# WATER QUALITY OF SENECA LAKE, NEW YORK: A 2007 UPDATE.

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## INTRODUCTION

Seneca Lake provides Class AA drinking water to ~80,000 people in the region with total permitted withdrawals of ~9 million gallons of water per day. The lake is also essential for the economic and social structure of the region by injecting ~$100 million per year into the local economy through tourism and recreation alone, and influencing a tax base of over $1 billion. Seneca Lake has over 50% of the water contained in all eleven Finger Lakes with a volume of 15.5 $km^3$ and depth of 186 m (Bloomfield, 1978; Mullins et al., 1996). Its watershed covers 1,586 $km^2$ (including Keuka watershed because Keuka flows into Seneca) and spans portions of Ontario, Seneca, Yates, Schuyler, Stueben (Keuka watershed) and Chemung counties. The lake surface area is 172 $km^2$. Seneca's surface and watershed areas are slightly smaller than those at Cayuga Lake. Its residence time is 18.6 years, the longest of the Finger Lakes (Wing et al., 1995; Callinan, 2001). This suggests that the lake responds slowly to pollutant threats and also remediation and other protection efforts. The complete response typically takes 5 to 10 residence times for conservative (nonreactive) materials. Thus, Seneca Lake is a critical resource for the region and should be protected now if water quality threats exist, because once stressed or perturbed, it will take a generation or more to restore the lake back to its less stressed state.

A 2005 water quality survey, conducted 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. 1., Halfman and Bush, 2006). The ranking was based on monthly surface and bottom 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 ranking indicated that Seneca, Owasco, and Honeoye Lakes had the worst water quality, whereas Skaneateles, Canandaigua and Keuka Lakes had the best water quality. Cayuga Lake

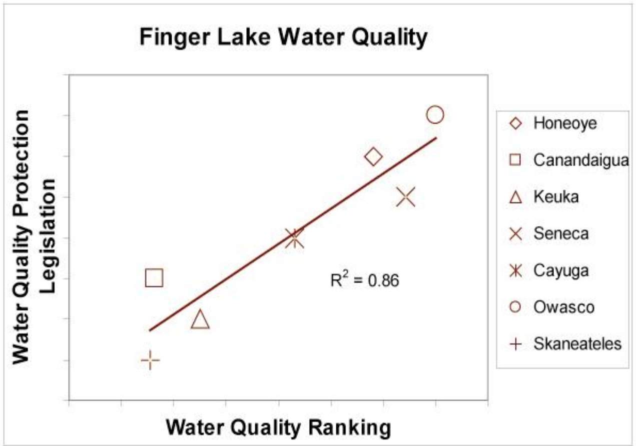


Fig. 1. The 2005 water quality ranking of 7 Finger Lakes.

fell in between the end-members. The 2005 preliminary report also noted a correlation between the ranking and a first-order, qualitative assessment of water quality protection legislation. However, more study is required to determine the significance of this correlation as water quality may alternatively reflect, for example, land use activities and/or the impact of recent exotics like zebra and quagga mussels. Data from 2006 and 2007 suggest that Seneca Lake is still within the most impaired lakes in the survey.

Here, we report on our current understanding of the limnology and hydrogeochemistry of the lake based on ongoing monitoring efforts at Hobart and William Smith Colleges (HWS). The program was initiated in the early 1990s with the addition of a limnologist on the faculty of HWS. This position was first occupied by Prof. M. Wing and then Prof. J.D. Halfman. Since the mid-1990's, the program comprised of weekly monitoring of four lake sites in the northern end of the lake, and seven streams in or adjacent to the watershed. The objectives were to:

1. establish consistent and comprehensive monitoring to document spatial and temporal trends in the limnology and other water quality parameters in the lake;
2. bring particular focus to the extent and sources of nutrients to the lake and associated watershed-lake interactions;
3. provide water quality data to local government agencies, watershed protection groups and concerned citizens; and,
4. promote the development of effective and comprehensive watershed management policies to initiate the protection and if required the remediation of Seneca Lake.

This report builds on the lake and stream water quality chapters in the 1999 State of the Seneca Lake Watershed Report (Halfman and many undergraduate students, 1999), and subsequent updates in other reports, publications and presentations by Halfman and his students.

## WATER QUALITY INDICATORS

The Seneca watershed is dominated by a rural landscape with a mix of agricultural (46%) and forested (36%) land, and smaller amounts of urban (5%) and other land uses (Fig. 2). The distribution suggests that the primary water quality threat to the lake is nutrient loading, as it stimulates algal productivity and nearshore plant growth, and progressively reduces water quality until the lake becomes impaired and eutrophic.

Nutrients, dissolved nitrates ($NO_3^-$), phosphates ($PO_4^{-3}$) and silica ($H_2SiO_4^{-2}$), are critical for aquatic life. In a basic aquatic nutrient cycle (Fig. 3), nutrients dissolved in water are assimilated by phytoplankton (algae, microscopic aquatic plants) and macrophytes (nearshore rooted plants) through photosynthesis and then converted into amino acids, proteins, cell tissue, RNA and DNA, and other critical compounds. When the algae are eaten, these organic compounds are passed up the food chain to other organisms like zooplankton and lake trout. When these organisms die, bacteria ultimately decompose the organic material and release dissolved nutrients back into the water column to be assimilated by algae and other plants once again. Due to their scarcity in lakes, lake ecosystems are very proficient at recycling nutrients. Thus nutrient concentrations are fundamental to and critical indicators of algal productivity, the trophic status and eutrophication.

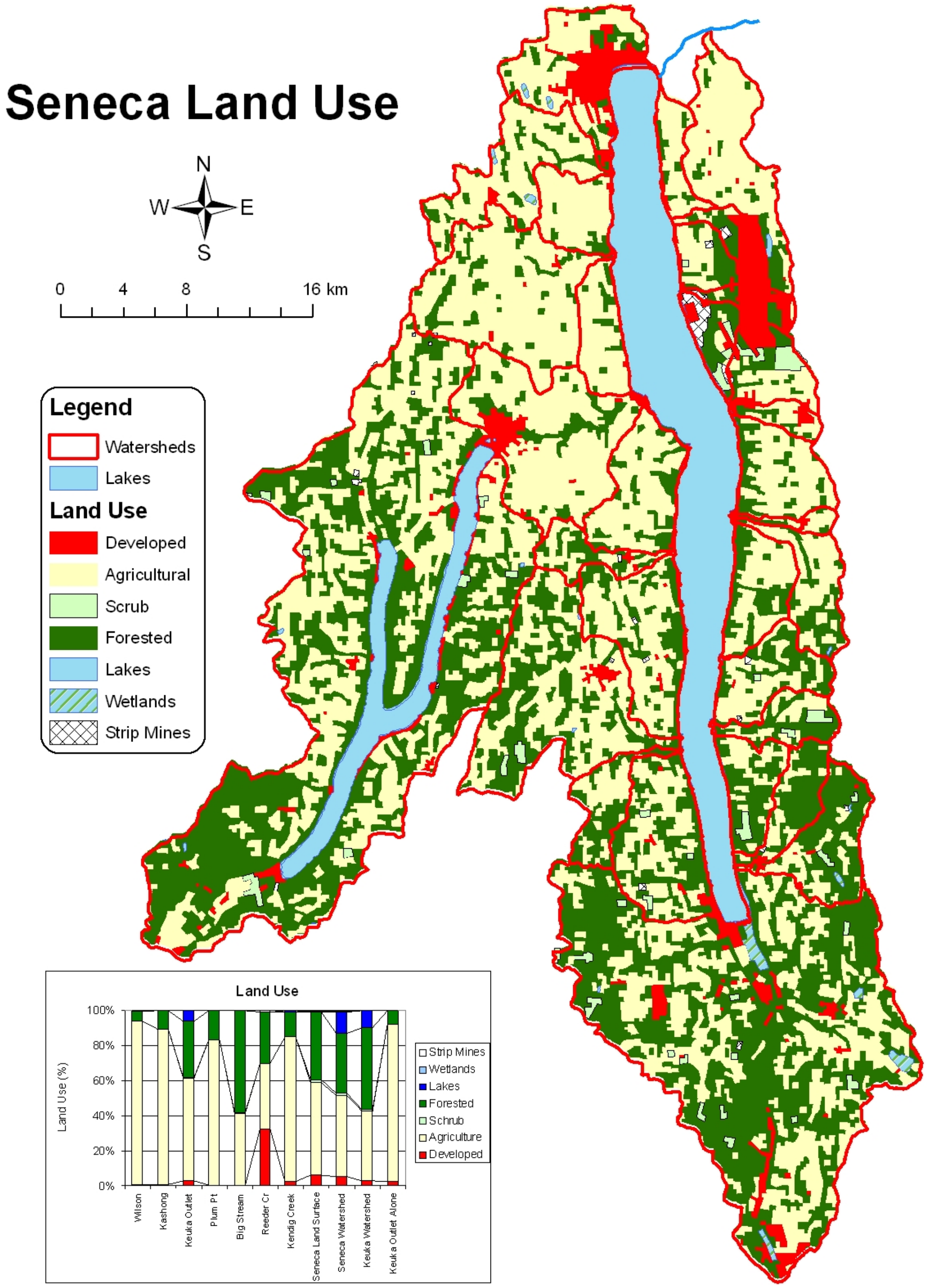


Fig. 2. Land use in Seneca and neighboring watersheds. Keuka watershed is show because it drains into Seneca Lake and is thus part of the Seneca watershed. Kendig Creek is shown because it was routinely sampled even though it is outside the Seneca watershed.

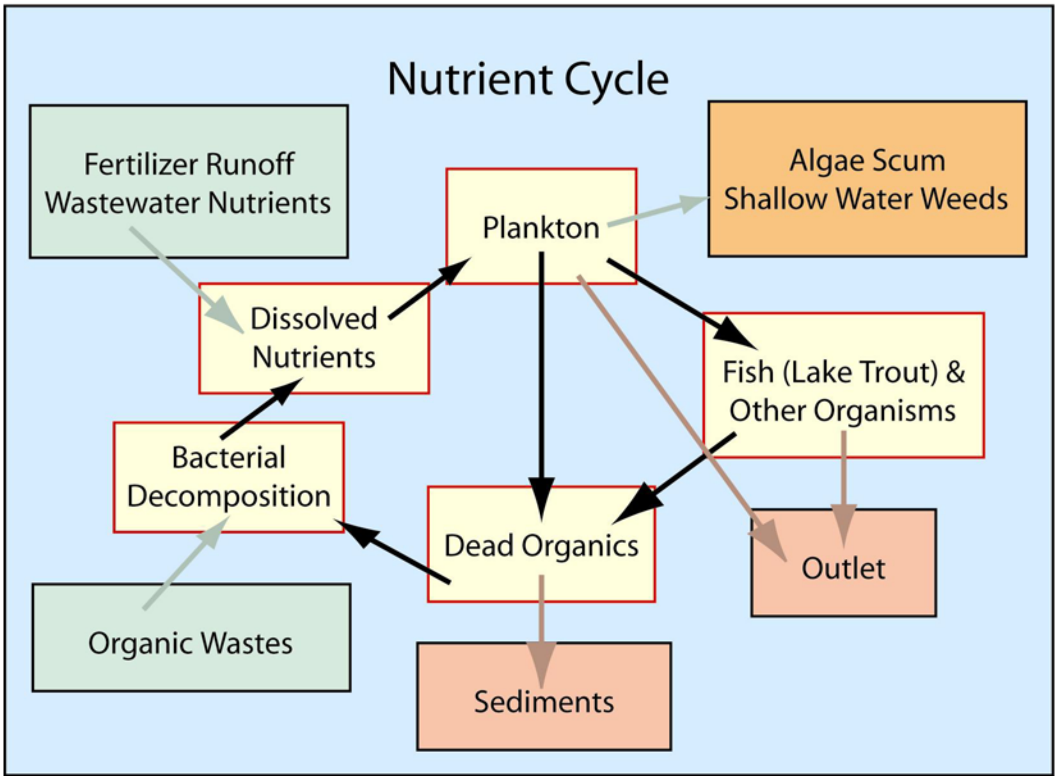


Fig. 3. A typical nutrient cycle for lake ecosystems (yellow boxes). Typical human-induced additions (green boxes), their impact (orange box), and natural sinks (red boxes) from the nutrient cycle are also shown.

