BOTTOM WATER PHOSPHATES AND SUSPENDED SEDIMENTS IN SOUTHERN CAYUGA LAKE, NEW YORK.

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INTRODUCTION

Water quality is critical to the health, well being and economy of the region. In 2005, the Finger Lakes Institute initiated a water quality survey of the eastern Finger Lakes, Otisco (since 2008), Skaneateles, Owasco, Cayuga, Seneca, Keuka, Canandaigua and Honeoye Lakes. The survey's annual water quality ranking indicated that Cayuga Lake moved from a middle ranking in 2005 to 2nd worst in 2006, and remained 2nd worst in 2007 and 2008 (Fig. 1; Halfman and O'Neill, 2009). The ranking is based on monthly secchi disk depths and surface water analyses for total coliform and *E. coli* bacteria (only in 2005), chlorophyll-a (algae concentrations), nutrient concentrations (total phosphates since 2006, soluble reactive phosphates, nitrates and dissolved silica), and suspended sediment concentrations from at least two mid-lake, deep-water sites in each lake. The water quality degradation in Cayuga Lake is disturbing and consistent with documented impairment of the lake's southern end.

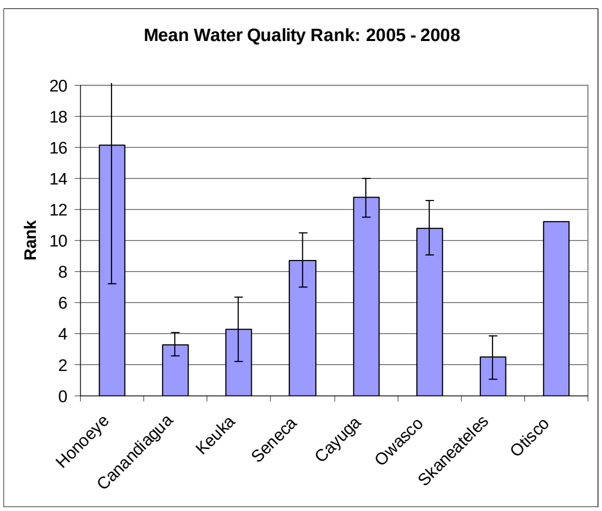
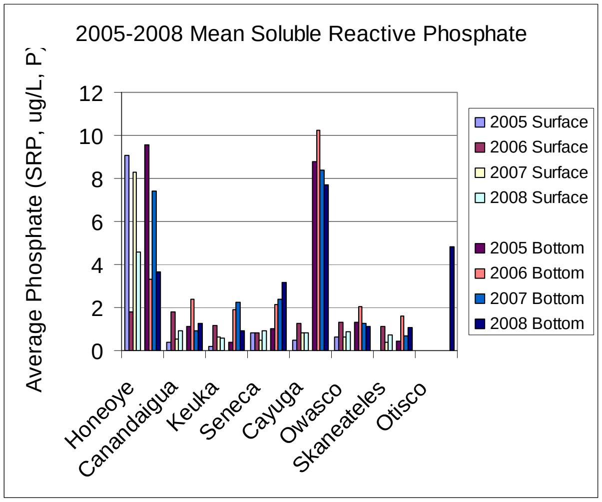


Fig. 1. *Mean of annual water quality rankings from2005 to 2008 (Halfman and O'Neill, 2009).*

The water quality ranking was based on surface water data, and ignored bottom water data. Including bottom water data would further decrease water quality in Cayuga Lake because hypolimnetic (bottom-water) data revealed more total phosphates (~10 μg/L, P), nitrates (~1.5 mg/L, N), soluble reactive phosphates (SRP, ~10 μg/L, P) and total suspended sediments (TSS, ~3 mg/L), than bottom water results from the other lakes. This dichotomy was especially prominent for SRP and TSS (Fig. 2). The elevated phosphate concentrations are a concern because algal and macrophyte growth will be promoted when these bottom waters are exposed to the sunlit surface waters.

Natural and human-induced mechanisms bring bottom water to the surface. For example, fall and spring overturn mix the entire water column. Internal seiche activity, initiated by strong axial winds, can bring hypolimnetic (bottom) water to the lake's surface at the northern and southern ends of the lake. Cornell's Lake Source Cooling Project also draws hypolimnetic water and returns the water, albeit warmer, back to the epilimnion of the lake. Thus, a two year study was initiated in 2007 to understand the sources of phosphates and suspended sediments to the hypolimnion (bottom waters) of southern Cayuga Lake. This report summarizes our 2007 and 2008 findings, substantiates and expands on the initial hypotheses outlined in our preliminary report (Halfman et al., 2008), and recommends a number of future projects to answer questions initiated by this investigation.



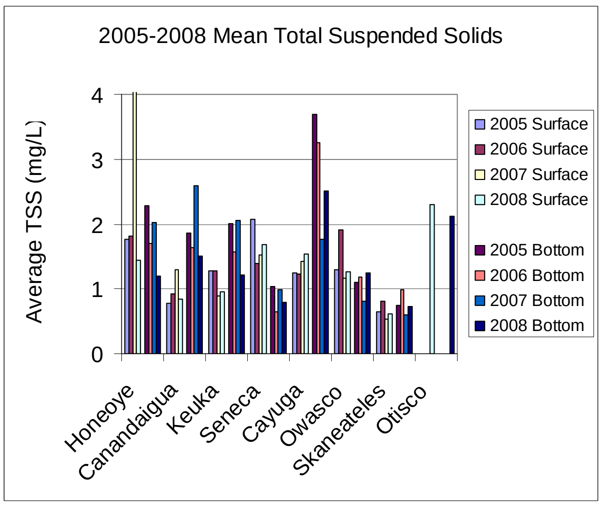


Fig. 2. *Annual mean SRP and TSS data from the FLI Finger Lake survey (Halfman and O'Neill, 2009).*

BACKGROUND:

Nutrients, phosphates (PO_4^{-3}) and nitrates (NO_3^-), are essential for life because they are required for critical life-sustaining compounds including amino acids, proteins, cell tissue, RNA and DNA. In a basic aquatic nutrient cycle (Fig. 3), dissolved nutrients enter the food chain through assimilation and incorporation by plants, phytoplankton (algae, microscopic, free-floating, aquatic plants) and macrophytes (nearshore rooted vegetation). When the algae and other plants are eaten, these nutrients are passed up the food chain. 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 where they are available for plant assimilation once again.

Excessive nutrient loading leads to impaired water bodies and transforms an oligotrophic (poorly productive) lake to a eutrophic (highly productive) lake. The extra nutrients stimulate additional algal and macrophyte growth, and increase the amount of material in each box of the nutrient cycle over time. Other, typically undesirable but related impairments 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. Thus nutrient concentrations are indicators of water quality.

Dissolved oxygen concentrations also measure water quality. When the algae die (algae live for only a few days), bacterial respiration consumes dissolved oxygen and releases carbon dioxide. As a lake becomes more productive, bacterial decomposition of the excess organics removes additional dissolved oxygen from the summer-time hypolimnion (water mass below the thermocline). When the removal decreases dissolved oxygen concentrations to 6 mg/L or below, each species has its own level of tolerance, respiratory stress is placed on all aquatic animals like lake trout, crawfish and worms. Complete de-oxygenation of the bottom waters happens in eutrophic lakes.

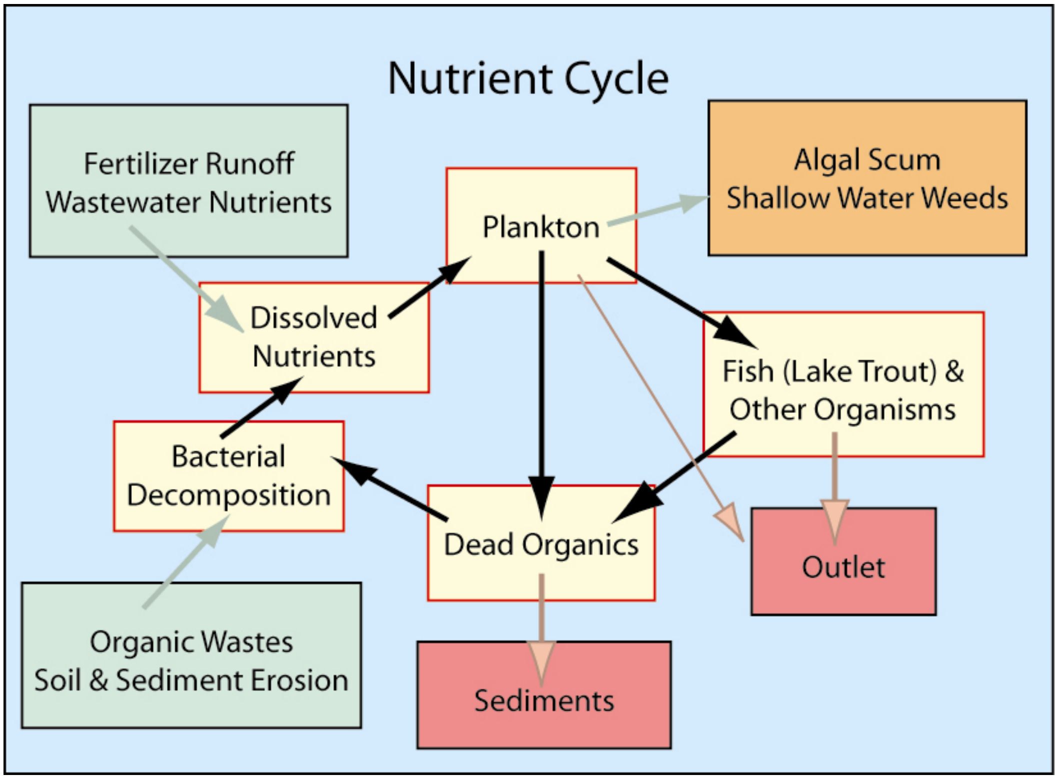


Fig. 3. *A nutrient cycle for lake ecosystems (yellow boxes). Natural and human-induced additions (green boxes), their impact (orange box), and natural sinks (red boxes) from the nutrient cycle are also shown.*

Algal concentrations are another indicator of lake productivity and the ecological health of a lake, as larger concentrations of algae are typically indicative of more productive systems. 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, these parameters are typically used in combination to define the trophic status and/or water quality of aquatic systems (Table 1). In New York, the Department of Environmental Conservation (NYS DEC) focuses on total phosphate concentrations to measure water quality impairment because phosphate is the limiting nutrient for algal growth in most New York lakes. Impaired (i.e., eutrophic) water bodies contain at least 20 μg/L of phosphate.

