supports water quality protection measures to offset water supply filtration costs. Owasco Lake is developing additional protection protocols and recently hired a watershed inspector. Other examples exist. Balyszak & Rootes-Murdy (2008) detail the various programs currently in effect through out the Finger Lakes region.

CONCLUSIONS, RECOMMENDATIONS & FUTURE RESEARCH

Water quality varies across the seven Finger Lakes and range from oliogotrophic to eutrophic systems. Skaneateles, Canandaigua and Keuka Lakes are the oligotrophic end members and exhibit the best water quality, whereas Seneca, Owasco, Cayuga, Honeoye and Otisco Lake are the impaired mesotrophic to eutrophic end members and exhibit the worst water quality.

The eutrophic status of Honeoye and Otisco Lakes is a concern, and steps should be taken to improve water quality in these lakes. The mesotrophic status of Owasco, Cayuga and Seneca Lakes is also a concern because the large volume of water in these lakes probably precludes significant depletion of hypolimnetic dissolved oxygen throughout the summer season. Annual changes in rank are attributed to differences in nutrient loading and other "bottom-up" perturbations and/or various "top-down" perturbations. Of special concern is Seneca Lake because it contains 50% of the water in the Finger Lakes, and boasts an internationally known wine industry along its shores. Once Seneca Lake is degraded, it will stay degraded for generations.

Nutrient sources include both point and non-point sources and include wastewater treatment facilities, stream bank erosion, and runoff over agricultural areas. On-site systems and enhanced lakeside lawn care provide additional concerns. Everyone has a stake in protecting and preserving water quality in the Finger Lakes because they provide critical sources of drinking water and are essential to the regional economy. Lets all work together to reverse disturbing water quality trends and projected outcomes. If we do, then the preliminary evidence from Owasco Lake suggests that water quality in these lakes will improve after "turning off" multiple sources of nutrients from their watershed. Outstanding models exist and are ready to implement across the entire region.

A few future water quality research topics are highlighted here. First, continued monitoring is critical in each basin to assess the impact of nutrient loading on the water quality in these lakes and the relative change between lakes. Second, future studies must investigate the relative contributions of peak versus base flow conditions on nutrient loading from the watershed to the lake. This data are critical to differentiate the relative contribution of point-source pollutants like waste water treatment facilities important during base flow to non-point source pollutants like runoff from agricultural areas, both plant and animal operations, during peak flow. Third, more research is required to assess the impact of on-site systems, enhanced lawn care and other perturbation along the lake shore. Finally, stakeholders within each watershed should constantly re-evaluate their water quality protection legislation and degree of enforcement/compliance within the watershed. Only concerted efforts from every stakeholder in the watershed will maintain and hopefully improve water quality in the Finger Lakes for generations to come.

ACKNOWLEDGEMENTS

The research was supported by grants from Hobart & William Smith Colleges, the Kloman Foundation, The Environmental Research Fund, the Emerson Foundation, the Triad Foundation, the Booth-Ferris Foundation, New York State, the Mellon Foundation and other Foundations. We especially thank the John Ben Snow Foundation whose generous support financed the purchase and outfitting of the 25-ft, trailerable, research vessel, the JB Snow, and the 2007 and 2008 research on the Finger Lakes. We thank Captain John Nichols and John Abbott for their professional service on the William Scandling our 65-ft research vessel on Seneca Lake. Marion Balyszak, Jay Bloomfield, Cliff Callinan, Joe Makarewicz, Bob Brower, Steve Effler, Ed Mills, Bruce Gilman, Meghan Brown, Bin Zhu and numerous others for fruitful discussions on water quality issues in the Finger Lakes. Special thanks are extended to Prabi Basnet, Sam Georgian, Katherine Horning who assisted with the 2008 research, and many other undergraduate students from previous summers for assistance in the field and laboratory.

References:

Balyszak, M. and K. Rootes-Murdy, 2008. Watershed quality and protection legislation in the Owasco Lake watershed. In: Halfman, J.D., M.E. Balyszak and S.A. Meyer (eds.), A 2007 Water Quality Study of Owasco Lake, New York. Finger Lakes Institute, Hobart and William Smith Colleges. 26 pg.