Nutrient loading from human and other 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 the amount of material in each “box” of the nutrient cycle increases over time. If the aquatic system becomes eutrophic, then a foul smelling/tasting scum of blue-green algae typically dominates the algal community (base of the food chain) and covers the surface of the lake with a green slime. The increase in algae decreases water clarity (transparency), as the extra algae impede the transmission of light through water, and increases 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 while consuming dissolved oxygen and recycling nutrients back into the environment. If the removal of oxygen from the summer-time bottom waters (depths below the thermocline) is severe enough (somewhere below 6 mg/L, as each species has its own level of tolerance), it places respiratory stress on all aquatic animals like lake trout, crawfish and worms, because dissolved oxygen is required for survival. Complete de-oxygenation of the bottom waters happens in eutrophic lakes and induces fish kills. If sulfur is available, the hypolimnion releases 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, and continue to “fertilize” plant growth at enhanced levels. Anoxic bottom waters also allow phosphates, previously buried in the sediments as particles (oxides) in oxygen-rich oligotrophic systems, to subsequently dissolve and re-enter the water column.

Thus, algal and dissolved oxygen concentrations are additional trophic status indicators. Algal concentrations are measured directly by the concentration of chlorophyll, and indirectly by fluorometer, total suspended solids and secchi disk depths. Typically, a combination of nutrient concentrations, algal concentrations, secchi disk depths, and dissolved oxygen concentrations 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 |

## HYDROGEOCHEMISTRY & OTHER WATER QUALITY INDICATORS

Major ion, pH, coliform bacteria, herbicide, pesticide, heavy metal and other materials, are additional measures of water quality. The major ions, chloride, sulfate, alkalinity, sodium, potassium, calcium and magnesium, combine to determine the salinity of the lake. Chloride concentrations above 250 mg/L (ppm) pose a health risk because the associated sodium ions hamper the development of kidneys in small children, and aggravate heart problems in older individuals. Water with total dissolved ion concentrations above 2,000 mg/L is too salty to drink because it promotes nausea and dehydration. Seawater, at ~35,000 mg/L, significantly exceeds drinking water limits. An acceptable range for pH in natural waters is neutral to slight basic, i.e., between 6.5 and 8.5. Lakes underlain by susceptible bedrock have been acidified through the dry and wet deposition of sulfuric and nitric acids from the atmosphere because the pH of rainfall in the central New York region is 4.1 to 4.4. These acids are created from the burning of fossil fuels. Finally, industrial release and agricultural runoff of heavy metals, herbicides, pesticides and other pollutants impact water quality. Each pollutant has numerous point and nonpoint sources and different maximum contaminant levels (MCLs), concentration limits for safe drinking water. For example, atrazine is a common herbicide use to control broadleaf weeds in corn, sorghum, sugar cane, pineapple and other crops. It is a also health threat, and has been shown to cause adrenal degradation and congestion of the lungs, liver and kidneys. Many water supplies in the mid-west corn-belt are contaminated with atrazine, with concentrations above the EPA’s 3 µg/L MCL for safe drinking water. Total coliform and *E. coli* bacteria are used to monitor the presence of human organic wastes and associated disease causing organisms. However, these bacteria pose minimal health threats, except for a few strains of *E. coli*, and can originate from geese, dogs, deer and other warm blooded, wild and domesticated, animals.

Hardness is defined by the concentration of divalent cations (ionic charge of 2+) with hard water exceeding a total concentration of 80 mg/L, expressed as the equivalent mass of $CaCO_3$, and calculated by $2.5(Ca^{2+}) + 4.1(Mg^{2+})$. Its occurrence reflects the concentration of calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$) dissolved from limestones and other soluble calcium and magnesium-rich rocks. The variability in alkalinity, calcium and magnesium reflect the availability of limestone in the underlying bedrock and/or glacial till for the individual drainages. Hard water is not harmful to drink as long as the total salt concentration is less than 2,000 mg/L, and some studies have shown that drinking hard water may reduce the risk of heart disease. However, hard water is a nuisance problem by preventing the lathering of soap, yellowing of white clothes, and precipitating a carbonate scum on pots, pans, and inside hot water pipes, water heaters and other plumbing. Water softeners reduce water hardness by passing the water through an ion-exchange material. The process typically exchanges calcium (or magnesium) for sodium (or potassium). Rock salt (NaCl) is used to periodically recharge the ion-exchange mineral with sodium (or KCl exchanging potassium). Softeners can effectively reduce the hard water problem for a household but the rock salt softeners create new problems for those on low-sodium diets and waste 10% of water used in the home.

## METHODS

***Lake Research:*** Data collection started in 1991 but was progressively more frequent and more parameters were analyzed after 1996. Lake sites focused on four representative locations in the northern portion of the lake (Table 2, Fig. 4). The four sites maximized the nearshore/offshore and shallow/deep water diversity in Seneca Lake while minimizing the expense during a ½ day cruise aboard the HWS Scandling, the Colleges' 65 ft steel-hulled research vessel. These sites are also used for the Finger Lake Institute's comparative water quality survey. Sites 1 and 3 were located at the middle of the lake; whereas Sites 2 and 4 were from the lake margins, with only Site 4 located adjacent to a major tributary (Kashong Creek). Water quality samples were collected from surface (< 1m) and bottom water (within 2m of the lake floor) depths at Sites 1 & 3, and only surface water samples at the other two sites. All sites were sampled weekly from mid-April through mid-October. In 1998, monthly data were collected from five additional sites distributed from the northern survey area southward along the axis of the lake southward towards Watkins Glen to assess the similarity of the northern and southern portions of the lake. The entire-lake survey revealed similar water quality data as the four northern sites, and was subsequently discontinued from lack of funding.

Table 2. Lake site locations and maximum water depths.

| Site | Latitude | Longitude | Water Depth (m) |
|---|---|---|---|
| Site 1 | 42° 50.80' N | 76° 57.56' W | 22 m |
| Site 2 | 42° 46.82' N | 76° 55.99' W | 25 m |
| Site 3 | 42° 46.28' N | 76° 57.00' W | 115 m |
| Site 4 | 42° 45.79' N | 76° 58.01' W | 25 m |

A conductivity, temperature and depth (CTD) water quality profile, secchi disk depth, plankton tows, and water samples were collected at each site. The CTD was lowered from the surface to ~2m above the lake floor, electronically collecting data every 0.5 seconds along the downcast. The data were subsequently uploaded to a computer for analysis. Before 2007, the SeaBird SBE-19 CTD collected water column profiles of temperature, conductivity (reported as specific conductance), dissolved oxygen, pH, and light transmission (water clarity, inversely proportional to turbidity). In 2007, the CTD was upgraded to a SeaBird SBE-25 with additional sensors for photosynthetically active radiation (PAR), and chlorophyll-a by fluorescence. Water samples were collected and filtered for laboratory analyses, and typically analyzed onsite for temperature, conductivity, dissolved oxygen, pH and alkalinity using hand-held Oakton probes and field titrations, and analyzed in the laboratory for nutrients (total phosphate in 2006 and 2007 only, dissolved phosphate, nitrate and silica), chlorophyll-a, total suspended solids, and major ions, specifically, sodium ($Na^+$), calcium ($Ca^{+2}$), magnesium ($Mg^{+2}$), potassium ($K^+$), chloride ($Cl^-$), and sulfate ($SO_4^{-2}$). In 1999 and 2000, additional water samples were collected and analyzed for atrazine, a common herbicide, and in 2003 through 2005 for total coliform and *E. coli* bacteria assays.

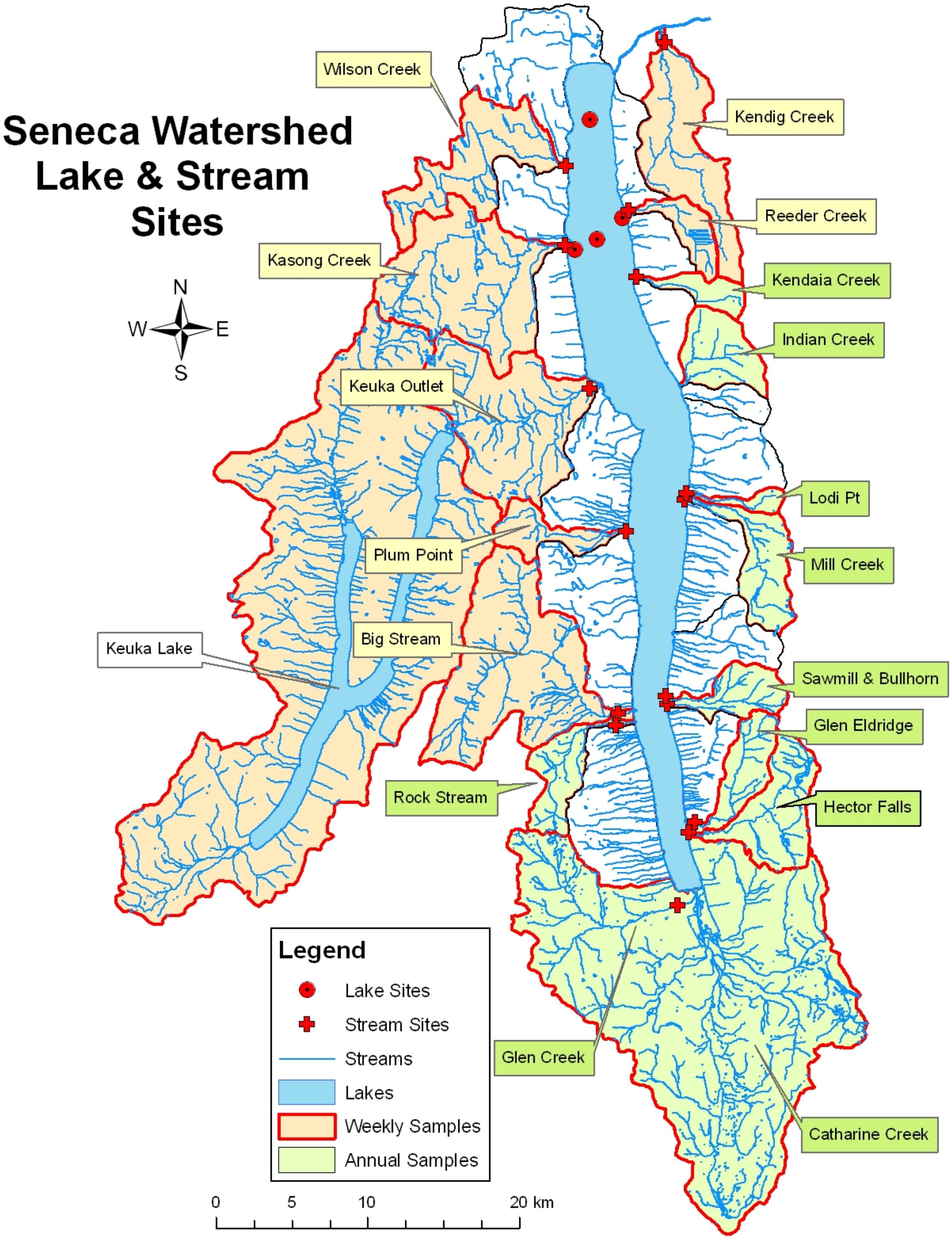


Fig. 4. Lake and stream sites.

***Stream Research:*** The collection of stream data started in 1998. The stream sites focused on the major tributaries that enter the western and northeastern sides of the lake focusing on the largest drainages that maximized the range of land use in the watershed (from agricultural to forest dominated drainages) while minimizing the expense during a ½ day excursion around the northern and western side of the lake (Fig. 4). The streams surveyed included from N to S along the west side: Wilson Creek (93% agr), Kashong Creek (89% agr), Keuka Outlet (40% agr), Plum Pt Creek (83% agr), and Big Stream (41% agr), and in the northeast Reeder Creek (37% agr) and Kendig Creek (83% agr). Even though Kendig Cr. is not in the watershed, it was included in the survey because it drained one of the most agricultural landscapes in this group. Sample sites were located near the terminus of the stream, typically at the intersection of the stream and Rt. 14 or East Lake Road. Keuka Outlet was sampled at Milo Street in Dresden, Plum Pt. Creek at Hall Road, and Kendig Creek at Marshall Road. These streams were typically sampled weekly from May through July (unless they dried up earlier). Once or twice a year, samples were also collected form the other major tributaries to the lake including Rock Stream, Glen Creek, Catharine Creek, Hector Falls, Glen Eldridge, Sawmill, Bullhorn, Mill, Lodi Pt, Indian, and Kendaia Creeks. Segment analysis, analysis at a series of locations distributed from the mouth to the headwaters of the stream, was performed along Big Stream in 2001 and Keuka Outlet in 2003 to pinpoint sources of nutrients and other contaminants (Bowser, 2002; Hintz, 2004).