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

Thermal Stratification: The seasonal cycle of thermal stratification complicates this story. In the early spring when the entire water column is isothermal and cold, 4º C (39º F), the lake "turns over" and the entire water column mixes with a minimal amount of wind stress. The physical mixing also distributes nutrient and other constituents uniformly throughout the water column.

Moving forward into the summer, the lake warms. Warming is restricted to the upper portion of the water column because the intensity of light decreases exponentially with water depth as sunlight is either scattered or absorbed by the water. Warmer water is progressively less dense than the colder bottom water, thus the warmer water "floats" buoyantly at the lake's surface. The hypolimnion of most deep lakes remains at 4º C, because it is the temperature of maximum density in freshwater. For a while winds may be strong enough to mix the water column and warm the hypolimnion by a few degrees, especially in shallow lakes, but eventually the surface water becomes too warm and too buoyant to completely mix with the colder water below. Thus, the warmer water "floats" at the surface of the lake and gradually warms to 20 to 30º C (70 to 90º F) by the end of summer as it absorbs more energy from the sun than the lake radiates away or it loses by evaporation to the atmosphere.

The thermal stratification of the summer season isolates the sunlit and warm epilimnion (surface) waters from the dark and cold hypolimnion (bottom) waters (Fig. 4). The occasional wind events and surface currents will keep the epilimnion well mixed and isothermal. The magnitude and duration of the wind events defines the extent of mixing and depth of the epilimnion. Between the epilimnion and hypolimnion, water temperatures decrease exponentially with depth and define the metalimnion (Fig. 4). The planar surface corresponding to the depth of maximum temperature decrease defines the thermocline. The depth of the photic (sunlit) zone corresponds to the base of the metalimnion.

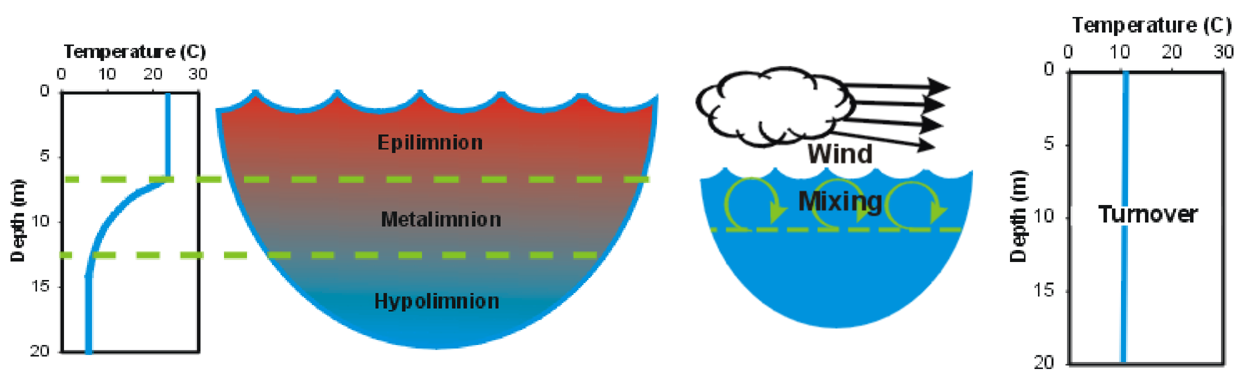


Fig. 4. *Thermal stratification of a typical small lake. Left: Summer stratification, and the resulting epilimnion, metalimnion and hypolimnion. Center: Surface water mixing by winds created the isothermal epilimnion. Right: Fall isothermal conditions and overturn after the autumnal decay of the surface warmth (from www.OurLake.org/).*

As solar inputs decline and the weather cools into the fall, the epilimnion cools as well. The epilimnion mixes to greater depths as the density difference between the epilimnion and hypolimnion declines. The process mixes metalimnetic water into the epilimnion. The depth of mixing continues to deepen as the surface temperatures decline. Once surface waters cool to hypolimnetic temperatures (typically 4º C in deep lakes), the entire water column can "turn over". As the atmosphere cools even more, the surface water continues to cool until it typically freezes during a very calm and cold night. Water colder than 4º C and more importantly ice are less dense than water at 4º C, thus the colder water "floats" on the surface of the lake but the density differences for the water masses are small, thus the winter water stratification is not as intense as the summer stratification. Seneca and Cayuga Lakes typically are too turbulent to cool a thin surface water layer down to 0º C, and have it remain at the lake's surface to remove sufficient latent heat to then freeze. The entire water column in these lakes typically continues to mix through out the winter season except for some ice near the shore and/or either end.

Algae & Nutrient Seasonal Profiles: The water column mixing and summer stratification complicate the distribution of algae and nutrients. During spring overturn, algae are mixed with the circulating water, thus spend only a small portion of the day in the sunlit surface waters and the rest in the dark bottom waters. Thus, algal photosynthesis and growth is typically light limited. When the lake becomes stratified, algae are no longer mixed through the entire water column, and remain in the sunlit epilimnion (or metalimnion if enough sunlight is available). A spring bloom results from the excess sunlight and nutrients. The amount of algae depends on the amount of light and concentration of nutrients. Algae quickly assimilate the available nutrients in the epilimnion and the bloom of algae eventually declines to the summer standing crop due to the lack of new nutrients to support larger populations and increased predation pressures by herbaceous zooplankton.

During the summer, epilimnetic recycling of nutrients is intense. As individual plankton die and/or excrete organic wastes, bacteria decompose the organic matter and release nutrients back into the water column. These recycled nutrients are quickly assimilated by new algae. Some of the biomass however, sinks below the epilimnion before bacterial decomposition, and therefore some nutrients are released to the hypolimnion, where it is too dark for photosynthesis. Thus, nutrients are slowly transferred from the sunlit and algal-rich epilimnion to the dark hypolimnion through the stratified summer season.

Two mechanisms can increase algal populations during the stratified season, (1) increase the supply of nutrients ("bottom up" ecosystem mechanisms) as described above, and/or (2) decrease herbaceous pressures by zooplankton ("top down" ecosystem pressures). For example, "top down" pressures result from exotic carnivorous zooplankton grazing on herbaceous zooplankton (e.g., Brown & Balk, 2008). When herbaceous zooplankton populations decline, algal populations bloom without the predation pressures. The "bottom-up", nutrient stimulation, pressures are most relevant to this study because the hypolimnion of Cayuga Lake is significantly more enriched with nutrients than any other Finger Lake. Thus, any mechanism to transport nutrient rich bottom water to the surface would stimulate faster algal growth and promote a larger mid-summer bloom in Cayuga Lake than any other Finger Lake.

A number of natural mechanisms transport nutrient-rich bottom water to the surface (Fig. 5). Autumnal cooling mixes nutrient-rich metalimnetic water into the epilimnion. Thus a fall bloom naturally occurs during the autumnal decay of the summer stratification. Surface currents flowing past an irregular shoreline and other bathymetric features may induce localized upwelling as well. Finally, strong wind events induce internal seiche activity, which upwells nutrient-rich bottom water to the surface. The process is simple. Strong, lake-parallel winds, due to a passing weather system, push and pile the epilimnion towards the downwind end of the lake. The thermocline tilts downward by a few 10s of meters from the upwind to downwind end. Once the winds stop, the epilimnion then sloshes back to the other end of the lake, tilting the thermocline downward towards the other end. The back and forth sloshing continues for a few more days, tilting the thermocline up and down like a seesaw along the long axis of the lake.

Nutrients are introduced to the epilimnion because turbulence along the thermocline mixes bottom water nutrients into the epilimnion, and the tilt in the thermocline can be severe enough to expose bottom waters at the lake's surface on the upwind side.

Cornell's Lake Source Cooling (LSC) is a human-induced mechanism to bring nutrient-rich bottom water to the surface (Fig. 5, www.utilities.cornell.edu). Bottom water is pumped from 75 m (250 ft) below the surface of the lake to a heat exchanger facility on the shore. This cold water absorbs the heat from the refrigerant used for air conditioning at Cornell and Ithaca High School. The warmer lake water is then released back to the surface of the lake.