Brown, M, and M. Baulk, 2008. The potential link between lake productivity and the invasive zooplankter *Ceropagis pengoi* in Owasco Lake (New York, USA). In: Halfman, J.D., M.E. Balyszak and S.A. Meyer (eds.), A 2007 Water Quality Study of Owasco Lake, New York. Finger Lakes Institute, Hobart and William Smith Colleges. 12 pg.

Callinan, C., 2001. Water Quality Study of the Finger Lakes. New York State Department of Environmental Conservation Report.

Evans, B., 2008. Computer-based simulation of loads and water quality responses within the Owasco Lake watershed. In: Halfman, J.D., M.E. Balyszak and S.A. Meyer (eds.), A 2007 Water Quality Study of Owasco Lake, New York. Finger Lakes Institute, Hobart and William Smith Colleges. 19 pg.

Georgian, S.E., and J.D. Halfman, 2008, Comparison of Methods to Determine Algal Concentrations in Freshwater Lakes. American Geophysical Union Annual Fall Meeting Abstracts with Programs.

Gilman, B., J. Foust, and B Zhu, 2008. Composition, seasoknal standing crop biomass and estimated annual productivity of macrophyte communities in Owasco Lake. In: Halfman, J.D., M.E. Balyszak and S.A. Meyer (eds.), A 2007 Water Quality Study of Owasco Lake, New York. Finger Lakes Institute, Hobart and William Smith Colleges. 17 pg.

Halfman, J.D., and C.K. Franklin, 2008. Water Quality of Seneca Lake, New York: A 2007 Update. Finger Lakes Institute, Hobart and William Smith Colleges.

Halfman, J.D., and K. F. Bush, 2006. A preliminary water quality study of selected Finger Lakes, New York. Finger Lakes Institute, Hobart and William Smith Colleges. 15 pg.

Halfman, J.D., B.L. Holler, and H.M. Philip, 2006. A preliminary water quality study of Owasco Lake, NY, and its watershed. Finger Lakes Institute, Hobart and William Smith Colleges. 26 pg.

Halfman, J.D., E.S. Brown, T.F. Ware, K.A. O’Neill, C.K. Franklin and R.E. Dye, 2008. Owasco Lake, New York: Water Quality and Nutrient Sources. In: Halfman, J.D., M.E. Balyszak and S.A. Meyer (eds.), A 2007 Water Quality Study of Owasco Lake, New York. Finger Lakes Institute, Hobart and William Smith Colleges. 37 pg.

Makarewicz, J., P. D’Aiuto, and I. Bosch, 2007. Elevated nutrient levels from agriculturally dominated watershed stimulate metaphyton growth. J Great Lakes research. 33, 437-448.

Pionke, H, W. Giburek, R. Schnabel, A. Sharpley, and G. Elwinger, 1999. Seasonal flow, nutrient concentrations and loading patterns in stream flow draining an agricultural hill-land watershed. J or Hydrology, 220, 62-73.

Wetzel, R. and G. Likens, 2000. Limnological Analyses. 3rd Edition. Springer, New York.

Wing, M.R., Preston, A., Acquisto, N. and Ahrnsbrak, W.F., 1995, Intrusion of saline groundwater into Seneca and Cayuga Lakes, New York. *Limnology and Oceanograpgy*, v. 40, p. 791-810.