Water samples were measured onsite for temperature, conductivity, dissolved oxygen, pH and alkalinity using hand-held Oakton probes or field titrations. Samples were also transported to the laboratory and analyzed for nutrients (total phosphate only in 2006 & 2007, dissolved phosphate, nitrate and silica), total suspended solids and major ion concentrations. Stream discharge (the volume of water per unit time) was calculated from measured stream width, depth and velocity using a Marsh-McBirney flow meter. Both velocity and depth were typically measured at five or ten equally distributed locations aligned perpendicular to stream flow.

***Laboratory Analyses:*** Laboratory procedures for nutrient, chlorophyll-a, and total suspended solid concentrations followed standard limnological techniques (Wetzel and Likens, 2000). A known volume of sample water was filtered through a pre-weighed 0.45 μm glass-fiber filter. The filter and residue were dried at 80°C overnight. The weight gain and filtered volume determined the total suspended sediment concentration. Another known volume 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 dissolved (soluble reactive) 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. Before 2001, nitrates were measured on unfiltered water on site with a Hach Low Range Nitrate Kit (Model NI-14). Since 2001, nitrates were prepared with the same Hach reagents but concentrations were colorimetrically detected by spectrophotometer using a 1-cm cell at 540 nm in the laboratory using filtered water samples. A third unfiltered water sample was analyzed for total phosphates colorimetrically by spectrophotometer using the SRP procedure after digestion the particulate phosphorus in potassium persulfate at 100ºC for 1 hour. 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 the HWS Laboratory results are statistically equivalent to the Life Science Laboratory results ($r^2 = 0.84$ 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 analysis at either lab, 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 HWS detection limit or phosphate concentrations below 3 μg/L for TP and SRP compared to the 1 μg/L HWS detection limit. Thus, Life Sciences could not provide data for 15% of the nitrate samples, 70% of the SRP samples, and 40% of the TP samples.

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). Atrazine, a common herbicide, was analyzed using the Atrazine RaPID Assay Kit that utilizes an enzyme-linked immunosorbent assay to detect atrazine (Omicron Environmental Diagnostics). The precision of the procedure was 0.06 μg/L and minimum detection limit was 0.05 μg/L. 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 & DISCUSSION

***CTD Profiles, Results and Interpretations:*** The CTD profiles were typical for an oligotrophic to mesotrophic, temperate lake (Fig. 5). A thermocline typically developed in May as the surface waters warmed from 4ºC in the early spring up to 30ºC by mid-summer. The thermocline persisted until the end of November as the surface waters cooled back to isothermal conditions (4ºC). When present, the thermocline was typically at a depth of 20 m. However, its depth oscillates vertically in response to internal seiche activity and season warming and cooling of the epilimnion. Its location is fundamental to lake processes because it vertically stratifies the warmer, less-dense epilimnion from the colder, more-dense hypolimnion, in the lake from spring to fall overturn (isothermal conditions). Thus, it typically isolates the hypolimnion from sunlight, stream inputs and atmospheric oxygen.

Specific conductance (salinity) was isopycnal in early spring, and decreases by 40 to 50 μS/cm in the epilimnion through the stratified season until fall overturn. The lake wide specific conductance would decrease by ~10 μS/cm each year. Dissolved oxygen (DO) concentrations were saturated in the epilimnion through the field season. DO was slightly below saturation just

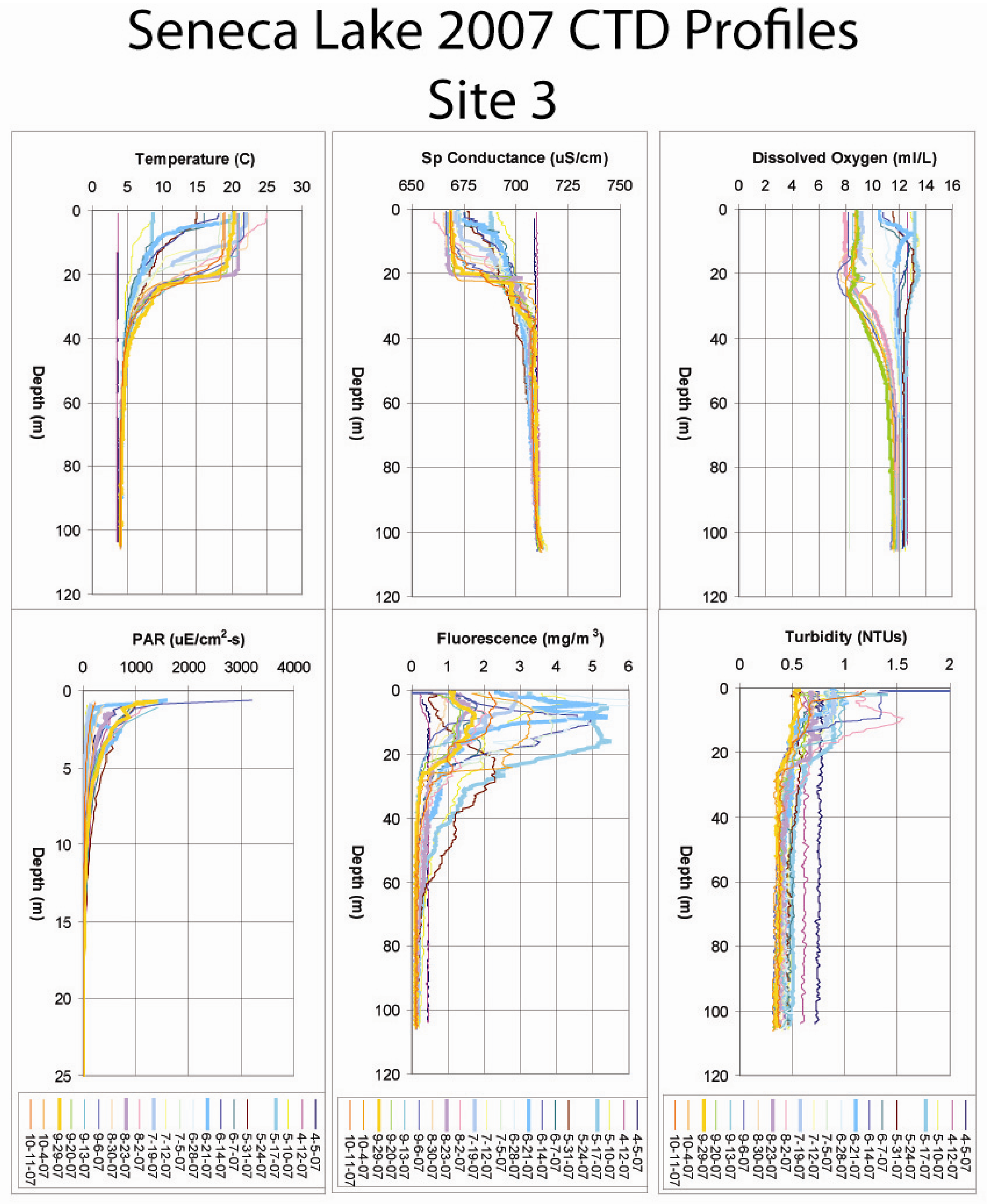
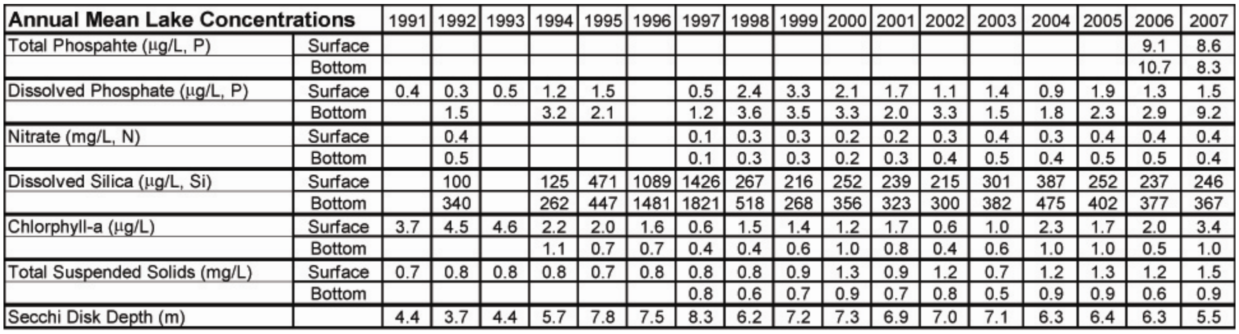


Fig. 5. Site 3 CTD profiles from 2007.

below the thermocline late in the stratified season, reflecting more respiration than photosynthesis at that depth. Photosynthetically active radiation intensities decreased exponentially from the surface of a few hundred to 3000 μE/cm$^2$-s to ~1% surface intensities at 15 to 20m depth. The surface variability reflected the season, cloud cover and the boat's shadow. Occasionally PAR data would depart to low light levels from the typical exponential decay just below the surface of the lake as the CTD travelled through the shadow of the boat. Algae, as detected by fluorescence profiules, were found through out the epilimnion and occasionally extended into the metalimnion of the lake. The algal peak was typically 10 to 20 m deep, and typically rose and fell with light availability. The turbidity was also larger in the epilimnion, and probably reflects the epilimnetic algae, and on rare occasions algal blooms and calcite precipitation or suspended sediments from fluvial inputs along the lake surface.

***Lake Nutrient, Chlorophyll-a, Secchi Disk, & TSS Data:*** The annual average total phosphate, soluble reactive phosphate, dissolved silica, nitrate, chlorophyll-a, secchi disk and TSS data are presented in Table 3 and Fig. 6. Total phosphate and nitrate analyses were initiated in 1997 and 2006, respectively. None of these open-lake concentrations are a health threat nor do they indicate an impaired lake, as the nitrate concentrations are always below the US EPA's MCL of 10 mg/L and phosphate concentrations are always below NYS DEC's 20 μg/L threshold for impaired water bodies. The mean open-lake concentrations indicate that the lake fluctuated between oligotrophic and borderline oligotrophic – mesotrophic status through out the study. The epilimnion to hypolimnion increase in nutrient concentrations and decrease in chlorophyll-a concentrations over the stratified season are consistent with the normal seasonal progression of algal growth from the uptake and removal of nutrients in the epilimnion, and algal decomposition and nutrient release by bacteria in the hypolimnion. The nitrogen to phosphorus ratios (N:P) in the open-lake samples were ~100:1 or larger. Because nitrates typically limit algal growth with an N:P ratio below 10 and phosphates typically limit algal growth with an N:P ratio over 20, the nutrient concentrations indicate that algal growth in Seneca Lake is phosphate limited. Dissolved silica concentrations below 500 μg/L will limit the growth of diatoms as they require silica to build their frustules.