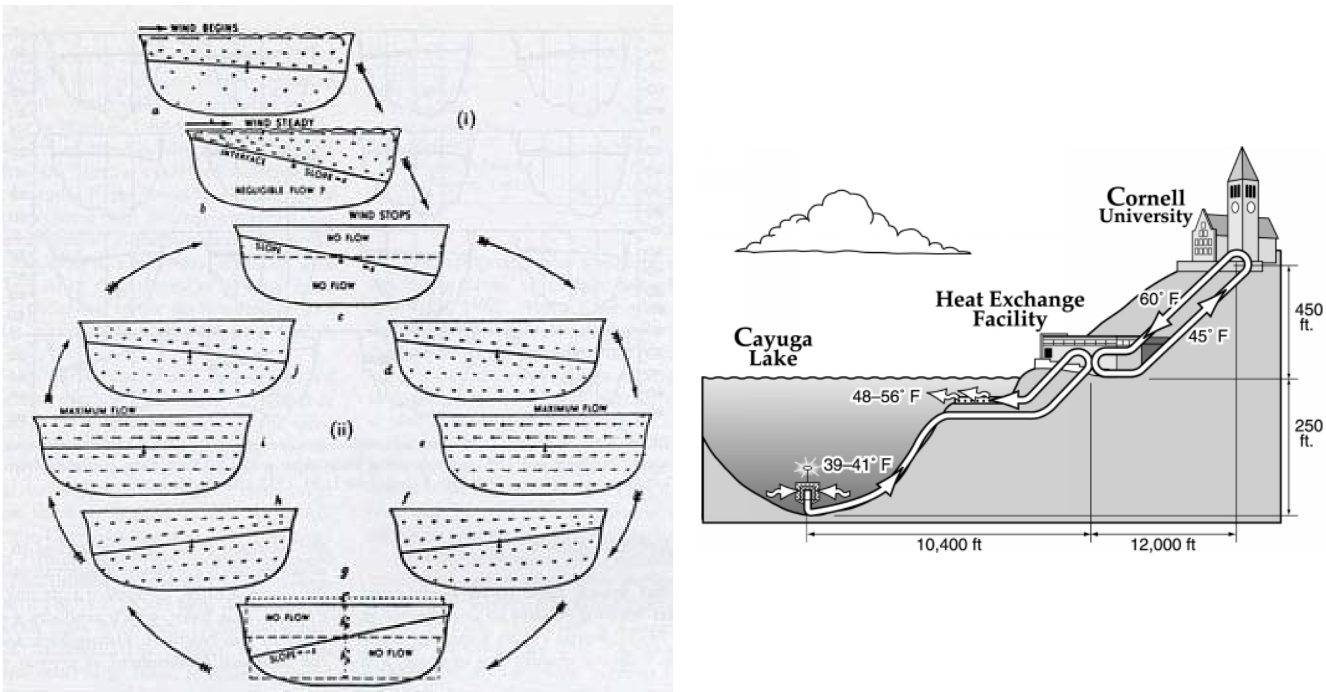


Fig. 5. *Seiche activity (left; Wetzel, 2001) and Cornell's Lake Source Cooling (right; www.utilities.cornell.edu/). Both mechanisms bring nutrient-rich bottom water to the epilimnion of the lake.*

Other significant nutrients sources exist in the Finger Lakes region. Agricultural land use activities, both plant and animal agriculture, dominate (46%) the rural landscape. Forested land (38%), lakes (9%) and urban areas are the other major land use practices. Water quality impairment of the Finger Lakes correlates to agricultural land use, in that the most impaired lakes contain the larger percentage of agricultural land in the watershed (Easton et al., 2007; Markarewicz et al., 2007; Evans, 2008; Sharpley et al., 2008; Halfman et al., 2008; Halfman & Franklin, 2008; Halfman & O'Neill, 2009). The treatment of human wastes from the rural and urban areas by on-site (individual septic) or urban municipal waste water treatment facilities can also add nutrients to lakes and streams (Halfman et al., 2008).

METHODS:

The 2007 and 2008 field seasons utilized nine sites within the southern end of Cayuga Lake (Fig. 6, Table 2). Sites 1 & 2 were used in the Finger Lake water quality survey. Site 1 sampled the bathymetric basin north of the AES Cayuga coal plant. Site 2 sampled the bathymetric basin offshore of Taughannock and Salmon Creeks. Sites A & C were located directly offshore of Taughannock and Salmon Creeks to assess potential fluvial inputs of suspended sediments to the lake. Four more sites, B, D, E, F & G, were located along a mid-lake transect from Site 2 southward to the shelf-break offshore of the southern end of the lake to assess concentration gradients along the axis of the lake. Site F, located at the shelf-break, was used on the first few sample dates in 2007 and subsequently replaced with the slightly deeper site G. Surveys were performed every two weeks starting in late May through the early part of the summer and less frequently later in the summer and into the fall. We also wanted to survey immediately after major precipitation and/or wind events in 2008, but major precipitation events were lacking in 2008.

Table 2. Site Locations

Site #	Latitude (ºN)	Longitude (ºW)	Water Depth (m)	Sample Depths
1	42.63195	76.67222	122	S, M & B
2	42.55417	76.59167	110	S, M & B
A	42.55000	76.59833	55	
B	42.53333	76.55500	88	S, M & B
C	42.53683	76.55383	50	
D	42.51667	76.53667	90	S, M & B
E	42.49167	76.52500	73	S, M & B
F	42.47500	76.51667	5	S
G	42.48333	76.55383	54	S, M & B

A secchi disk depth, plankton tows and a water-column CTD profile were collected at each site. Our SeaBird SBE-25 CTD was lowered from the surface to approximately two meters above the lake floor and collected water profiles of conductivity (specific conductance, μS/cm), temperature (ºC), pH, dissolved oxygen (ml/L), turbidity (WetLabs ECO-FLU, suspended sediment by backscattering NTUs), photosynthetic active radiation (Biospherical PAR, $\mu E/cm^2$-s) and fluorescence (WetLabs ECO-FLU, algal concentrations, mg/m^3, ~ppb). At each mid-lake site, surface (< 1 m depth), mid-depth (40 m above the lake floor), and bottom water (within 2 m of the lake floor) water samples were collected by Niskin bottles and analyzed onsite for pH, conductivity, temperature, dissolved oxygen and alkalinity, and back in the laboratory for total phosphate, soluble reactive phosphate, nitrate, dissolved silica, chlorophyll-a, and total suspended sediment (TSS) concentrations. This configuration positioned the mid-depth sample in the hypolimnion at Sites 1, 2, B, & D, but in the metalimnion for Site E and G.

The laboratory analyses followed standard limnological techniques (Wetzel and Likens, 2000). Total suspended solids (TSS) were determined by weight gain after filtration (0.45 μm filtration) of 3 to 4 liters of water and subsequent drying at 90º C overnight using pre-weighed glass-fiber filters. Another 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 90% acetone for 6 to 24 hours and analyzed at 750, 664, 647, 630, 510 and 480 nm using a 1-cm cell in a spectrophotometer. The filtrate was analyzed for soluble reactive (dissolved) phosphate (SRP), nitrate and dissolved silica by spectrophotometer. Samples were treated in an acidic molybdate reagent and analyzed using a 10-cm cell at 885 for phosphates and 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 detected using a 1-cm cell at 540 nm. A third unfiltered water sample was analyzed for total phosphates. The particulate organic matter was digested in potassium persulfate at 100ºC for 1 hour to release all particulate phosphates into solution, which was subsequently analyzed by the SRP procedure. Laboratory precision was determined annually by 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. The plankton and major ion analyses were performed but not elaborated on in this report.

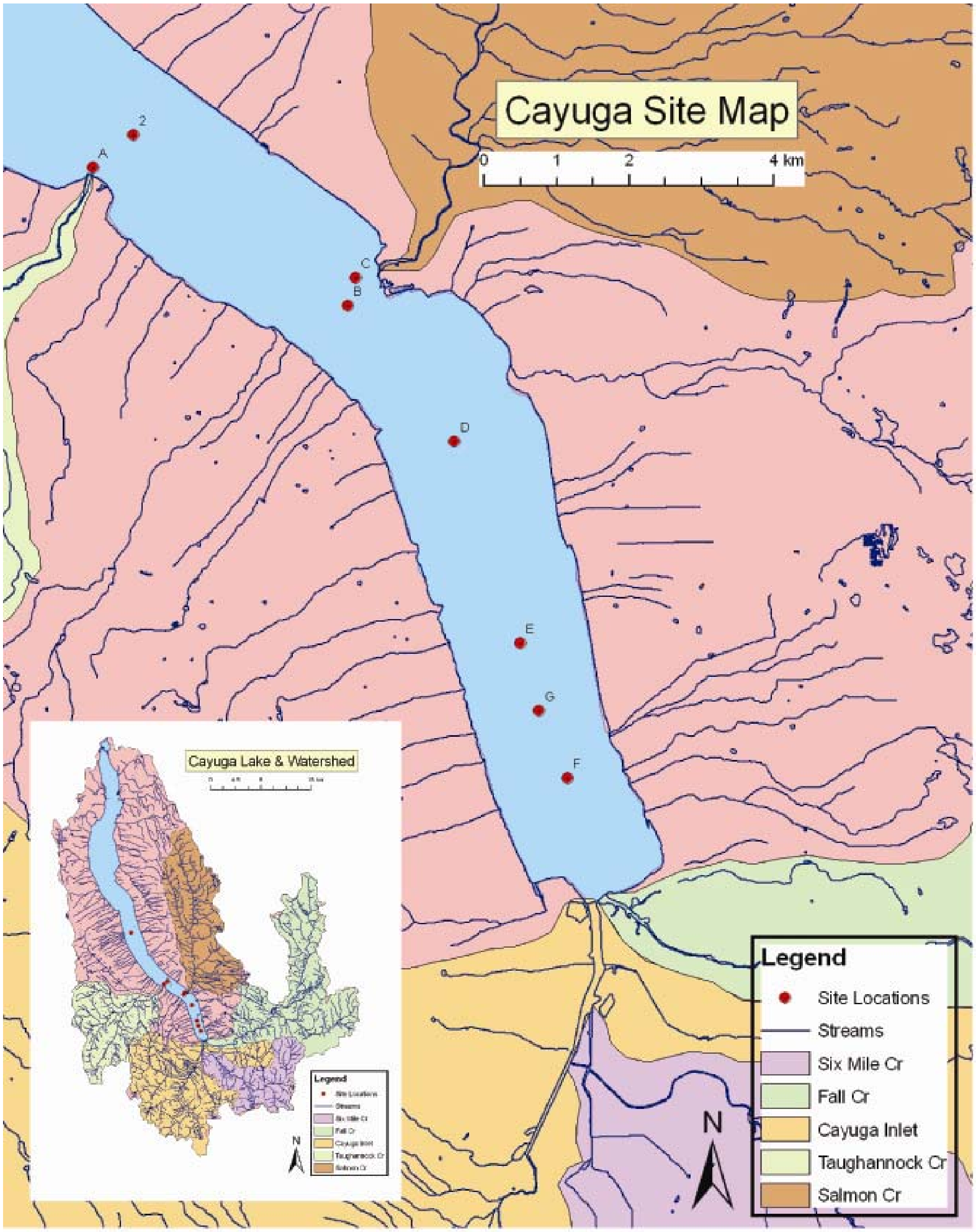


Fig. 6. *Sample sites for the survey. Site 1, the northernmost site, is only shown in the map insert, and is almost halfway to the northern end of the lake.*

During the course of the 2007 field season, over 100, randomly selected sample splits were analyzed by a commercial laboratory for total phosphate (TP), soluble reactive phosphate (SRP) and nitrate concentrations within a few weeks of sample collection for quality control. The results from both labs were statistically the same (r^2 = 0.84 for nitrate, 0.93 for SRP, and 0.76 for TP), and hampered by the time delay between sample collection and analysis, a few TP outliers, and more importantly the detection limits for each lab. The detection limits for the commercial laboratory were 0.2 mg/L for nitrate and 3 μm/L for phosphate, and thus unfortunately, the commercial laboratory could not detect over 70% of the SRP, 40% of the TP, and 15% of the nitrate sample splits. The commercial laboratory's unacceptable detection limit and analogous results between both labs convinced us to abandon commercial laboratory analysis of splits in 2008.