Annual Mean Lake Data:

2005 Average Values (± 1σ)	Honeoye	Canandaigua	Keuka	Seneca	Cayuga	Owasco	Skaneateles
Secchi Depth (m)	4.4 ± 1.5	6.2 ± 1.9	4.4 ± 0.5	3.8 ± 1.3	4.4 ± 1.4	3.8 ± 0.5	6.9 ± 1.2
Total Suspended Solids (mg/L), Surface	1.8 ± 1.3	0.8 ± 0.4	1.3 ± 0.7	2.1 ± 1.0	1.2 ± 0.4	1.3 ± 0.3	0.6 ± 0.3
Total Suspended Solids (mg/L), Bottom	2.3 ± 1.3	1.9 ± 1.0	2.0 ± 1.0	1.0 ± 0.6	3.7 ± 2.4	1.1 ± 0.3	0.7 ± 0.4
Phosphate (µg/L, SRP), Surface	9.1 ± 12.7	0.4 ± 0.6	0.2 ± 0.2	0.8 ± 1.5	0.5 ± 0.8	0.6 ± 0.8	0.0 ± 0.0
Phosphate (µg/L, SRP), Bottom	9.6 ± 14.0	1.1 ± 1.3	0.4 ± 0.5	1.0 ± 1.3	8.8 ± 5.2	1.3 ± 0.8	0.5 ± 0.6
Nitrate as N (mg/L), Surface	0.0 ± 0.0	0.1 ± 0.1	0.1 ± 0.1	0.3 ± 0.1	1.0 ± 0.3	0.7 ± 0.3	0.5 ± 0.2
Nitrate as N (mg/L), Bottom	0.0 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.5 ± 0.3	1.4 ± 0.8	1.2 ± 0.6	0.6 ± 0.2
Silica (SR µg/L), Surface	868 ± 346	1091 ± 135	489 ± 223	120 ± 56	257 ± 163	529 ± 140	157 ± 80
Silica (SR µg/L), Bottom	834 ± 381	1569 ± 156	1077 ± 94	319 ± 193	1018 ± 110	1547 ± 129	708 ± 78
Chlorphyll a (µg/L), Surface	3.6 ± 2.4	1.5 ± 1.0	1.4 ± 0.9	2.6 ± 1.6	2.5 ± 1.4	4.1 ± 2.1	0.6 ± 0.4
Chlorphyll a (µg/L), Bottom	4.4 ± 3.0	0.1 ± 0.1	4.4 ± 4.4	1.5 ± 1.3	0.7 ± 1.5	0.3 ± 0.3	0.4 ± 0.6
Total Coliform (colonies/100mL), Surface	67.2 ± 104.7	22.5 ± 20.1	44.3 ± 32.8	115.3 ± 185.6	19.1 ± 33.6	170.8 ± 221.4	12.2 ± 12.5
Total Coliform (colonies/100mL), Bottom	140.3 ± 140.0	46.3 ± 95.2	62.7 ± 53.5	28.0 ± 38.8	27.3 ± 22.9	139.2 ± 106.7	96.7 ± 204.7
E. coli (colonies/100mL), Surface	6.8 ± 15.0	0.7 ± 1.0	6.4 ± 12.0	31.3 ± 87.7	0.1 ± 0.2	7.9 ± 14.1	0.1 ± 0.2
E. coli (colonies/100mL), Bottom	1.3 ± 1.9	0.9 ± 1.8	0.4 ± 0.9	0.5 ± 0.6	0.8 ± 1.3	8.7 ± 15.3	1.8 ± 2.1