Table 3. Annual Mean Lake data.



| **Annual Mean Lake Concentrations** | | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total Phospahte (μg/L, P) | Surface | | | | | | | | | | | | | | | | 9.1 | 8.6 |
| | Bottom | | | | | | | | | | | | | | | | 10.7 | 8.3 |
| Dissolved Phosphate (μg/L, P) | Surface | 0.4 | 0.3 | 0.5 | 1.2 | 1.5 | | 0.5 | 2.4 | 3.3 | 2.1 | 1.7 | 1.1 | 1.4 | 0.9 | 1.9 | 1.3 | 1.5 |
| | Bottom | | 1.5 | | 3.2 | 2.1 | | 1.2 | 3.6 | 3.5 | 3.3 | 2.0 | 3.3 | 1.5 | 1.8 | 2.3 | 2.9 | 9.2 |
| Nitrate (mg/L, N) | Surface | | 0.4 | | | | | 0.1 | 0.3 | 0.3 | 0.2 | 0.2 | 0.3 | 0.4 | 0.3 | 0.4 | 0.4 | 0.4 |
| | Bottom | | 0.5 | | | | | 0.1 | 0.3 | 0.3 | 0.2 | 0.3 | 0.4 | 0.5 | 0.4 | 0.5 | 0.5 | 0.4 |
| Dissolved Silica (μg/L, Si) | Surface | | 100 | | 125 | 471 | 1089 | 1426 | 267 | 216 | 252 | 239 | 215 | 301 | 387 | 252 | 237 | 246 |
| | Bottom | | 340 | | 262 | 447 | 1481 | 1821 | 518 | 268 | 356 | 323 | 300 | 382 | 475 | 402 | 377 | 367 |
| Chlorphyll-a (μg/L) | Surface | 3.7 | 4.5 | 4.6 | 2.2 | 2.0 | 1.6 | 0.6 | 1.5 | 1.4 | 1.2 | 1.7 | 0.6 | 1.0 | 2.3 | 1.7 | 2.0 | 3.4 |
| | Bottom | | | | 1.1 | 0.7 | 0.7 | 0.4 | 0.4 | 0.6 | 1.0 | 0.8 | 0.4 | 0.6 | 1.0 | 1.0 | 0.5 | 1.0 |
| Total Suspended Solids (mg/L) | Surface | 0.7 | 0.8 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 | 0.8 | 0.9 | 1.3 | 0.9 | 1.2 | 0.7 | 1.2 | 1.3 | 1.2 | 1.5 |
| | Bottom | | | | | | | 0.8 | 0.6 | 0.7 | 0.9 | 0.7 | 0.8 | 0.5 | 0.9 | 0.9 | 0.6 | 0.9 |
| Secchi Disk Depth (m) | | 4.4 | 3.7 | 4.4 | 5.7 | 7.8 | 7.5 | 8.3 | 6.2 | 7.2 | 7.3 | 6.9 | 7.0 | 7.1 | 6.3 | 6.4 | 6.3 | 5.5 |

***Plankton Data:*** Phytoplankton were dominated by the diatoms *Asterionella*, *Tabellaria*, *Diatoma* and *Flagillaria*, and the dinoflagellates *Dinobryon* and *Ceratium* (Table 4). The seasonal succession moved from *Asterionella* to *Tabellaria* & *Diatoma* to *Flagillaria*, *Diatoma*, *Dinobryon* & *Ceratium* to *Flagillaria*. Zooplankton were dominated by copepods, with some cladocerans. The plankton data are not discussed further in this report.

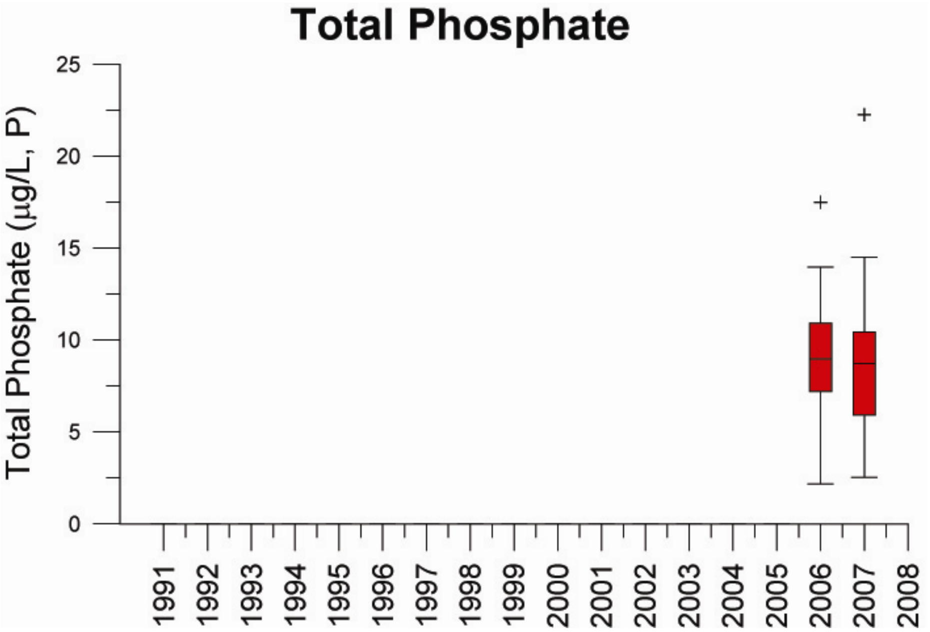


Fig. 6. Total phosphate (TP) concentrations. Box and whisker plots show the 25%, 75% and median concentrations with the box. The line reveals extreme values, and data points outliers in an given year.

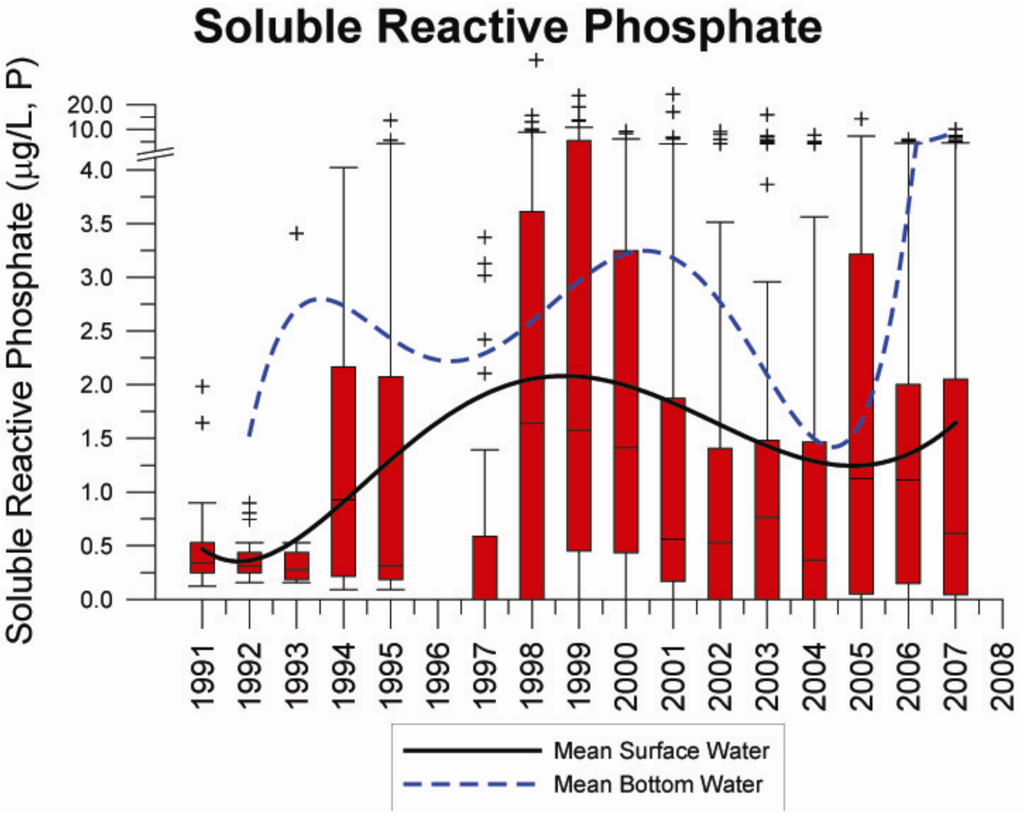


Fig. 6 (continued). Soluble reactive phosphate (SRP) concentrations. In this and subsequent plots, the solid and dashed lines are polynomial fits through the surface and bottom water annual mean data.

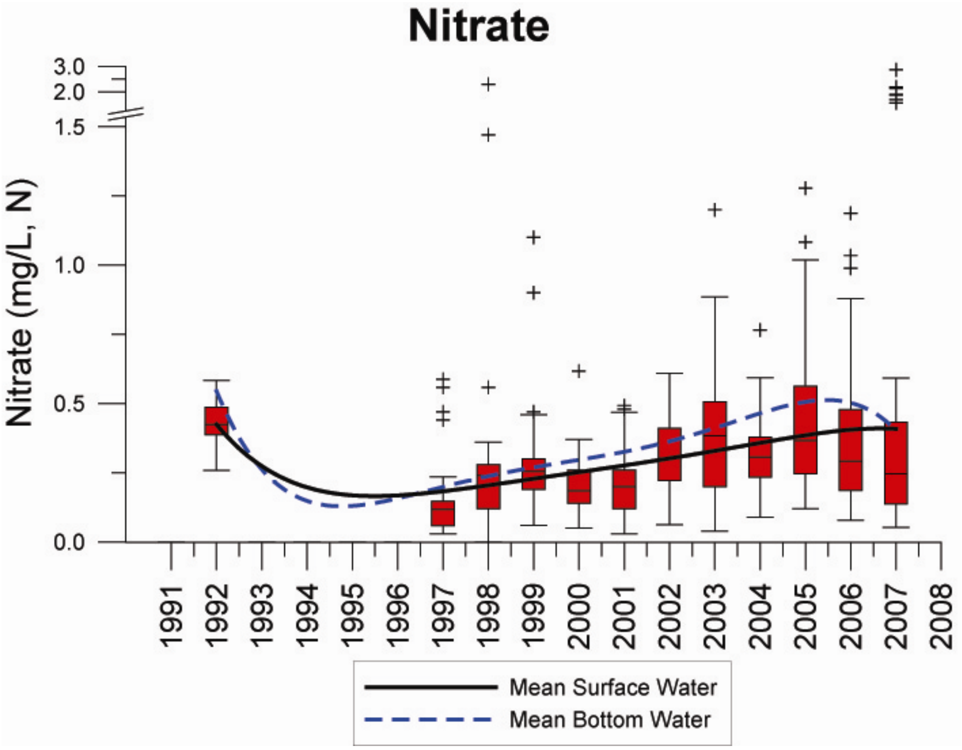


Fig. 6 (continued). Lake nitrate concentrations.

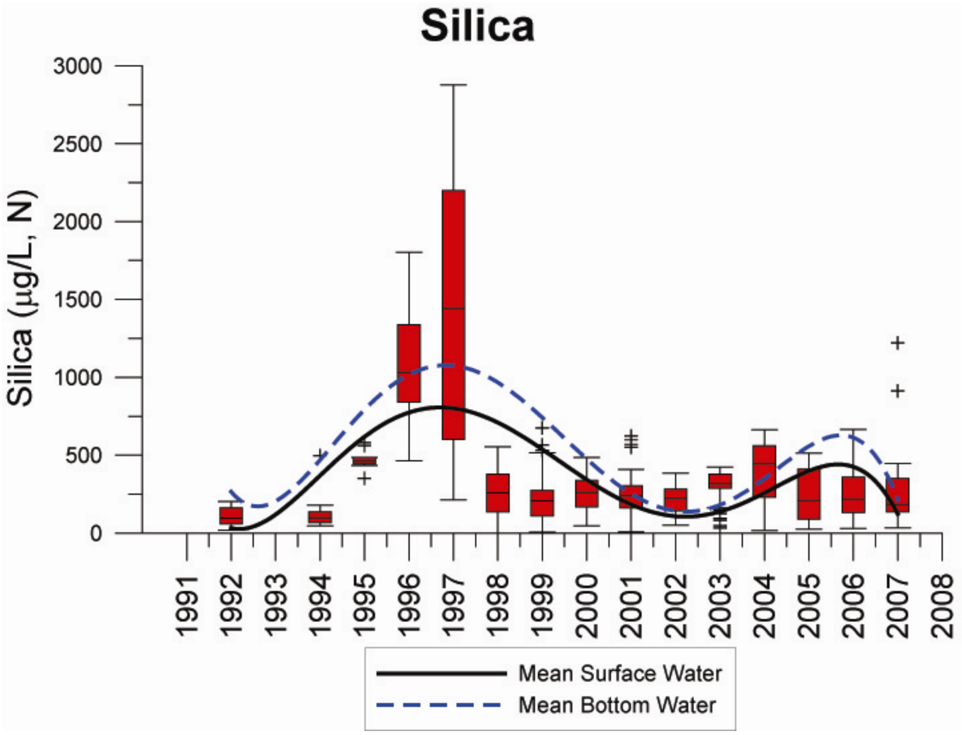


Fig. 6 (continued). Lake dissolved silica concentrations.