RESULTS:

CTD Profiles (Figs. 7 & 8): The water temperature profiles were typical for any relatively deep, temperate lake and were consistent between sites on any specific day. Surface water temperatures rose from ~10º C to ~ 25º C from late spring to the mid to late summer and subsequently cooled by the fall, and bottom water temperatures stayed very close to 4º C through out the survey. The thermocline typically developed at 15 to 20 meters. The thermocline depth varied from day to day, and was related to the onset or decay of thermal stratification and/or internal seiche activity.

Specific conductance in the epilimnion ranged from 400 to just over 425 μS/cm in 2007 and just under 400 to 425 μS/cm in 2008, and conductivities decreased through the summer season. Hypolimnion specific conductivities ranged from 430 to 440 μS/cm in 2007 and up to 450 μS/cm in 2008, and conductivities increased with water depth within 20 meters of the lake floor. The increase was progressively more pronounced through the stratified season at the deepest site (Site 1). The small surface water decrease in salinity is interpreted to reflect the input of slightly less saline river water into more saline lake water through the summer. The even smaller deepwater increase in salinity is interpreted to reflect the seepage of ions through the sediments from the underlying evaporite and carbonate bedrock and/or decomposition of organics by bacteria. Interestingly, the lake was slightly less saline in 2008 than 2007. A similar year-to-year freshening was also observed over the past few decades in Seneca Lake, and suggests that the inputs of salts have decreased over this time frame (Halfman & Franklin, 2008).

Algae, by fluorescence, were detected throughout the epilimnion and into the metalimnion. Algal concentrations ranged from near 0 to almost 8 μm/L (mg/m^3) in 2007 and up to 7 μm/L in 2008. The largest concentrations occurred during spring (5/22/07, 6/6/07), mid-summer (7/18/07, 7/19/08, 7/28/08), and late summer (8/26/08) blooms. The peak in algal density was typically 10 to 20 m below the lake surface. Algal concentrations typically declined to below 1 μm/L by 40 m. This depth range is concurrent with the photic zone. Specifically, PAR profiles revealed 1% surface light intensities (the lower limit for net algal production) at water depths of 15 to 25 meters, the specific depth on any given day reflecting the density of algae, suspended sediments, cloud cover, and lake surface roughness.

Dissolved oxygen (DO) and pH profiles were typical for an oligotrophic-mesotrophic lake. Epilimnetic DO concentrations remained near saturation, and were supersaturated during algal blooms. Hypolimnetic DO concentrations remained near saturation, 12 ml/L (> 16 mg/L), and declined slightly, by 3 ml/L (4 mg/L), within 20 to 30 m of the lake floor. Dissolved oxygen concentrations steadily decreased from saturated conditions 10 to 20 meters above the lake floor by 1 to 2 ml/L within 2 m of the lake floor. Profiles of pH revealed more basic water in the epilimnion (pH ~ 9) than the hypolimnion (pH ~8.2).

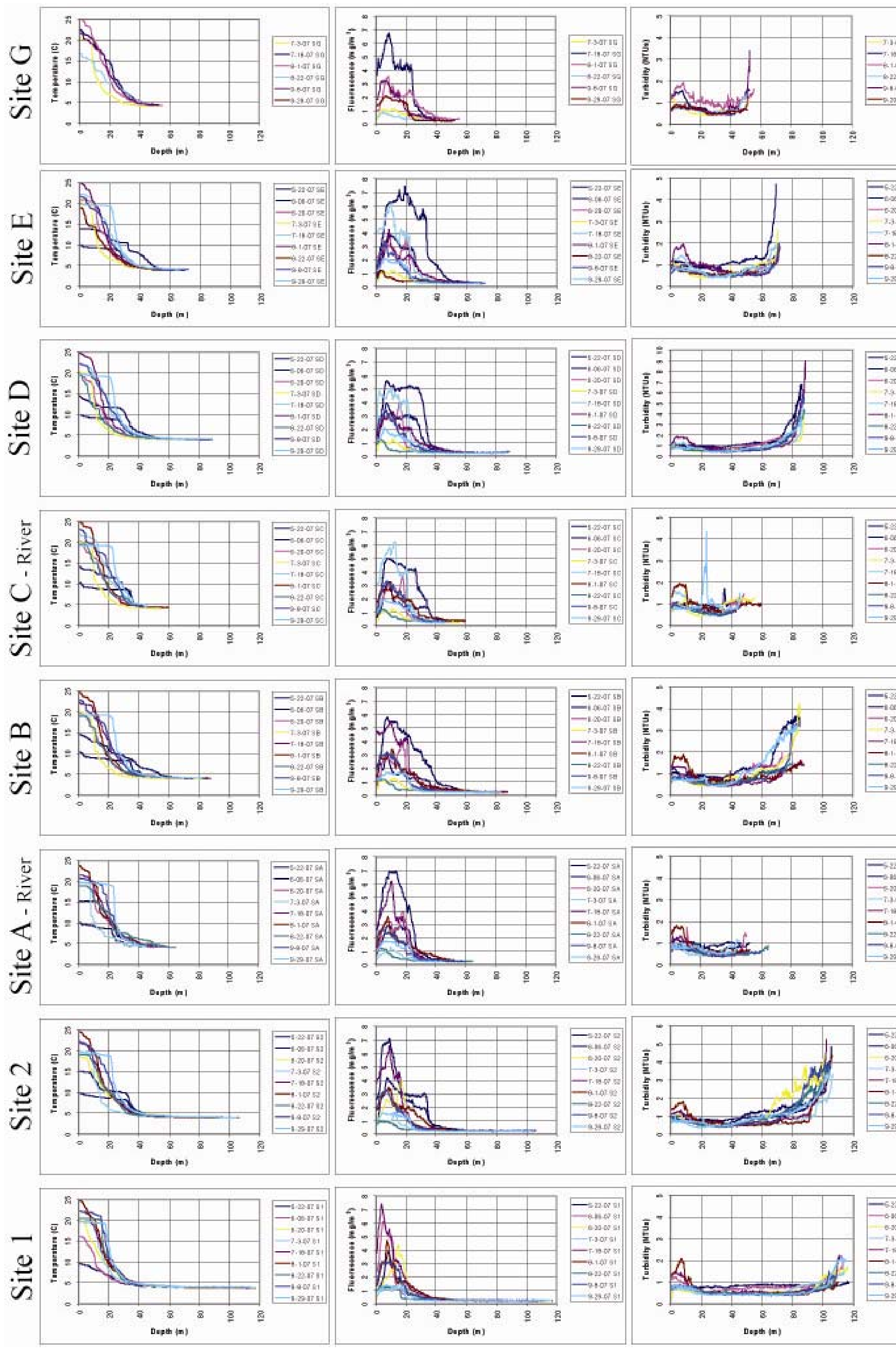


Fig. 7a. *2007 CTD temperature, fluorescence and turbidity profiles from each survey date and each site.*