2006 Average Values (± 1σ)	Honeoye	Canandaigua	Keuka	Seneca	Cayuga	Owasco	Skaneateles
Secchi Depth (m)	3.9 ± 1.8	5.9 ± 1.6	4.5 ± 1.0	5.3 ± 2.4	3.8 ± 1.0	3.4 ± 1.5	7.3 ± 2.0
Total Suspended Solids (mg/L), Surface	1.8 ± 1.5	0.9 ± 0.5	1.3 ± 0.6	1.4 ± 0.4	1.2 ± 0.4	1.9 ± 0.8	0.8 ± 0.3
Total Suspended Solids (mg/L), Bottom	1.7 ± 1.6	1.6 ± 1.0	1.6 ± 0.6	0.7 ± 0.3	3.3 ± 1.5	1.2 ± 0.3	1.0 ± 0.4
Dissolved Phosphate (µg/L, SRP), Surface	1.8 ± 1.3	1.8 ± 3.1	1.2 ± 1.0	0.8 ± 1.0	1.3 ± 1.3	1.3 ± 1.6	1.1 ± 1.9
Dissolved Phosphate (µg/L, SRP), Bottom	3.3 ± 1.8	2.4 ± 2.2	1.9 ± 2.5	2.2 ± 2.0	10.2 ± 2.6	2.0 ± 1.5	1.6 ± 2.2
Total Phosphate (µg/L, TP), Surface	16.0 ± 3.7	7.4 ± 1.9	7.8 ± 2.1	8.4 ± 2.7	11.2 ± 4.6	7.5 ± 2.5	4.0 ± 1.0
Total Phosphate (µg/L, TP), Bottom	18.3 ± 3.8	7.8 ± 2.2	8.1 ± 2.8	7.4 ± 1.9	10.3 ± 3.8	7.4 ± 2.4	5.1 ± 2.4
Nitrate as N (mg/L), Surface	0.0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.3 ± 0.2	1.2 ± 0.4	0.7 ± 0.2	0.5 ± 0.2
Nitrate as N (mg/L), Bottom	0.0 ± 0.0	0.2 ± 0.1	0.2 ± 0.1	0.4 ± 0.2	1.5 ± 0.3	0.7 ± 0.3	0.6 ± 0.2
Silica (SR µg/L), Surface	660 ± 178	1090 ± 172	579 ± 118	158 ± 76	595 ± 126	595 ± 145	298 ± 113
Silica (SR µg/L), Bottom	694 ± 136	1506 ± 329	1077 ± 284	314 ± 169	991 ± 212	1473 ± 779	701 ± 182
Chlorphyll a (µg/L), Surface	3.9 ± 3.9	1.7 ± 1.2	2.0 ± 1.2	2.4 ± 1.8	2.8 ± 1.5	2.1 ± 1.3	0.7 ± 0.4
Chlorphyll a (µg/L), Bottom	3.4 ± 2.8	0.3 ± 0.2	0.5 ± 0.3	0.7 ± 0.9	0.3 ± 0.2	0.4 ± 0.3	0.2 ± 0.1

2007 Average Values (± 1σ)	Honeoye	Canandaigua	Keuka	Seneca	Cayuga	Owasco	Skaneateles
Secchi Depth (m)	4.2 ± 2.0	7.1 ± 2.0	5.9 ± 0.7	5.0 ± 1.6	4.2 ± 1.1	4.9 ± 1.2	8.6 ± 1.0
Total Suspended Solids (mg/L), Surface	6.0 ± 9.4	1.3 ± 0.7	0.9 ± 0.2	1.5 ± 0.5	1.4 ± 0.5	1.2 ± 0.5	0.5 ± 0.2
Total Suspended Solids (mg/L), Bottom	2.0 ± 0.7	2.6 ± 2.0	2.1 ± 1.1	1.0 ± 0.5	1.8 ± 0.8	0.8 ± 0.1	0.6 ± 0.2
Dissolved Phosphate (µg/L, SRP), Surface	8.3 ± 8.6	0.5 ± 0.8	0.7 ± 0.7	0.5 ± 0.7	0.8 ± 1.3	0.6 ± 0.7	0.4 ± 0.4
Dissolved Phosphate (µg/L, SRP), Bottom	7.4 ± 8.2	0.9 ± 0.6	2.2 ± 2.7	2.4 ± 2.8	8.4 ± 3.6	1.3 ± 0.8	0.7 ± 0.7
Total Phosphate (µg/L, TP), Surface	35.3 ± 28.7	8.0 ± 5.9	5.7 ± 1.2	8.9 ± 3.0	9.9 ± 3.6	7.7 ± 2.3	3.8 ± 1.9
Total Phosphate (µg/L, TP), Bottom	23.2 ± 10.2	5.2 ± 3.1	4.8 ± 2.5	7.8 ± 3.7	12.6 ± 4.5	5.7 ± 2.4	4.5 ± 2.4
Nitrate as N (mg/L), Surface	0.0 ± 0.0	0.1 ± 0.1	0.1 ± 0.0	0.7 ± 0.9	0.9 ± 0.2	0.7 ± 0.2	0.5 ± 0.1
Nitrate as N (mg/L), Bottom	0.0 ± 0.0	0.3 ± 0.1	0.2 ± 0.1	0.5 ± 0.3	1.3 ± 0.3	1.0 ± 0.2	0.6 ± 0.2
Silica (SR µg/L), Surface	868 ± 58	966 ± 275	542 ± 179	263 ± 184	366 ± 144	676 ± 227	319 ± 117
Silica (SR µg/L), Bottom	866 ± 56	1322 ± 289	1194 ± 349	381 ± 195	1025 ± 211	1454 ± 283	727 ± 201
Chlorphyll a (µg/L), Surface	28.2 ± 52.8	2.0 ± 1.7	2.6 ± 3.5	4.0 ± 2.2	3.6 ± 1.9	2.4 ± 1.8	0.7 ± 0.4
Chlorphyll a (µg/L), Bottom	5.5 ± 3.6	0.9 ± 0.6	1.8 ± 3.1	1.1 ± 1.2	1.7 ± 5.9	0.7 ± 0.5	1.0 ± 0.9