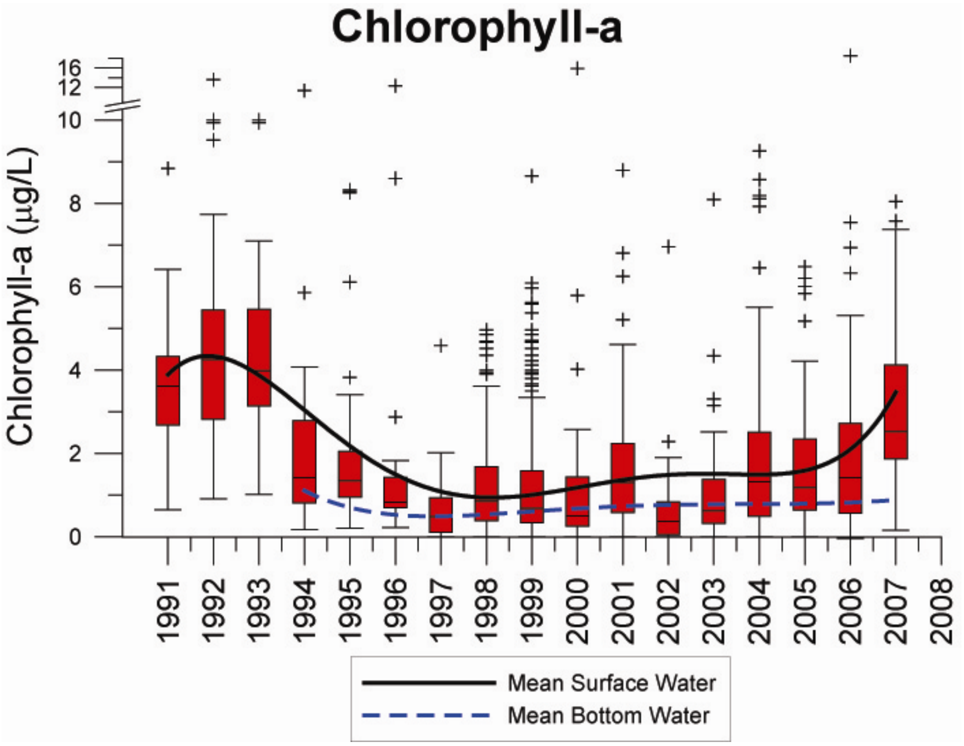


Fig. 6 (continued). Lake chlorophyll-a concentrations.

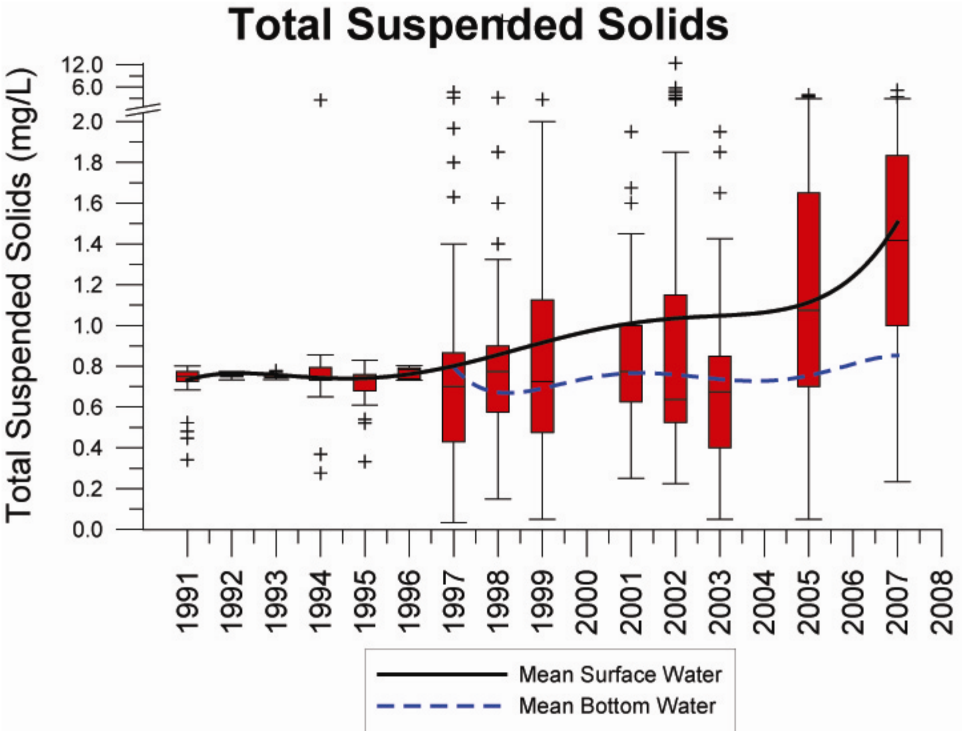


Fig. 6 (continued). Lake total suspended solids concentrations.

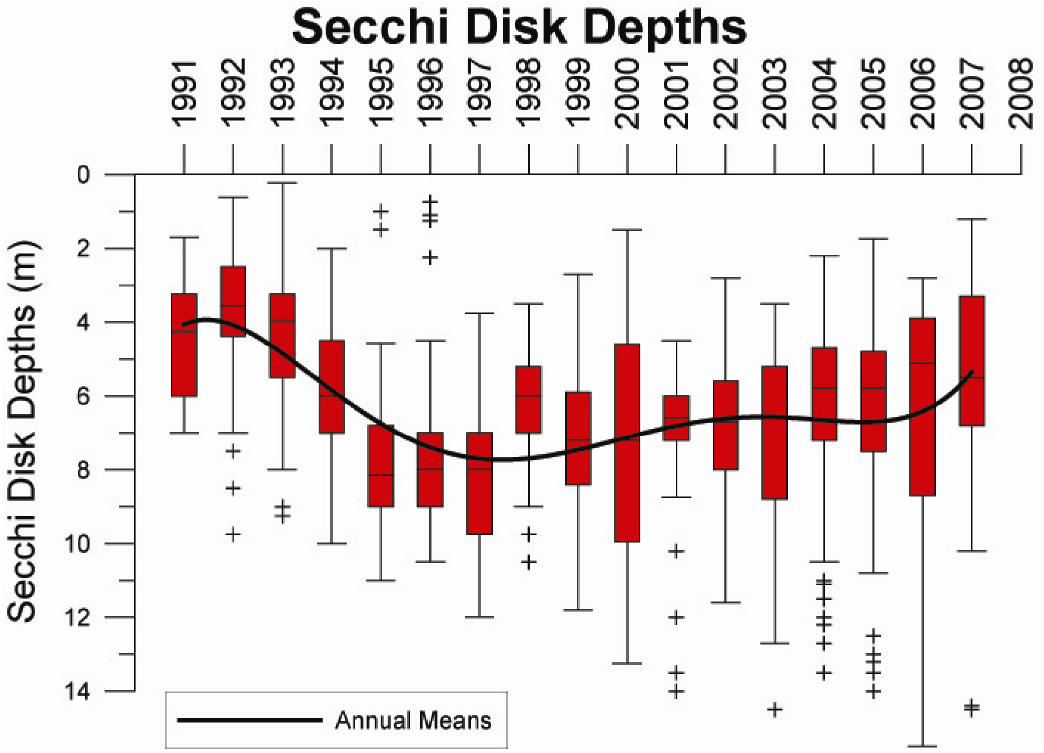
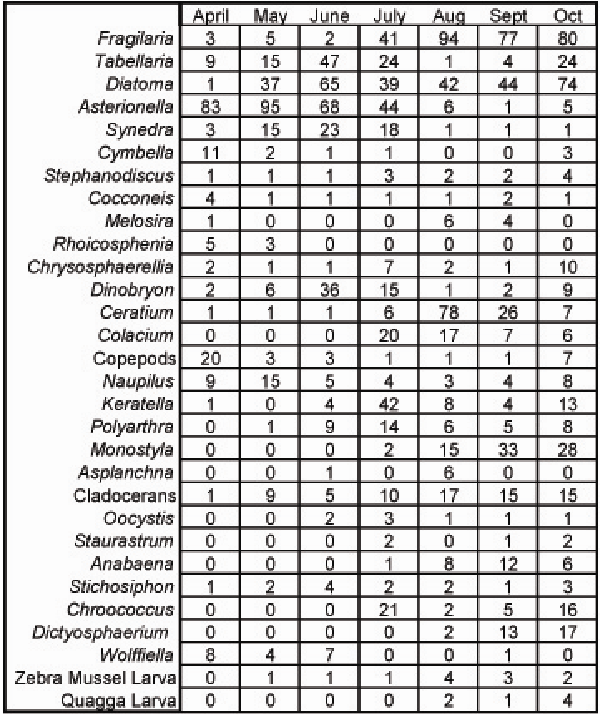


Fig. 6 (continued). Lake secchi disk depths.

***Seneca Lake Trends:*** Significant changes are observed in the limnology of Seneca Lake over the past 15 years. The data divide into three multiyear trends: from 1992 to 1997, 1998 to 1999 or 2000, and 2000 to 2007. For example, annual average secchi disc depths became progressively deeper from 4m in the early 1990's to over 8m by the end of 1997, rebounded slightly and deepened again from 1999 through 2000, and since 2000 steadily rose to 5.5m by 2007. Chlorophyll-a concentrations decreased from an annual average of 4.5 μg/L in the early 1990's to 0.6 μg/L by 1997, increased and decreased slightly from 1998 through 2000, and then steadily increased to 3.4 μg/L by 2007. Dissolved silica surface water concentrations increased from near 100 μg/L in 1994 to 1,400 μg/L in 1997, to subsequently decrease to below 300 μg/L by 1998 and remain low through the end of 2007. Nitrate and phosphate concentrations were 0.1 mg/L and 0.5 μg/L, respectively, before 1998 until they doubled (0.3 mg/L and 3.3 μg L) in 1998 and 1999, then declined for a year or two, only to increase again from 2003 or 2004 to 2007 with 2007 concentrations of 0.4 mg/L and 1.5 μg/L, respectively.

The 1992 through 1997 trend is highlighted by progressively deeper secchi disc depths, increased water clarity and smaller algal concentrations. These trends are consistent with increased grazing by the growing population of filter-feeding zebra mussels (Halfman et al., 2001). Zebra mussels were first detected in 1992, and within a few years they had successfully colonized Seneca Lake. The trend has implications on the limnology of the lake (Fig. 7). As more algae are eaten, algal concentrations progressively decline. The nutrients in the eaten algae are sequestered into the mussel biomass, and are thus isolated from the nutrient cycle. Reductions in nutrient concentrations were observed in the lake. Zebra mussels typically sequester half or more of the originally available total phosphorus during their establishment in an area. Fewer

Table 4. Monthly-averaged, relative abundance plankton data.



| | April | May | June | July | Aug | Sept | Oct |
|---|---|---|---|---|---|---|---|
| *Fragilaria* | 3 | 5 | 2 | 41 | 94 | 77 | 80 |
| *Tabellaria* | 9 | 15 | 47 | 24 | 1 | 4 | 24 |
| *Diatoma* | 1 | 37 | 65 | 39 | 42 | 44 | 74 |
| *Asterionella* | 83 | 95 | 68 | 44 | 6 | 1 | 5 |
| *Synedra* | 3 | 15 | 23 | 18 | 1 | 1 | 1 |
| *Cymbella* | 11 | 2 | 1 | 1 | 0 | 0 | 3 |
| *Stephanodiscus* | 1 | 1 | 1 | 3 | 2 | 2 | 4 |
| *Cocconeis* | 4 | 1 | 1 | 1 | 1 | 2 | 1 |
| *Melosira* | 1 | 0 | 0 | 0 | 6 | 4 | 0 |
| *Rhoicosphenia* | 5 | 3 | 0 | 0 | 0 | 0 | 0 |
| *Chrysosphaerellia* | 2 | 1 | 1 | 7 | 2 | 1 | 10 |
| *Dinobryon* | 2 | 6 | 36 | 15 | 1 | 2 | 9 |
| *Ceratium* | 1 | 1 | 1 | 6 | 78 | 26 | 7 |
| *Colacium* | 0 | 0 | 0 | 20 | 17 | 7 | 6 |
| Copepods | 20 | 3 | 3 | 1 | 1 | 1 | 7 |
| *Naupilus* | 9 | 15 | 5 | 4 | 3 | 4 | 8 |
| *Keratella* | 1 | 0 | 4 | 42 | 8 | 4 | 13 |
| *Polyarthra* | 0 | 1 | 9 | 14 | 6 | 5 | 8 |
| *Monostyla* | 0 | 0 | 0 | 2 | 15 | 33 | 28 |
| *Asplanchna* | 0 | 0 | 1 | 0 | 6 | 0 | 0 |
| Cladocerans | 1 | 9 | 5 | 10 | 17 | 15 | 15 |
| *Oocystis* | 0 | 0 | 2 | 3 | 1 | 1 | 1 |
| *Staurastrum* | 0 | 0 | 0 | 2 | 0 | 1 | 2 |
| *Anabaena* | 0 | 0 | 0 | 1 | 8 | 12 | 6 |
| *Stichosiphon* | 1 | 2 | 4 | 2 | 2 | 1 | 3 |
| *Chroococcus* | 0 | 0 | 0 | 21 | 2 | 5 | 16 |
| *Dictyosphaerium* | 0 | 0 | 0 | 0 | 2 | 13 | 17 |
| *Wolffiella* | 8 | 4 | 7 | 0 | 0 | 1 | 0 |
| Zebra Mussel Larva | 0 | 1 | 1 | 1 | 4 | 3 | 2 |
| Quagga Larva | 0 | 0 | 0 | 0 | 2 | 1 | 4 |

nutrients promote declining algal productivity in a positive feedback loop. In contrast, dissolved silica concentrations significantly increased from 1995 through and including 1997. The increase is still consistent with mussel predation. Diatoms dominate the spring (*Asterionella*), summer and fall (*Tabellaria*, *Diatoma* & *Fragilaria*) phytoplankton in Seneca Lake. Diatoms require dissolved silica for their frustules. The reduction in phosphate availability reduces algal productivity in the lake, especially during 1996 and 1997, and less diatom growth presumably reduced the uptake of dissolved silica from the lake. Thus, dissolved silica concentrations do not decline but instead increase in the lake during the height of the mussel predation. Unfortunately, zebra mussel and macrophyte densities were not definitively measured over the past 10 years to confirm this hypothesis.