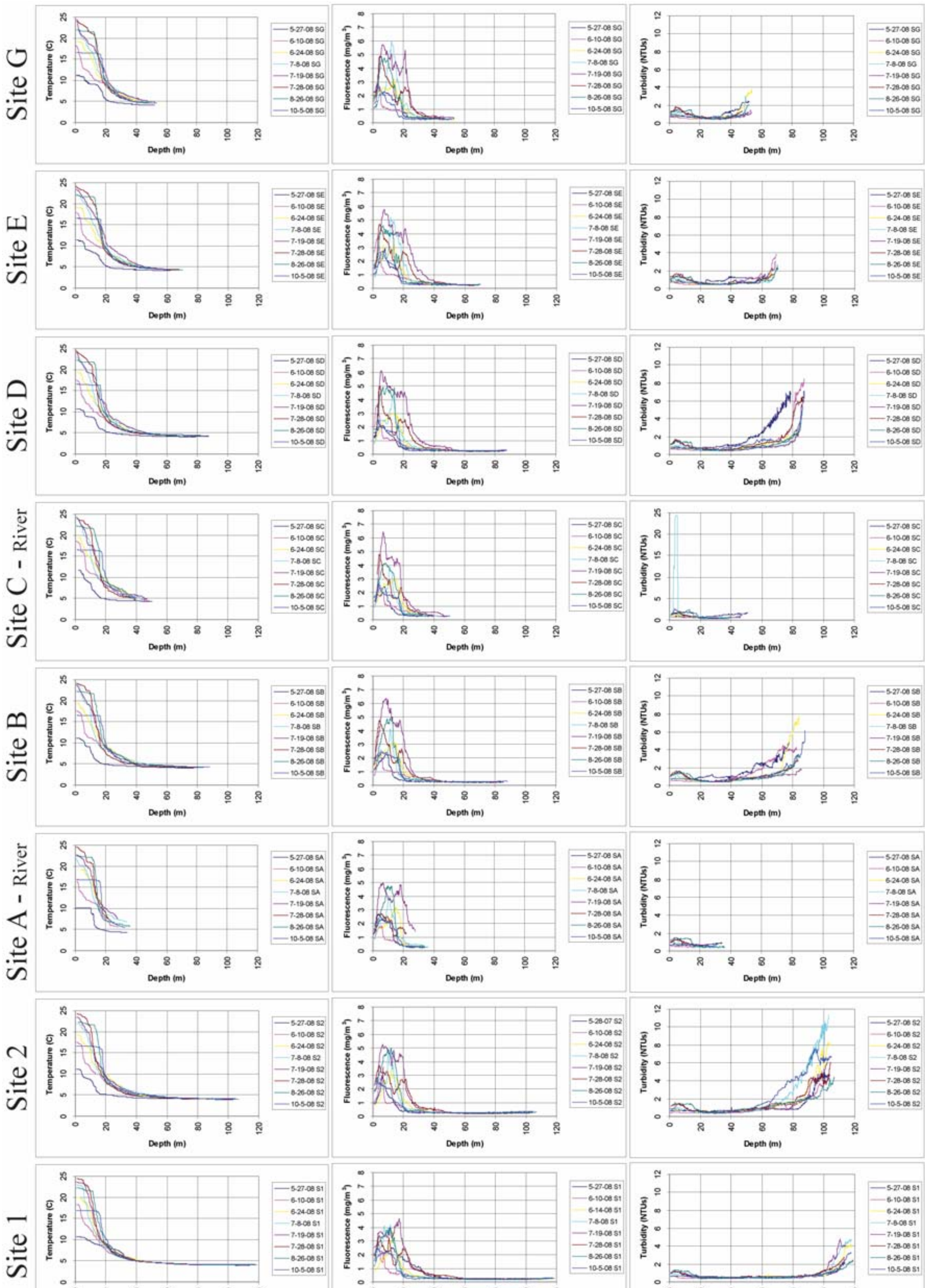


Fig. 7b. *2008 CTD temperature, fluorescence and turbidity profiles from each survey date and each site.*

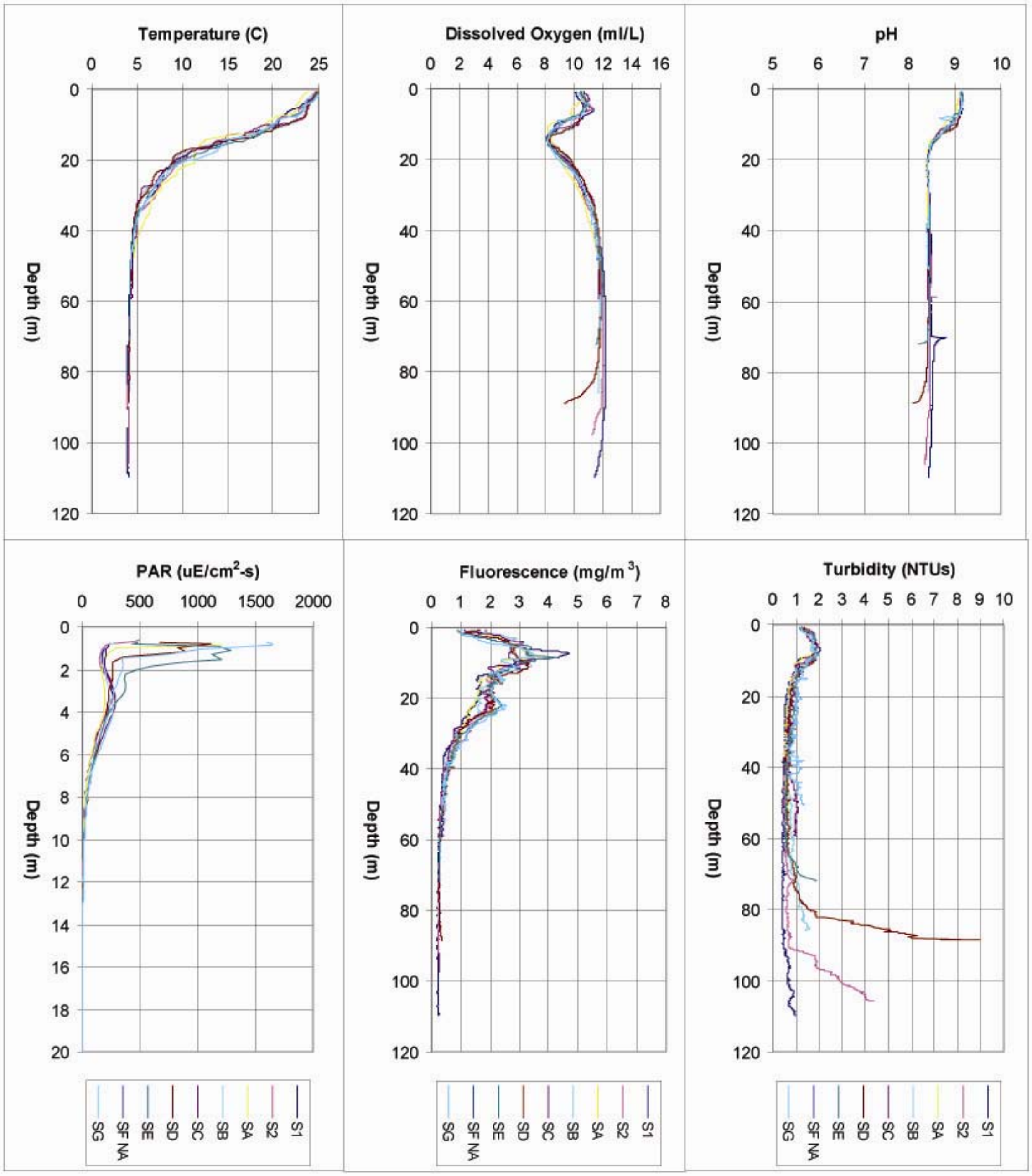


Fig. 8a. *CTD Profiles from each site on 8-1-07.*

Total suspended sediment concentrations ranged from near 0 to 9 NTUs in 2007 and 0 to almost 12 NTUs in 2008. Concentrations up to 2 NTUs were detected in the epilimnion. The surface water turbidity probably corresponds to the population of algae. The largest turbidities were detected just above the lake floor. The bottom water turbidity, when developed, depicted a classic nepheloid layer. Suspended sediment concentrations exponentially increased from background concentrations of just below 1 NTU about 20 m above the lake floor to the largest turbidities in the profile just above the lake floor. Sites 2, B and D revealed the best developed nepheloid layers in both years. On two sample dates, a turbid, thermocline-depth, plume was detected offshore of Salmon Creek on 9/29/07 and 7/8/08. The geometry suggests that turbid but warm stream water entered the lake from Salmon Creek and extended lakeward just above the colder but less turbid and presumably denser bottom waters.