2008 Average Values (± 1σ)	Honeoye	Canandaigua	Keuka	Seneca	Cayuga	Owasco	Skaneateles	Otisco
Secchi Depth (m)	4.6 ± 0.9	6.7 ± 1.6	6.5 ± 0.7	4.7 ± 2.8	3.8 ± 1.0	4.2 ± 1.2	7.8 ± 1.2	3.1 ± 0.9
Total Suspended Solids (mg/L), Surface	1.4 ± 0.8	0.9 ± 0.5	1.0 ± 0.2	1.7 ± 0.8	1.5 ± 0.5	1.3 ± 0.7	0.6 ± 0.2	2.3 ± 1.9
Total Suspended Solids (mg/L), Bottom	1.2 ± 0.2	1.5 ± 1.0	1.2 ± 0.5	0.8 ± 0.4	2.5 ± 1.5	1.2 ± 0.6	0.7 ± 0.4	2.1 ± 0.7
Dissolved Phosphate (µg/L, SRP), Surface	4.6 ± 6.1	0.9 ± 0.6	0.6 ± 0.5	0.9 ± 1.3	0.8 ± 0.8	0.9 ± 0.7	0.7 ± 0.5	0.8 ± 1.2
Dissolved Phosphate (µg/L, SRP), Bottom	3.7 ± 5.2	1.3 ± 0.9	0.9 ± 0.6	3.2 ± 3.1	7.7 ± 4.2	1.1 ± 1.1	1.1 ± 1.1	4.8 ± 9.7
Total Phosphate (µg/L, TP), Surface	19.2 ± 5.6	7.9 ± 3.3	5.4 ± 2.7	9.8 ± 2.9	8.0 ± 1.4	7.4 ± 2.7	3.4 ± 1.7	12.8 ± 3.1
Total Phosphate (µg/L, TP), Bottom	18.4 ± 3.8	7.4 ± 4.5	6.8 ± 4.3	9.4 ± 3.0	12.5 ± 3.7	8.9 ± 2.0	4.8 ± 2.1	14.2 ± 9.6
Nitrate as N (mg/L), Surface	0.0 ± 0.0	0.2 ± 0.2	0.0 ± 0.0	0.2 ± 0.1	0.7 ± 0.4	0.6 ± 0.2	0.4 ± 0.2	0.3 ± 0.1
Nitrate as N (mg/L), Bottom	0.0 ± 0.0	0.3 ± 0.2	0.2 ± 0.1	0.3 ± 0.1	1.1 ± 0.5	0.9 ± 0.4	0.6 ± 0.2	0.3 ± 0.2
Silica (SR µg/L), Surface	823 ± 266	994 ± 163	462 ± 148	309 ± 291	358 ± 188	751 ± 514	290 ± 89	334 ± 413
Silica (SR µg/L), Bottom	865 ± 252	1589 ± 513	1157 ± 419	470 ± 117	1033 ± 225	1474 ± 531	825 ± 231	1298 ± 890
Chlorphyll a (µg/L), Surface	2.7 ± 1.9	1.6 ± 1.0	2.0 ± 1.1	4.6 ± 2.7	4.0 ± 1.4	2.6 ± 1.3	0.7 ± 0.3	3.7 ± 0.6
Chlorphyll a (µg/L), Bottom	1.9 ± 0.9	0.9 ± 1.1	0.5 ± 0.2	1.5 ± 1.4	0.3 ± 0.2	0.8 ± 0.6	0.4 ± 0.2	3.0 ± 1.7