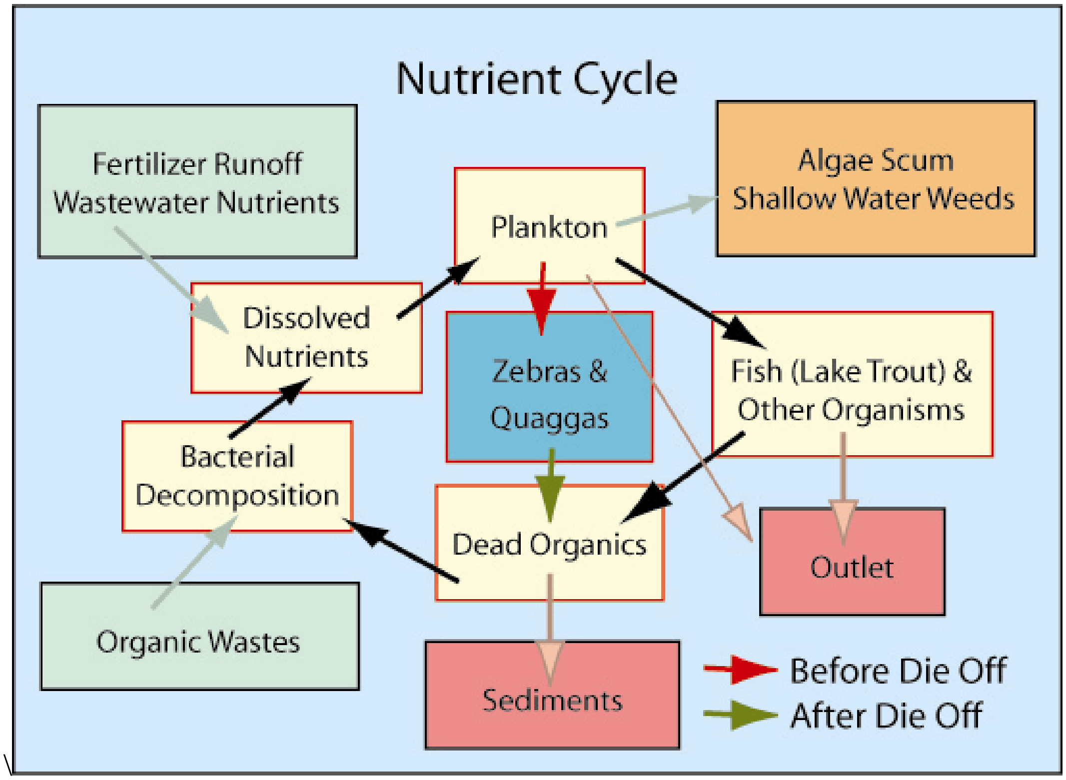


Fig. 7. The impact of zebra and quagga mussels on the nutrient cycle and algal concentrations. Initial sequestering of nutrients before the 1998 die off and subsequent release of the sequestered nutrients after the die off are shown by the red and green arrows, respectively.

A bump in the trends is observed from 1997 through 1999. Secchi disk depths oscillated from deep to shallow to deep again, whereas chlorophyll-a, phosphate, nitrate concentrations increased from 1997 concentrations only to decline by 1999. Land use practices in the watershed and nutrient concentrations in the major tributaries did not change during this time interval thus could not promote the observed change in the lake at this time. This period however marked the first major die off of zebra mussels. The die off and associated bacterial decomposition of the mussel biomass would release the previously sequestered nutrients back into the water column during 1998 and 1999. The natural life span of zebra mussels is consistent with the interval of time between their establishment in the lake and the maximum reduction in algal biomass by 1997. The reduced algal biomass would also induce more mussel deaths by starvation. Air and lake water temperatures were unusually warm in 1998 and 1999 which would promote faster and more complete bacterial recycling of dead organic matter directly to the epilimnion. Therefore, we hypothesize that the zebra mussel die-off, and subsequent release of their sequestered nitrogen and phosphorus to the epilimnion, stimulated significant algal productivity and decreased water clarity and the other limnological changes from 1997 to 1999. This event would impact phosphate more than nitrate because phosphate is ~100 times less concentrated than nitrates in Seneca Lake. A similar release of phosphates was observed to accompany zebra mussel die offs in neighboring Finger Lakes.

Since 1999, zebra mussel populations rebounded and were joined by their relative, the quagga mussel (same genus different species) in the early 2000's. The exact timing of the quagga mussel introduction is unknown. Sediment dredges by various HWS classes suggest that the zebra mussels were progressively replaced by quagga mussels. Quaggas were 90% of the mussel lake floor density (mass/area) in 2007 with densities from ~200 to 400 $g/m^2$ or 4,000 to 10,000 individuals/$m^2$ in water depths less than 60 m (Zhu, unpublished data). Yet, another transparent, algal poor, and nutrient rich episode, as severe as 1997, was not observed in the remaining record. In fact, water clarity decreased, and algal and nitrate concentrations increased from 2000 through 2007. Thus, the mussels appear to have established an equilibrium with the lake's ecosystem, and other factors must be increasing the nutrient concentrations in the lake.

Seasonal patterns in secchi disk depths also changed during the past 4 to 5 years (Fig. 8). Secchi depths were ~2m deeper in the spring but ~2m shallower in the mid-summer compared to previous years. These trends parallel seasonal changes in algal concentrations. The exact reasons for the increased water clarity are unclear but perhaps are due to grazing mussels and light limitations as both decrease algal concentrations in the near isothermal spring. The limited winter and spring algal populations perhaps also limit the mussel population, and expanded the opportunity for early spring and deeper water macrophyte growth. In contrast, the shallow secchi depths in mid-summer suggest that nutrient loading and sufficient light increases algal populations in the summer. The shallow depths in mid-summer dictate the decrease in the annual mean depths observed over the past 4 or 5 years. Thus, Seneca Lake is becoming more productive despite grazing by the mussel populations. The data indicate that Seneca Lake is nearly a mesotrophic lake, and suggests that Seneca Lake has a nutrient loading problem and should be protected from this water quality threat before the lake becomes eutrophic.

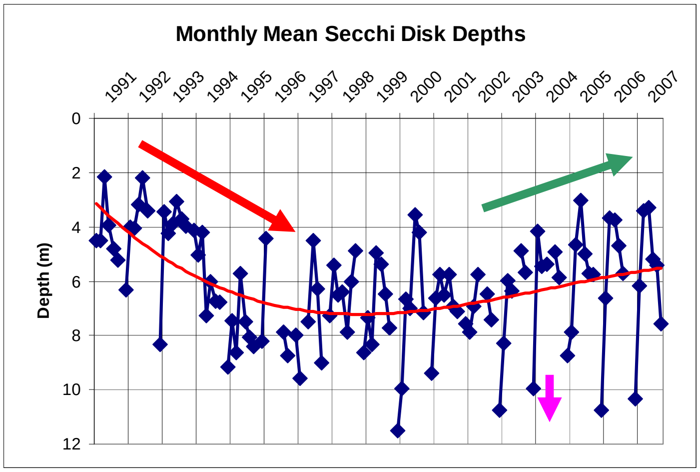


Fig. 8. Seasonal changes in secchi disk depths.

***Nutrient Loading:*** The annual, site averaged, stream concentration data are summarized in Table 5 and Fig. 9. Total coliform and *E. coli* bacteria data were only available from 2003 through 2006, and total phosphate (TP) data from 2006 and 2007. All of the nutrient, TSS and bacteria concentrations were larger in the streams than the lake by an order of magnitude or more and confirm the nutrient loading hypothesis. For example, total phosphate concentrations average 20 μg/L in the streams and are below 10 μg/L in the lake, mean nitrate concentrations are between 0.5 to just over 2 mg/L in the streams but 0.4 mg/L or smaller in the lake. Thus, Seneca gains nutrients each year from the watershed.

Nutrient concentrations are not uniform across the watershed. Variations in dissolved phosphate (SRP) concentrations are critical because phosphate is the limiting nutrient in the lake, and dissolved phosphates stimulate algal growth quicker than particulate phosphates. Wilson Creek, Big Stream Kendig Creek, and especially Reeder Creeks reveal the largest SRP concentrations compared to the other tributaries. Unfortunately, no one source accounts for these differences (Spitzer, 1999). Wilson and Kendig Creeks drain large portions of agricultural land. Thus, runoff from agricultural nonpoint sources probably contributes to these large SRP loadings. This is especially critical during intense storms, because phosphate concentrations and fluxes increase by 10 to 100 times during flood events (Fig. 10, Kostick and Halfman, 2003). Total suspended solid concentrations also significantly increased during the storm runoff. Insufficient event samples are available to quantitatively compare runoff to base flow fluxes in the Seneca watershed. Events typically provide 50% of the total nutrient flux to a lake elsewhere. In contrast, Big Stream drains much less agricultural land but contributes more phosphates to the lake than other streams. Stream segment analysis in 2001 indicated that the Dundee wastewater treatment facility and perhaps runoff of fertilizers from lawns in the town were critical sources of nutrients to this stream (Bowser, 2002). Every facility does not load the watershed with the same amount of nutrients. For example, a similar segment analysis along the Keuka Outlet indicated that the Penn Yan wastewater treatment facility was not a significant point source of nutrients to Keuka Outlet (Hintz, 2004). Additional research is required to determine the impact of the other facilities in the watershed. Why Kashong, Plum Pt., and Keuka Outlet have smaller phosphate concentrations even though all three drain a similar percentage of agricultural land as Wilson Creek is unclear. Perhaps the agricultural activity was less intense or more fields were idle in these three watersheds. Keuka Lake probably assimilates the majority of the phosphorus before the runoff from the Keuka watershed reaches the Keuka Outlet and eventually Seneca Lake.