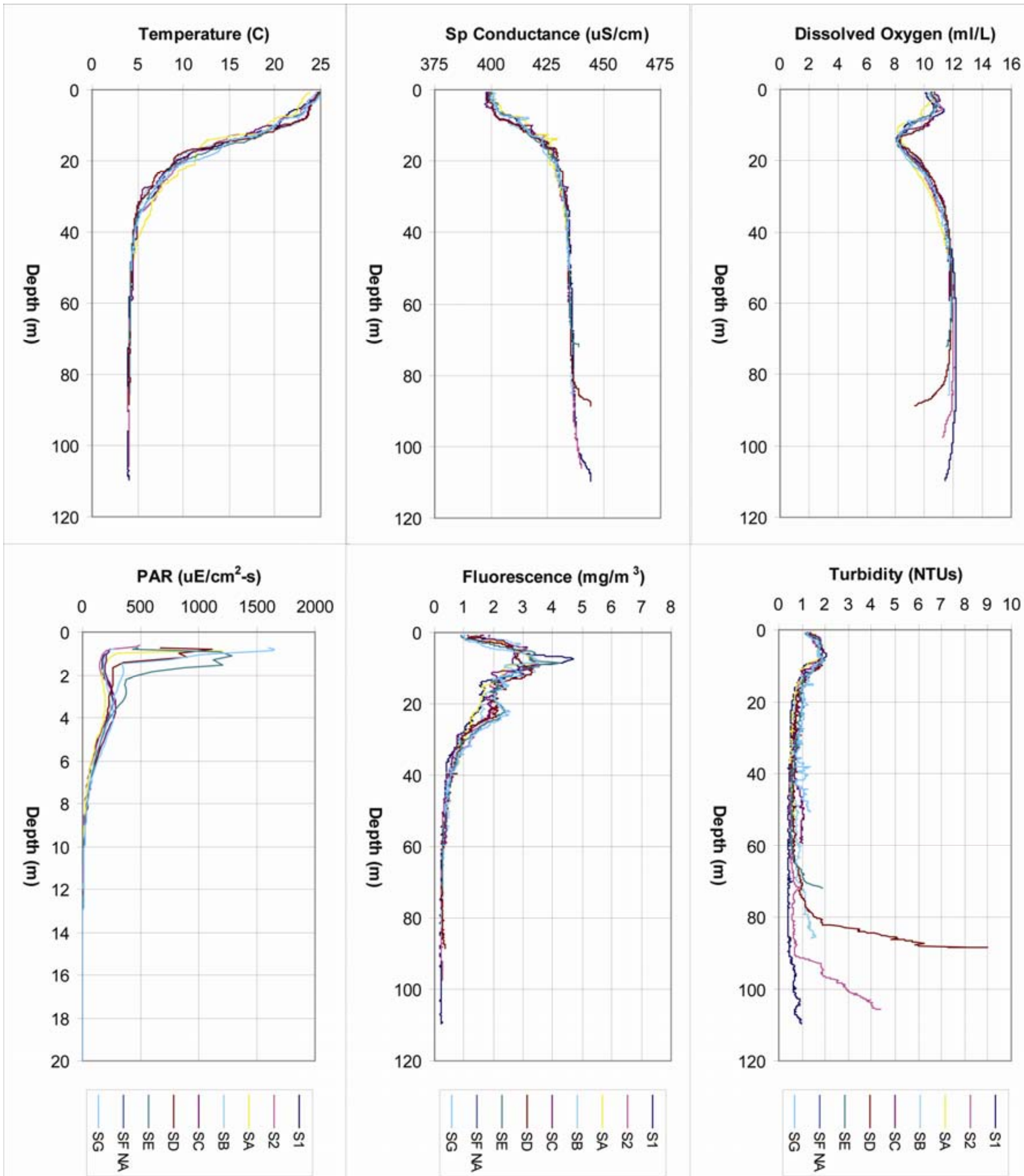


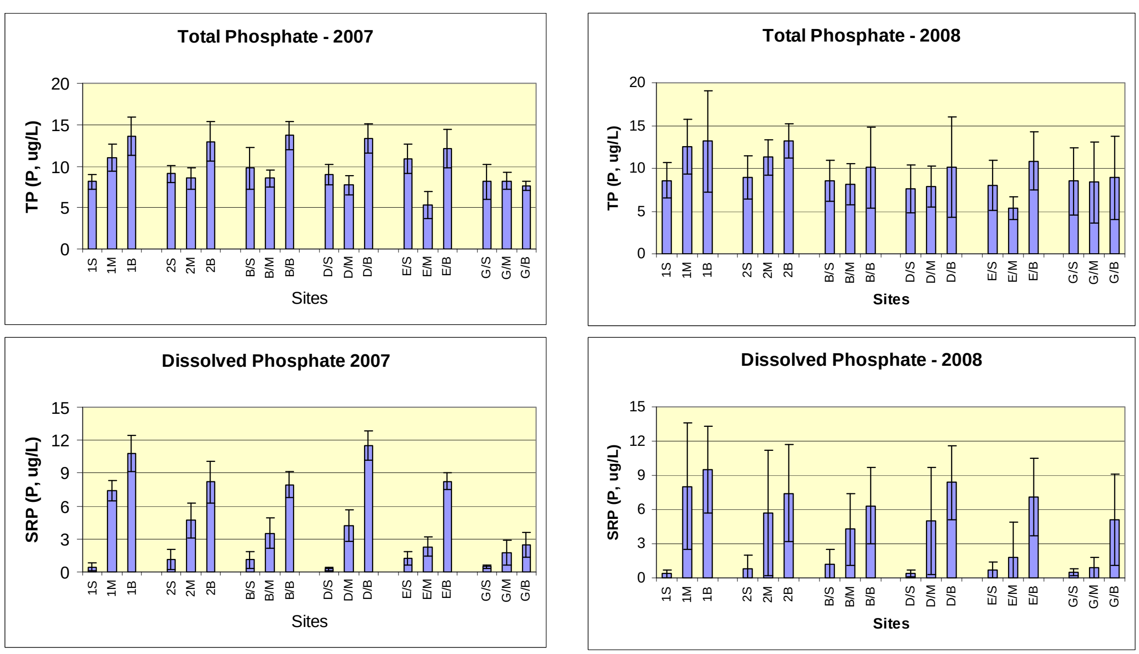
Fig. 8b. *CTD Profiles from each site on 7-28-08.*

Secchi Disk, Chlorophyll-a, Total Suspended Solids and Nutrient Concentrations (Fig. 9): Annual mean secchi disk depths were near 4 m, and were slightly deeper at the northernmost site, Site 1, and got shallower towards the southernmost site, Site G by a few tenths of a meter in both 2007 and 2008. Variability between sample dates at any site corresponds to changes in the algal density described above.

Chlorophyll-a data were larger in the epilimnion than the hypolimnion. Annual mean concentrations ranged from 2.6 to 4.0 μg/L in the surface vs. always below 1.1 and typically below 0.5 μg/L, in the hypolimnion in 2007 and 3.2 to 5.2 μg/L in the surface vs. always below 1.1 and typically below 0.5 μg/L, in the hypolimnion in 2008. The observed changes from day to day and between sites are consistent with the fluorescence results.

Annual mean total suspended solids concentrations ranged from 1.1 to 2.6 mg/L in 2007 and 1.4 to 4.2 mg/L in 2008. The surface mean TSS concentrations were similar across the lake from 1.6 to 1.7 mg/L, except for smaller concentrations at Site G in both years. The largest TSS concentrations were detected in the bottom water at Sites 2, B and D in both years, 2008 slightly exceeding 2007 concentrations. One exceptionally large result of 15.9 mg/L from Site B on 7/3/07 was excluded from the site average due to the possible collection of CTD disturbed sediments in the sample. Decaying leaf matter and other sediments were collected in this bottom water sample. In contrast, the bottom water TSS concentrations at other sites (1, A, C, E, F & G) were less turbid than the surface water in both years, except for Site 1 in 2008.

Mean nutrient concentrations were typically smaller in the epilimnion than the hypolimnion, except at Sites E and G. Mean nitrate concentrations ranged from 0.8 to 1.0 mg/L in the epilimnion to 1.1 to 1.3 mg/L in the hypolimnion in both years. Mean dissolved silica concentrations ranged from 289 to 410 μg/L in the epilimnion to 936 to 1011 μg/L in the hypolimnion. Mean total phosphate concentrations ranged from 5.3 to over 13 μg/L in both years. Largest concentrations were in the bottom water samples, and decreased to approximately 5 to 10 μg/L in the surface and mid-depth samples in both years. The exceptions were the mid-depth sample at Site E which revealed lower total phosphates than other depths, and all three depths at Site G, which were nearly identical to each other. These exceptions are probably the result of the shallower depths at these sites, where the mid-depth samples actually sampled the metalimnion rather than sampling the dark upper hypolimnion as the other sites. Mean soluble reactive phosphate concentrations ranged from ~0.3 to over 11 μg/L in both years. Largest concentrations were in the bottom water samples, and decreased by approximately 50% at the mid-depth sample and decreased again to less than 1.2 μg/L at the surface.



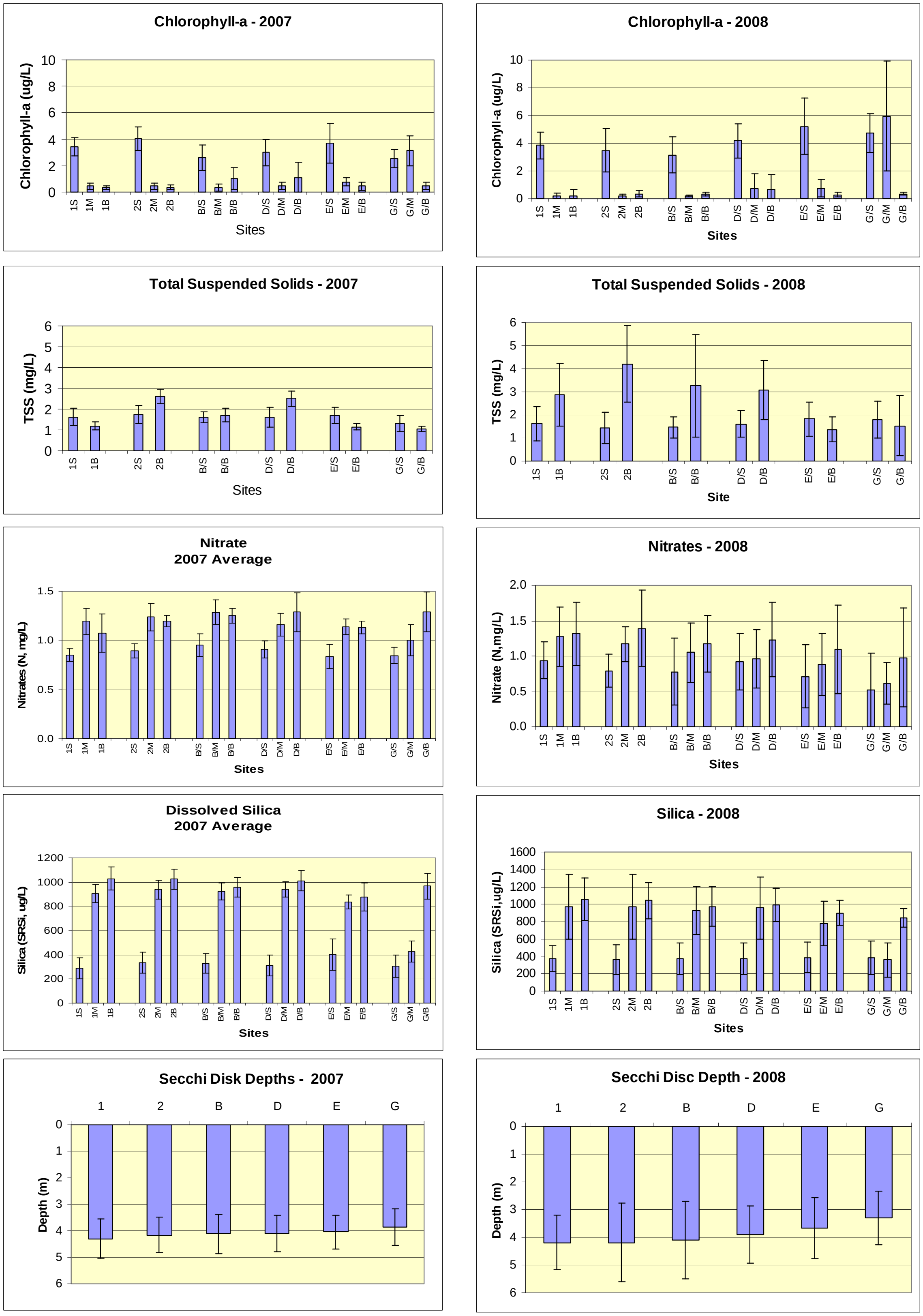


Fig. 9. *Site/Depth averaged annual water quality data (± 1σ standard deviation). Left: 2007 – Right: 2008.*

DISCUSSION

The observed secchi disk depths, dissolved oxygen, nutrient and chlorophyll-a concentrations indicate that Cayuga Lake is a borderline oligotrophic- mesotrophic lake. The shallower secchi disk depths and larger surface water chlorophyll-a and suspended sediment concentrations from Site 2 offshore of Taughannack Creek to the southern end of the lake, indicates a parallel decrease in water quality along this transect. The vertical changes in nutrient and chlorophyll-a concentrations with water depth are typical for a moderately productive temperate lake, and are interpreted to reflect the net algal growth and uptake of soluble nutrients during photosynthesis in the epilimnion and net bacterial release of soluble nutrients during decomposition of algae in the hypolimnion. These trends are similar to those reported by other studies (Upstate Freshwater Institute, 2000-2007; Callinan, 2001; Cayuga Lake Watershed Restoration and Protection Plan, 2001).