Average of the 4 Years (± 1σ)	Honeoye	Canandaigua	Keuka	Seneca	Cayuga	Owasco	Skaneateles	Otisco
Secchi Depth (m)	4.2 ± 0.3	6.5 ± 0.5	5.3 ± 1.1	4.7 ± 0.7	4.1 ± 0.3	4.1 ± 0.6	7.6 ± 0.8	3.1 ±
Total Suspended Solids (mg/L), Surface	2.7 ± 2.2	1.0 ± 0.2	1.1 ± 0.2	1.7 ± 0.3	1.4 ± 0.2	1.4 ± 0.3	0.7 ± 0.1	2.3 ±
Total Suspended Solids (mg/L), Bottom	1.8 ± 0.5	1.9 ± 0.5	1.7 ± 0.4	0.9 ± 0.2	2.8 ± 0.8	1.1 ± 0.2	0.8 ± 0.2	2.1 ±
Dissolved Phosphate (µg/L, SRP), Surface	5.9 ± 3.4	0.9 ± 0.6	0.7 ± 0.4	0.8 ± 0.2	0.9 ± 0.3	0.9 ± 0.3	0.6 ± 0.5	0.8 ±
Dissolved Phosphate (µg/L, SRP), Bottom	6.0 ± 3.0	1.4 ± 0.7	1.4 ± 0.8	2.2 ± 0.9	8.8 ± 1.1	1.4 ± 0.4	1.0 ± 0.5	4.8 ±
Total Phosphate (µg/L, TP), Surface	23.5 ± 10.4	7.8 ± 0.4	6.3 ± 1.3	9.0 ± 0.7	9.7 ± 1.6	7.5 ± 0.1	3.7 ± 0.3	12.8 ±
Total Phosphate (µg/L, TP), Bottom	20.0 ± 2.8	6.8 ± 1.4	6.6 ± 1.7	8.2 ± 1.1	11.8 ± 1.3	7.3 ± 1.6	4.8 ± 0.3	14.2 ±
Nitrate as N (mg/L), Surface	0.0 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.4 ± 0.2	0.9 ± 0.2	0.7 ± 0.0	0.5 ± 0.1	0.3 ±
Nitrate as N (mg/L), Bottom	0.0 ± 0.0	0.3 ± 0.0	0.2 ± 0.0	0.4 ± 0.1	1.3 ± 0.2	1.0 ± 0.2	0.6 ± 0.0	0.3 ±
Silica (SR µg/L), Surface	805 ± 99	1035 ± 65	518 ± 53	213 ± 88	394 ± 143	638 ± 97	266 ± 73	334 ±
Silica (SR µg/L), Bottom	815 ± 82	1496 ± 122	1126 ± 59	371 ± 72	1017 ± 19	1487 ± 41	740 ± 58	1298 ±
Chlorphyll a (µg/L), Surface	9.6 ± 12.4	1.7 ± 0.2	2.0 ± 0.5	3.4 ± 1.1	3.2 ± 0.7	2.8 ± 0.9	0.7 ± 0.1	3.7 ±
Chlorphyll a (µg/L), Bottom	3.8 ± 1.5	0.6 ± 0.4	1.8 ± 1.9	1.2 ± 0.4	0.7 ± 0.7	0.6 ± 0.2	0.5 ± 0.3	3.0 ±