The largest concentrations of SRP and TP were consistently detected in Reeder Creek, especially since 2002 when SRP concentrations rose from typical tributary values of ~20 μg/L to over 100 μg/L. It suggests a fundamental change in this drainage at this time. Reeder Creek drains

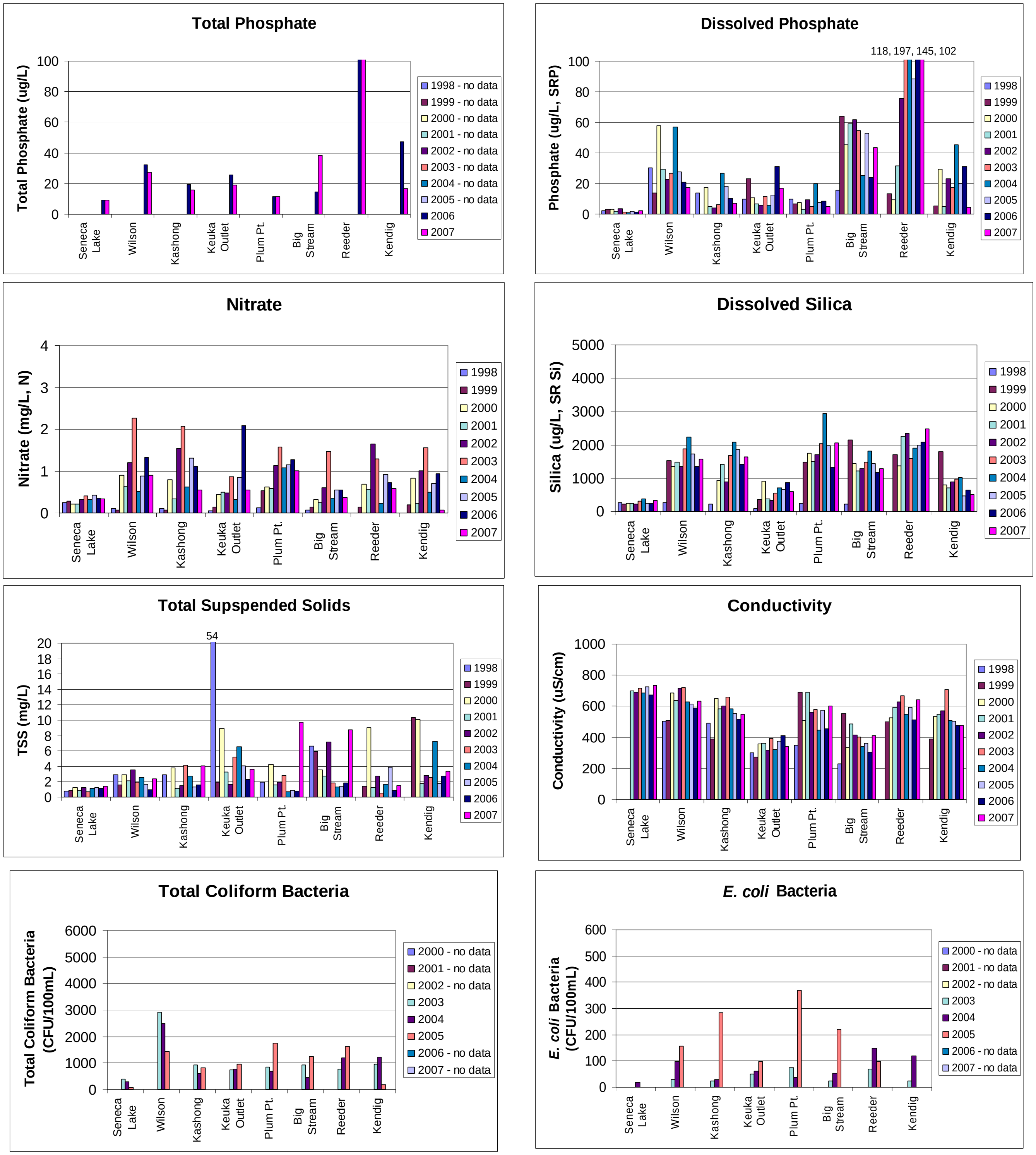


Fig. 9. Annual stream site-averaged water quality data. Annual Seneca Lake concentrations are included for comparison.

Table 5.  Site-Averaged Annual Stream Data.

| **Annual Mean Stream Concentrations** | | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total Phospahte (µg/L, P) | Wilson | | | | | | | | | 32.5 | 27.3 |
| | Kashong | | | | | | | | | 19.3 | 15.8 |
| | Keuka Outlet | | | | | | | | | 25.5 | 19.0 |
| | Plum Pt. | | | | | | | | | 11.4 | 11.6 |
| | Big Stream | | | | | | | | | 14.5 | 38.3 |
| | Reeder | | | | | | | | | 161 | 114 |
| | Kendig | | | | | | | | | 47.1 | 16.8 |
| Dissolved Phosphate (µg/L, P) | Wilson | 30.4 | 13.6 | 57.8 | 29.4 | 22.8 | 26.5 | 57.0 | 27.7 | 20.8 | 17.3 |
| | Kashong | 13.6 | | 17.6 | 4.8 | 4.1 | 6.3 | 26.5 | 18.2 | 10.1 | 7.1 |
| | Keuka Out | 9.8 | 23.3 | 10.9 | 6.5 | 5.7 | 11.5 | 5.7 | 12.4 | 31.1 | 16.9 |
| | Plum Pt. | 9.8 | 6.6 | 7.6 | 3.2 | 9.6 | 4.7 | 20.1 | 7.5 | 8.5 | 5.1 |
| | Big Stream | 15.3 | 63.9 | 45.3 | 59.2 | 61.6 | 54.8 | 25.4 | 52.7 | 24.0 | 43.6 |
| | Reeder | | 13.5 | 9.5 | 31.6 | 75.4 | 118 | 197 | 88.3 | 145 | 102 |
| | Kendig | | 5.2 | 29.4 | 5.1 | 22.9 | 17.5 | 45.1 | 20.1 | 31.2 | 4.5 |
| Nitrate (mg/L, N) | Wilson | 0.1 | 0.1 | 0.9 | 0.6 | 1.2 | 2.3 | 0.5 | 0.9 | 1.3 | 0.9 |
| | Kashong | 0.1 | 0.1 | 0.8 | 0.3 | 1.5 | 2.1 | 0.6 | 1.3 | 1.1 | 0.6 |
| | Keuka Out | 0.1 | 0.1 | 0.4 | 0.5 | 0.5 | 0.9 | 0.3 | 0.9 | 2.1 | 0.6 |
| | Plum Pt. | 0.1 | 0.5 | 0.6 | 0.6 | 1.1 | 1.6 | 1.1 | 1.1 | 1.3 | 1.0 |
| | Big Stream | 0.1 | 0.1 | 0.3 | 0.2 | 0.6 | 1.5 | 0.3 | 0.6 | 0.6 | 0.4 |
| | Reeder | | 0.1 | 0.7 | 0.6 | 1.6 | 1.3 | 0.2 | 0.9 | 0.7 | 0.6 |
| | Kendig | | 0.2 | 0.8 | 0.2 | 1.0 | 1.5 | 0.5 | 0.7 | 0.9 | 0.1 |
| Dissolved Silica (µg/L, Si) | Wilson | 260 | 1518 | 1356 | 1491 | 1359 | 1876 | 2232 | 1717 | 1343 | 1567 |
| | Kashong | 219 | | 921 | 1423 | 878 | 1679 | 2083 | 1848 | 1418 | 1643 |
| | Keuka Out | 84 | 350 | 904 | 367 | 336 | 545 | 710 | 670 | 855 | 603 |
| | Plum Pt. | 245 | 1480 | 1740 | 1502 | 1705 | 2033 | 2952 | 1959 | 1323 | 2062 |
| | Big Stream | 226 | 2150 | 1445 | 1228 | 1285 | 1488 | 1821 | 1439 | 1166 | 1290 |
| | Reeder | | 1694 | 1382 | 2255 | 2352 | 1584 | 1896 | 1994 | 2087 | 2480 |
| | Kendig | | 1794 | 802 | 705 | 875 | 980 | 1026 | 465 | 640 | 505 |
| Total Suspended Solids (mg/L) | Wilson | 2.9 | 1.6 | 2.9 | 2.1 | 3.6 | 2.0 | 2.6 | 1.7 | 1.0 | 2.4 |
| | Kashong | 2.9 | | 3.8 | 1.2 | 1.5 | 4.2 | 2.7 | 1.3 | 1.6 | 4.1 |
| | Keuka Out | 53.6 | 2.0 | 8.9 | 3.3 | 1.7 | 5.2 | 6.5 | 4.0 | 2.3 | 3.6 |
| | Plum Pt. | 1.9 | 0.0 | 4.2 | 1.6 | 2.0 | 2.8 | 0.7 | 0.9 | 0.8 | 9.7 |
| | Big Stream | 6.7 | 5.9 | 3.6 | 2.7 | 7.2 | 1.9 | 1.3 | 1.5 | 1.9 | 8.8 |
| | Reeder | | 1.4 | 9.0 | 1.2 | 2.7 | 0.5 | 1.7 | 3.9 | 0.9 | 1.5 |
| | Kendig | | 10.4 | 10.1 | 1.8 | 2.9 | 2.6 | 7.3 | 1.8 | 2.8 | 3.4 |
| Conductivity (µS/cm) | Wilson | 504 | 509 | 687 | 636 | 715 | 721 | 630 | 615 | 587 | 632 |
| | Kashong | 489 | 388 | 651 | 584 | 602 | 657 | 586 | 554 | 518 | 548 |
| | Keuka Out | 300 | 275 | 359 | 362 | 316 | 393 | 321 | 378 | 413 | 339 |
| | Plum Pt. | 350 | 690 | 510 | 689 | 563 | 580 | 447 | 575 | 456 | 603 |
| | Big Stream | 232 | 555 | 335 | 485 | 417 | 404 | 341 | 365 | 305 | 414 |
| | Reeder | | 499 | 524 | 591 | 626 | 668 | 550 | 595 | 514 | 643 |
| | Kendig | | 388 | 538 | 551 | 570 | 709 | 510 | 506 | 480 | 477 |
| *E. coli* Bacteria (#/100 mL) | Wilson | | | | | | 29 | 98 | 156 | | |
| | Kashong | | | | | | 24 | 30 | 285 | | |
| | Keuka Outlet | | | | | | 51 | 60 | 99 | | |
| | Plum Pt. | | | | | | 74 | 36 | 368 | | |
| | Big Stream | | | | | | 24 | 52 | 220 | | |
| | Reeder | | | | | | 69 | 148 | 98 | | |
| | Kendig | | | | | | 24 | 119 | 0 | | |
| Total Coliform Bacteria (#/100 mL) | Wilson | | | | | | 2915 | 2497 | 1439 | | |
| | Kashong | | | | | | 928 | 623 | 835 | | |
| | Keuka Outlet | | | | | | 745 | 765 | 960 | | |
| | Plum Pt. | | | | | | 856 | 678 | 1742 | | |
| | Big Stream | | | | | | 933 | 439 | 1240 | | |
| | Reeder | | | | | | 780 | 1182 | 1618 | | |
| | Kendig | | | | | | 946 | 1220 | 198 | | |

agricultural land and the Seneca Army depot. Concentrated animal feedlot operations (CAFOs) release phosphates from the bacterial decomposition of animal wastes spread on farmland. The army is systematically disposing of and exploding old munitions at the depot, and munitions contain phosphorus. Both events were initiated near this concentration transition. Thus, a cause and effect relationship is suggested but clearly more research is required to adequately assess the jump in phosphorus over the past few years.

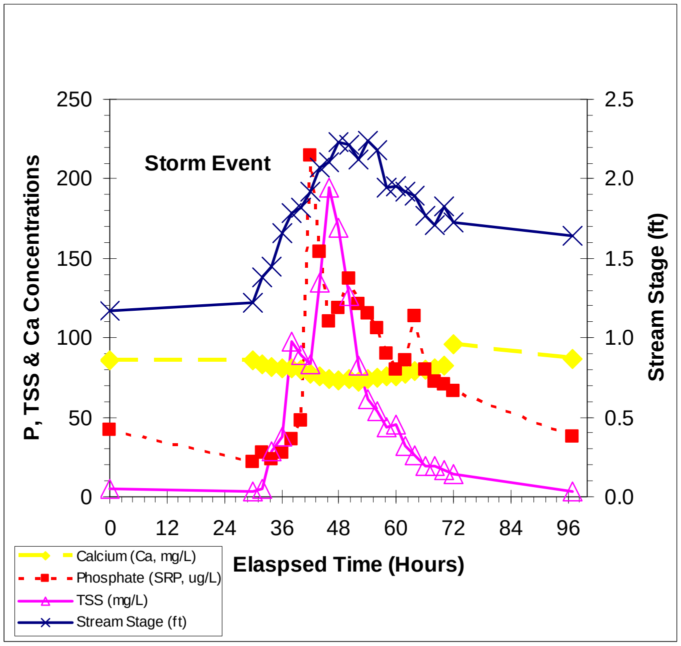


Fig. 10. Storm event increases in water, nutrient and total suspended sediment surface runoff, and decrease in (dilution of) calcium and other groundwater fed constituents (Kostick and Halfman, 2003)

The combined fluvial flux of phosphate to the lake is, on average, 17 metric tons of phosphorus per year, assuming a mean phosphate concentration of 20 μg/L and an estimated annual stream discharge of 863 x 10$^{6}$ m$^{3}$. This flux will be refined (most likely increased) as more research adds the relative contributions of peak to the mean base flow, the contributions from the fall, winter, and spring snowmelt to the available summer season data, and more thorough measurements of stream discharge to the lake. Nutrient budgets must also include nutrient losses from the lake to determine if the lake gained or lost nutrients over time. Seneca Lake looses nutrients through the outlet and to the sediments. The flux of phosphorus from the lake through the outlet is ~7 metric tons per year, assuming an outflow discharge of 760 x 10$^{6}$ m$^{3}$/year, and mean TP concentration of 9 μg/L in the lake. Thus, these preliminary estimates indicate that the lake gains more phosphorus from the watershed than it looses through the outlet. Sediment data are lacking to accurately calculate the phosphorus flux to the sediments. However, the phosphorus lost to the sediments is assumed to be minimal because aquatic ecosystems are very efficient at recycling nutrients back to the water column before the organic matter is buried into the sediments.