However, the vertical concentration differences are more pronounced in Cayuga Lake than the other large Finger Lakes (Halfman and O'Neill, 2009). In addition, CTD profiles from Cayuga Lake and bottom water total suspended sediment concentrations reveal the best developed and most turbid nepheloid layers among the sampled Finger Lakes. In our preliminary report, we hypothesized a common source for bottom water suspended sediments and nutrients, in particular the limiting nutrient phosphate (Halfman et al., 2008). Here, we expand on this hypothesis and develop a more complete scenario for suspended sediments and phosphates in Cayuga Lake, and highlights recommendations to more fully understand water quality concerns in the southern end of Cayuga Lake.

Bottom Water Suspended Sediments: Nepheloid layers can originate from three sources: fluvial events, resuspension events, and/or settling of algal remains. The available evidence supports each source, and will be briefly discussed below.

A fluvial source for the nepheloid layer is supported by the following observations. A thermocline-depth turbid plume was detected offshore of Salmon Creek (9/27/09 & 7/8/08) when it rained a day or two before a sample date. Subsequent particle settling to the lake floor could promote the development of the observed nepheloid layers. We believe additional plumes were not detected in 2007 and again in 2008 because both years were dry years, with 2007 rainfall totals 65% lower and 2008 totals 43% lower than totals in 2006 during the May-September field season (Ithaca Airport data). Similar decreases in rainfall were observed at Geneva, NY (Cornell's Agricultural Field Station data).

The nepheloid layer was best developed at Sites 2, B and D located in the southernmost bathymetric basin of the lake. Salmon, Taughannock, Fall, and Virgil Creeks, and the Cayuga Inlet all empty into the lake at or south of this basin. Turbid stream water would naturally flow downhill to the closest deep basin in the lake. Terrestrial organics (twigs and leaves) were detected in a bottom water sample at Site B, when the CTD accidently hit the lake floor. Research at Owasco Lake during the past two years indicated that the Owasco Inlet was a critical source of suspended sediments and phosphates to the lake in 2006, a wet year, but not in 2007, a dry year (Halfman et al., 2008). Flood events impaired lake water quality at the southern end of the lake in 2006 with mean annual total suspended sediment concentrations of 1.9 to 4.2 mg/L compared to 1.8 mg/L in 2007, and mean annual phosphate concentrations of 75 to 500 μg/L compared to 10 μg/L in 2007 at the southern end of the lake. Other studies investigating the impact of storm events on sediment yield provide consistent results (e.g., Nagle et al., 2007).

Finally, Cayuga Lake water quality reports, aerial photographs and lakeshore residents concurred that spring meltwaters and other significant runoff events generate offshore turbid plumes (Fig. 10). We believe that the nepheloid layer reflects this initial spring input, and then waxes and wanes through the remainder of the year as fluvial, resuspension and algal sources add and particle settling removes nepheloid sediments over time.

Fig.10. *Turbid plumes offshore of Taughannock Creek, left, and offshore the south end, right. Photos by Bill Hecht.*

Resuspension events due to wave action from strong northwesterly winds are important as well. The largest nepheloid turbidities were detected and coincided with sample dates just after major wind events. For example, the largest turbidities at Site 2 were detected on 5/27, 6/24 & 7/8, and strong winds occurred on 5/24, 6/22, 7/7 a day or two before the sample date. Calmer winds prevailed the few days just before other sample dates. Resuspension events influenced water clarity on the southern shelf (Upstate Freshwater Institute, 2008).

A minimal nepheloid layer in the northern basin, Site 1, a site far removed from the fluvial and resuspended events at the southern end of the lake, suggests that algal remains are less critical than fluvial and resuspension sources but still contribute to the development of the nepheloid layers in Cayuga Lake.

Bottom Water Phosphates: The delivery of suspended sediments would also bring organically bound and attached phosphates to the hypolimnion (e.g., Johnson et al., 1976; Pionke et al., 1999; Halfman et al., 2008). Estimates of annual phosphate loads to the lakes in the late 1990s confirm this hypothesis. Fall Creek and Cayuga Inlet provided ~ 10 metric tons of P / year (~60 lbs P/day, Cayuga Lake Watershed Restoration and Protection Plan, 2001). Taughannock and Salmon Creeks must be important contributors as well but were excluded from the study. Community Science Institute reported that phosphate and suspended sediment concentrations were larger, at times up to 5 times larger, at Taughannack and Salmon Creeks than the other major creeks entering the southern end of the lake in a March, 2008 event (Community Science Institute Report, 2008). Unfortunately, estimates of the phosphate flux to the lake floor by burial were not calculated as well.

The phosphates however probably do not remain attached to the particles and every particle does not have bound phosphates. A comparison of bottom water total phosphate and soluble reactive phosphates with total suspended sediment concentrations revealed no correlation ($r^2 = 0.05$ and 0.01, respectively). In addition, the high phosphate concentrations were not limited to the southern basin but were instead detected throughout the hypolimnion. We surmise that the transported organics are decomposed by bacterial respiration in the nepheloid layers, and soluble reactive phosphate is released to the hypolimnion. Subsequent lake-wide mixing during fall and spring overturn and internal seiche activity, distributes the phosphates uniformly throughout the lake, only to decline in the epilimnion and increase in the lower hypolimnion during summer stratification due to preferential epilimnetic algal uptake and hypolimnetic bacterial release. The multi-step process and eventual mixing dictates that these sediment-attached phosphates are not immediately available for algal growth, but are eventually available to stimulate algal growth.

Other sources of phosphates exist and include the Ithaca and Cayuga wastewater treatment facilities, Cornell's Lake Source Cooling project and geese (Kitchell et al., 1999; Cayuga Watershed Restoration & Protection, 2001). The wastewater and LSC phosphates are typically inorganic, soluble reactive forms, more readily available to stimulate algal growth. Wastewater treatment facilities dumped ~ 9 metric tons P/year (~50 lbs/day) and Cornell's Lake Source Cooling project added < 1 metric ton P/year (~2.3 lbs P/day) to the epilimnion of the lake. Our phosphate concentration data combined with Cornell's Lake Source Project water flow rates substantiate the LSC flux. Since these published estimates, a major tertiary treatment upgrade was installed at Ithaca's wastewater treatment facility reducing its loading from ~ 5 metric tons P/year (~34 lbs/day) to ~ 1.5 metric tons P/year (~ 10 lbs/day). A similar upgrade and phosphate reduction is slated for Cayuga wastewater treatment facility. The loading by geese is unknown.

All of these quantifiable sources at the southern end add approximately ~ 15 tons of P/year (~85 lbs/day) to the lake. This flux underestimates the total loading to the hypolimnion because the resuspension flux is unknown, and it ignores additional phosphorus loading at the north end of the lake. Yet even this underestimated flux is significant when compared to the 100 metric tons of phosphorus in the lake, assuming a lake volume of 9.4 km^3 and mean total phosphate concentration of 10 μg/L. A "back of the envelope" residence time for phosphorus is approximately 6 to 7 years (it will decrease as additional influxes are quantified), and is consistent with two observations. Loading at the southern end of the lake impacts water quality as observed in the north to south impairment trend. It also dictates that when these loadings are greatly reduced, a few decades are required to significantly reduce and naturally flush out phosphates in this lake. Future research must quantify all of these loadings and pinpoint sources in the watershed to clean up the lake. Focus on fluvial fluxes because they are the most significant input of phosphates to the lake.

The southern end of Owasco Lake is also impaired by the Owasco Inlet (Halfman et al., 2008). A two year study in 2006 and 2007 determined that various factors, most importantly, runoff events and municipal wastewater effluent, influenced the total suspended sediment and total phosphate fluxes from the Owasco Inlet to the southern end of the lake. Stream segment analysis pinpointed the Groton wastewater treatment facility as a major source of soluble phosphates to the Inlet. The plant added approximately 2 kg of P/day during 2006 but only 1.4 kg/day in 2007. The reduction was due to the addition of a pilot tertiary treatment facility to remove phosphates from the effluent. Runoff over agriculturally-rich landscapes and stream bank erosion added additional sediments and phosphates to the lake, especially during peak flow, i.e., major runoff events. The Owasco Inlet provided 3 to 6 kg of P/day, and the next largest stream, Dutch Hollow Creek, provided 0.5 to 4 kg of P/day, based primarily on base-flow data. The high flux was from 2006 and lower flux from 2007. The reduction reflected lower runoff in a drier 2007. Water quality at the southern end of the lake greatly improved from 2006 to 2007 as well. In

Owasco Lake's favor is a water residence time of a year or two, which enabled water quality to improve quickly once the supply of phosphates and suspended sediments were turned off in 2007. The observed improvement created incentive to remove the sources of suspended sediments and phosphates in the future. Unfortunately, the decade$^+$ water residence time for Cayuga Lake implies a much longer cleanup times than Owasco Lake, once the sources of phosphates and suspended sediments are curtailed in the southern watershed.

CONCLUSIONS:

The results of the 2007 and 2008 fieldwork indicate that southern Cayuga Lake is borderline oligotrophic-mesotrophic. Suspended sediments and phosphates (SRP) are more concentrated in the hypolimnion of Cayuga Lake compared to neighboring Finger Lakes and CTD casts revealed a classic nepheloid layer in the southern basin of Cayuga Lake. Suspended sediment sources for the nepheloid layers are primarily fluvial and resuspension events, with smaller amounts of algae. However, calculating exact percentages was hampered by low rainfalls in both years. These sediment sources can also contribute attached organically-bound phosphorus to the hypolimnion of the lake. Subsequent bacterial decomposition releases the organically bound-P as soluble reactive phosphate. Smaller sources of phosphates include wastewater treatment facilities, Lake Source Cooling and geese. A decade$^+$ water residence time for Cayuga Lake implies that a substantial wait is required to observe a cleaner lake once the nutrient loading is significantly curtailed.

FUTURE RECOMMENDATIONS:

Lake Surveys in Wet Years to Detect Fluvial Contributions: This project focused on the source of the elevated suspended sediment and phosphate concentrations in the hypolimnion of Cayuga Lake. The two years of data delineate fluvial, resuspension and other sources. However, the study spanned two dry years. We recommend continuing this southern-end lake survey into the future to catch fluvial fluxes in the act during wetter years, and substantiate our findings.

Nutrient Loading from Streams: The streams draining into the southern end of the lake are the primary sources of suspended sediments and phosphates to the lake. Sediment and nutrient flux data must be carefully measured to confirm earlier estimates and pinpoint the actual sources. Knowledge of the specific sources enables future remediation efforts to reduce or eliminate these sources and eventually clean the lake. We recommend continuing the existing citizen based network and local commercial laboratories to collect and analyze stream samples for suspended sediment and nutrient concentrations. Most importantly, we also recommend simultaneous determination of stream discharge to calculate the fluxes (loadings) of these materials from the major streams entering the southern end of the lake to evaluate their sources and budgets for the southern end of the lake. Enough sites must be sampled along each stream to isolate the primary point and non-point sources of these materials. Samples must also be collected through out the year to assess spring melt, storm event, base flow, and other loads.

Ecological Impacts and Outcomes: A direct consequence of excessive nutrient loading is the growth and proliferation of macrophytes, nearshore rooted aquatic vegetation like the exotic Eurasian milfoil (e.g., Gilman et al., 2008). Algal blooms can also be the consequence of "top down" ecological pressures (e.g., Brown & Balk, 2008). For example, various forms of exotic carnivorous zooplankton graze on herbaceous zooplankton. When herbaceous zooplankton populations decline, algal populations bloom without the predation pressures. We recommend that these ecological impacts/outcomes be investigated at the southern end of the lake.

Historical Record of Water Quality: Historical data suggests that water quality has degraded at the southern end of the lake. The same data suggest that water quality, measured by secchi disk depths, nutrient and chlorophyll-a concentrations, has perhaps improved in the past few decades. We recommend collecting a suite of short, well-dated (Pb-210 and Cs-137), sediment cores from the southern basin to substantiate the historical record of water quality over the past 50 to 100 years. The best cores will be analyzed for organic, carbonate, and phosphate concentrations, and other indicators of water quality like $\delta^{18}O$ and $\delta^{13}C$ stable isotope ratios and C/N elemental ratios of organic matter. The data also provide critical nutrient and sediment fluxes to the lake floor to establish a more robust nutrient and sediment budget for the lake.

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Appendix: Annual Average Data.

Annual Means - Water Quality Data (± 1σ)	Site 1			Site 2			Site B		
	Surface	Mid-Depth	Bottom	Surface	Mid-Depth	Bottom	Surface	Mid-Depth	Bottom
Total Suspended Sediments (mg/L or ppm)	1S	1M	1B	2S	2M	2B	B/S	B/M	B/B
2007	1.6 ± 0.4		1.2 ± 0.2	1.7 ± 0.4		2.6 ± 0.4	1.6 ± 0.3		1.7 ± 0.3
2008	1.6 ± 0.7		2.9 ± 1.4	1.4 ± 0.7		4.2 ± 1.7	1.5 ± 0.5		3.3 ± 2.2
Total Phosphate (μg/L or ppb, P)									
2007	8.1 ± 0.9	11.0 ± 1.6	13.6 ± 2.3	9.1 ± 1.1	8.5 ± 1.3	13.0 ± 2.4	9.8 ± 2.5	8.5 ± 1.1	13.7 ± 1.7
2008	8.6 ± 2.1	12.5 ± 3.2	13.2 ± 5.9	9.0 ± 2.6	11.3 ± 2.1	13.2 ± 2.0	8.5 ± 2.5	8.2 ± 2.4	10.1 ± 4.8
Soluble Reactive Phosphate (μg/L, P)									
2007	0.4 ± 0.4	7.4 ± 0.9	10.8 ± 1.6	1.2 ± 0.9	4.7 ± 1.6	8.2 ± 1.9	1.1 ± 0.8	3.5 ± 1.3	7.9 ± 1.2
2008	0.4 ± 0.4	8.0 ± 5.5	9.5 ± 3.8	0.8 ± 1.2	5.7 ± 5.5	7.4 ± 4.2	1.2 ± 1.3	4.3 ± 3.2	6.3 ± 3.3
Nitrate (mg/L, N)									
2007	0.9 ± 0.1	1.2 ± 0.1	1.1 ± 0.2	0.9 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.0 ± 0.1	1.3 ± 0.1	1.3 ± 0.1
2008	0.9 ± 0.3	1.3 ± 0.4	1.3 ± 0.4	0.8 ± 0.2	1.2 ± 0.2	1.4 ± 0.5	0.8 ± 0.5	1.0 ± 0.4	1.2 ± 0.4
Dissolved Silica (μg/L, Si)									
2007	289 ± 86	907 ± 75	1028 ± 95	333 ± 87	938 ± 77	1025 ± 83	327 ± 80	923 ± 70	956 ± 81
2008	373 ± 153	968 ± 370	1055 ± 244	364 ± 173	972 ± 370	1042 ± 211	370 ± 180	928 ± 280	974 ± 229
Chlorophyll-a (μg/L)									
2007	3.4 ± 0.7	0.5 ± 0.3	0.3 ± 0.2	4.0 ± 0.9	0.5 ± 0.2	0.4 ± 0.2	2.6 ± 1.0	0.4 ± 0.3	1.0 ± 0.8
2008	3.8 ± 1.0	0.2 ± 0.2	0.2 ± 0.5	3.5 ± 1.6	0.2 ± 0.2	0.4 ± 0.3	3.2 ± 1.3	0.2 ± 0.1	0.3 ± 0.1
Secchi Disk Depth (m)									
2007	4.3 ± 0.7			4.2 ± 0.7			4.1 ± 0.7		
2008	4.2 ± 1.0			4.2 ± 1.4			4.1 ± 1.4		

	Site D			Site E			Site G		
	Surface	Mid-Depth	Bottom	Surface	Mid-Depth	Bottom	Surface	Mid-Depth	Bottom
Total Suspended Sediments (mg/L or ppm)	D/S	D/M	D/B	E/S	E/M	E/B	G/S	G/M	G/B
2007	1.6 ± 0.5		2.5 ± 0.4	1.7 ± 0.4		1.2 ± 0.2	1.3 ± 0.4		1.1 ± 0.1
2008	1.6 ± 0.6		3.1 ± 1.3	1.8 ± 0.7		1.4 ± 0.6	1.8 ± 0.8		1.5 ± 1.3
Total Phosphate (μg/L or ppb, P)									
2007	9.0 ± 1.2	7.7 ± 1.2	13.3 ± 1.8	10.9 ± 1.8	5.3 ± 1.6	12.1 ± 2.4	8.1 ± 2.1	8.2 ± 1.0	7.6 ± 0.5
2008	7.6 ± 2.8	7.9 ± 2.4	10.2 ± 5.9	8.0 ± 3.0	5.3 ± 1.3	10.8 ± 3.4	8.5 ± 3.9	8.3 ± 4.8	8.9 ± 4.9
Soluble Reactive Phosphate (μg/L, P)									
2007	0.3 ± 0.2	4.2 ± 1.4	11.5 ± 1.3	1.2 ± 0.6	2.3 ± 0.9	8.3 ± 0.8	0.5 ± 0.2	1.7 ± 1.1	2.5 ± 1.1
2008	0.4 ± 0.3	5.0 ± 4.7	8.4 ± 3.3	0.7 ± 0.7	1.8 ± 3.1	7.1 ± 3.4	0.5 ± 0.3	0.9 ± 1.0	5.1 ± 4.0
Nitrate (mg/L, N)									
2007	0.9 ± 0.1	1.2 ± 0.1	1.3 ± 0.2	0.8 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	0.8 ± 0.1	1.0 ± 0.2	1.3 ± 0.2
2008	0.9 ± 0.4	1.0 ± 0.4	1.2 ± 0.5	0.7 ± 0.4	0.9 ± 0.4	1.1 ± 0.6	0.5 ± 0.5	0.6 ± 0.3	1.0 ± 0.7
Dissolved Silica (μg/L, Si)									
2007	312 ± 87	940 ± 63	1012 ± 83	401 ± 128	837 ± 55	875 ± 115	304 ± 92	428 ± 88	968 ± 105
2008	373 ± 179	959 ± 357	993 ± 195	388 ± 176	781 ± 257	901 ± 139	389 ± 192	359 ± 198	843 ± 109
Chlorophyll-a (μg/L)									
2007	3.0 ± 1.0	0.5 ± 0.3	1.1 ± 1.2	3.7 ± 1.5	0.8 ± 0.3	0.5 ± 0.3	2.5 ± 0.7	3.1 ± 1.1	0.5 ± 0.3
2008	4.2 ± 1.2	0.7 ± 1.1	0.7 ± 1.1	5.2 ± 2.0	0.8 ± 0.6	0.3 ± 0.1	4.7 ± 1.4	5.9 ± 4.0	0.3 ± 0.1
Secchi Disk Depth (m)									
2007	4.1 ± 0.7			4.0 ± 0.6			3.9 ± 0.7		
2008	3.9 ± 1.0			3.7 ± 1.1			3.3 ± 1.0		

Please Note:
Only CTD Casts were collected at Sites: A & C
Site F was replaced with G after the initial few dates