In conclusion, the Seneca Lake watershed has a number point and nonpoint sources of nutrients. These include municipal wastewater treatment facilities and onsite wastewater treatment (septic systems), runoff from agricultural land both crop farming and animal husbandry, and runoff of nutrients and other products from well manicured lawns. The relative impact from each source is difficult to determine. However, the combined impact has increased productivity in Seneca Lake. The lake will become eutrophic in one or two decades if steps are not taken to reduce these water quality threats.

***Herbicides and Coliform Bacteria:*** The source of atrazine in the Seneca Lake watershed was investigated in 1999 and 2000 (Fig. 11, McSweeney, 1999; Baldwin and Halfman, 2000). Atrazine concentrations were typically below 1.0 μg/L through out 1999. In 2000, concentrations were similar to 1999 values up to the end of May. After May, stream

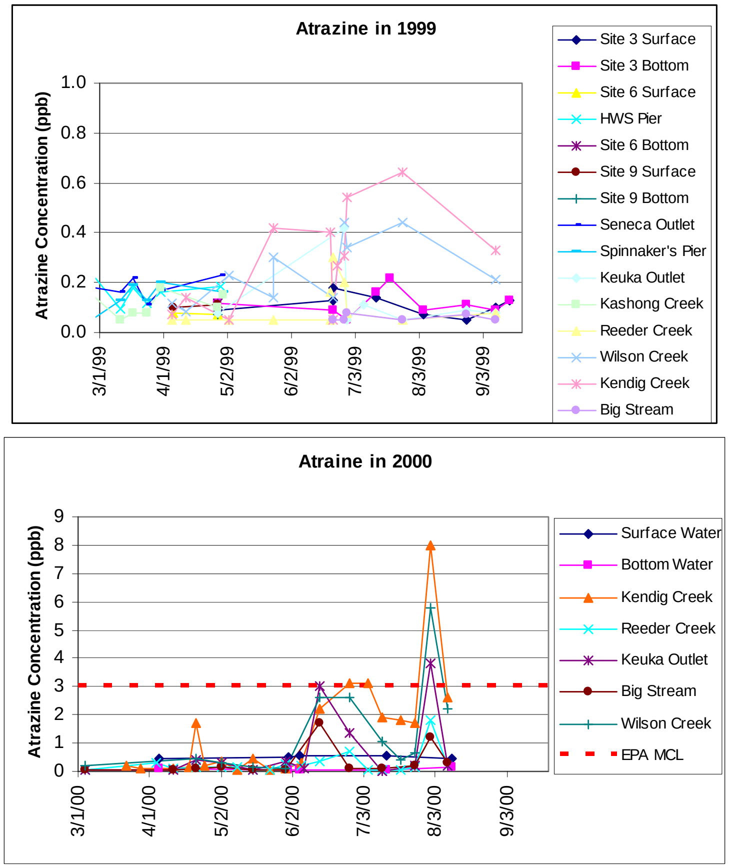


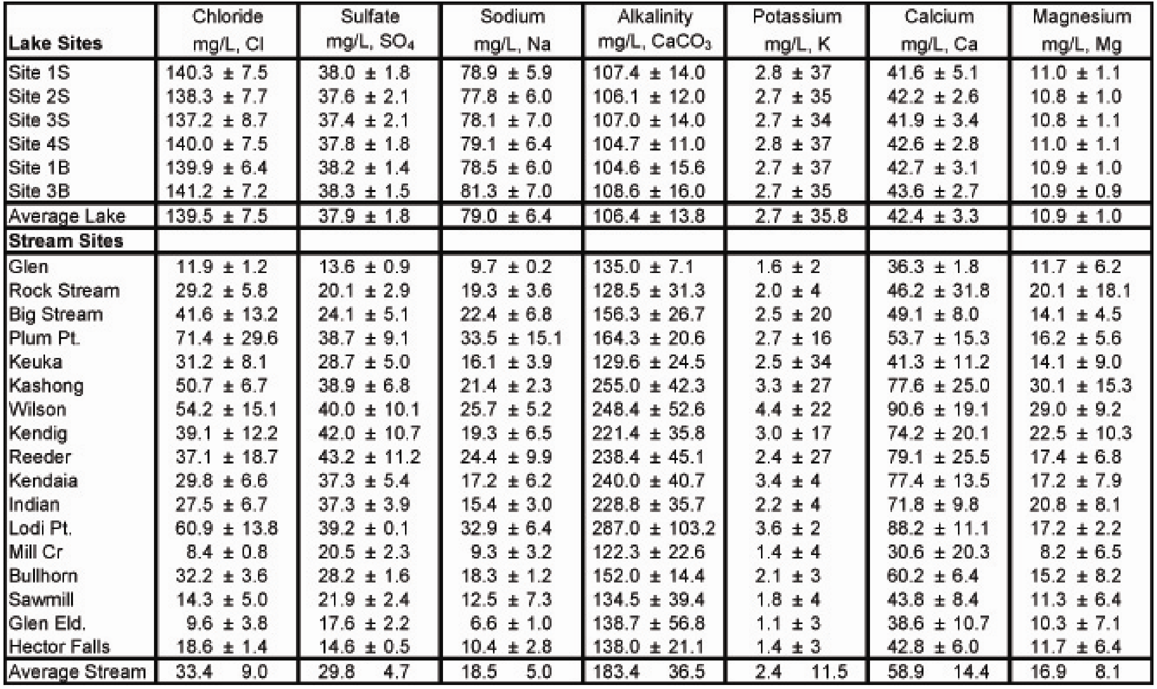
Fig. 11. Atrazine concentrations in Seneca Lake and its major tributaries from 1999 and 2000. Note the scale change between years (McSweeney, 1999; Baldwin and Halfman, 2000).

concentrations rose to or very close to 3 μg/L, the EPA's MCL, with the largest detected concentration of 8 μg/L at Kendig Creek (August, 2000). The following spatial and temporal changes were observed. First, streams draining more agricultural land had larger atrazine concentrations. Second, atrazine concentrations peaked during June, July and August, a timing that corresponds with the application of atrazine in the fields. Third, the amount of rainfall co-varied with the concentration of atrazine in the runoff. The largest concentrations were detected during a major rainfall event (August, 2000). The smaller concentrations in 1999 compared to 2000 corresponded to lower rainfall in 1999. Finally, none of the lake concentrations exceeded 1 μg/L, and were consistently below the EPA's MCL. However, atrazine in the lake increased from below 0.2 μg/L in 1999 to over 0.4 μg/L in 2000, perhaps reflecting the increased flux of atrazine from the watershed during 2000. Additional research is dictated to investigate the recent trends, lake concentrations, and initiate measurement of other herbicides, pesticides, and various antibodies, estrogens, hormones and human health care products. The future is unclear. For example, corn production may increase after the establishment of the proposed ethanol facility, and may further impact water quality in Seneca Lake.

Total coliform and *E. coli* bacteria were measured in lake and stream samples in 2003, 2004 and 2005 (Fig. 9, Bush and Halfman, 2004; Bush, 2006). Total coliform and *E. coli* bacteria concentrations were typically below the EPA's MCL for drinking water (geometric means of 2400 CFU/100mL for total coliform and 235 CFUs/100mL for *E. coli*). Lake samples were typically ten times less concentrated than stream water, and lacked any temporal or spatial trends. Bacteria concentrations were largest in the streams during runoff events, and a runoff event influenced the large mean counts in 2005. Wilson Creek and Hector Falls Creek, regularly had larger bacteria concentrations than the other streams, especially during runoff events. It suggests that agricultural and rural landscapes with aging septic systems input more bacterial than the other drainage systems, and pose potential but currently not detrimental threats to the Seneca Lake watershed.

***Seneca Lake Hydrogeochemistry:*** Seneca Lake is dominated by chloride, bicarbonate (measured as alkalinity), sodium and calcium with lesser amounts of sulfate, magnesium and potassium reflecting the weathering of carbonate-rich bedrock and soils (Table 6, Fig. 12). The lake is more saline than the other Finger Lake due to elevated chloride and sodium concentrations. For example, chloride and sodium concentrations are ~140 and ~80 mg/L in Seneca Lake and only ~40 and ~20 mg/L in the other Finger Lakes, respectively. These concentrations are not a drinking water concern but their source requires elaboration to assess if it may change in the future. The chloride and sodium concentrations in the tributaries are insufficient to provide concentrations detected in Seneca and Cayuga Lakes, and clearly additional source(s) are required for these lakes. In contrast, stream concentrations are similar to those detected in the other Finger Lakes, indicating that fluvial sources supply the bulk of their ions. Plum Pt. had larger sodium and chloride concentrations than the other tributaries, and is interpreted to reflect the drainage of an abandoned salt mine operations in the drainage.

Table 6. Site-Averaged Major Ion Data (Halfman et al., 2006).



| Lake Sites | Chloride mg/L, Cl | Sulfate mg/L, $SO_4$ | Sodium mg/L, Na | Alkalinity mg/L, $CaCO_3$ | Potassium mg/L, K | Calcium mg/L, Ca | Magnesium mg/L, Mg |
|---|---|---|---|---|---|---|---|
| Site 1S | 140.3 ± 7.5 | 38.0 ± 1.8 | 78.9 ± 5.9 | 107.4 ± 14.0 | 2.8 ± 37 | 41.6 ± 5.1 | 11.0 ± 1.1 |
| Site 2S | 138.3 ± 7.7 | 37.6 ± 2.1 | 77.8 ± 6.0 | 106.1 ± 12.0 | 2.7 ± 35 | 42.2 ± 2.6 | 10.8 ± 1.0 |
| Site 3S | 137.2 ± 8.7 | 37.4 ± 2.1 | 78.1 ± 7.0 | 107.0 ± 14.0 | 2.7 ± 34 | 41.9 ± 3.4 | 10.8 ± 1.1 |
| Site 4S | 140.0 ± 7.5 | 37.8 ± 1.8 | 79.1 ± 6.4 | 104.7 ± 11.0 | 2.8 ± 37 | 42.6 ± 2.8 | 11.0 ± 1.1 |
| Site 1B | 139.9 ± 6.4 | 38.2 ± 1.4 | 78.5 ± 6.0 | 104.6 ± 15.6 | 2.7 ± 37 | 42.7 ± 3.1 | 10.9 ± 1.0 |
| Site 3B | 141.2 ± 7.2 | 38.3 ± 1.5 | 81.3 ± 7.0 | 108.6 ± 16.0 | 2.7 ± 35 | 43.6 ± 2.7 | 10.9 ± 0.9 |
| Average Lake | 139.5 ± 7.5 | 37.9 ± 1.8 | 79.0 ± 6.4 | 106.4 ± 13.8 | 2.7 ± 35.8 | 42.4 ± 3.3 | 10.9 ± 1.0 |
| **Stream Sites** | | | | | | | |
| Glen | 11.9 ± 1.2 | 13.6 ± 0.9 | 9.7 ± 0.2 | 135.0 ± 7.1 | 1.6 ± 2 | 36.3 ± 1.8 | 11.7 ± 6.2 |
| Rock Stream | 29.2 ± 5.8 | 20.1 ± 2.9 | 19.3 ± 3.6 | 128.5 ± 31.3 | 2.0 ± 4 | 46.2 ± 31.8 | 20.1 ± 18.1 |
| Big Stream | 41.6 ± 13.2 | 24.1 ± 5.1 | 22.4 ± 6.8 | 156.3 ± 26.7 | 2.5 ± 20 | 49.1 ± 8.0 | 14.1 ± 4.5 |
| Plum Pt. | 71.4 ± 29.6 | 38.7 ± 9.1 | 33.5 ± 15.1 | 164.3 ± 20.6 | 2.7 ± 16 | 53.7 ± 15.3 | 16.2 ± 5.6 |
| Keuka | 31.2 ± 8.1 | 28.7 ± 5.0 | 16.1 ± 3.9 | 129.6 ± 24.5 | 2.5 ± 34 | 41.3 ± 11.2 | 14.1 ± 9.0 |
| Kashong | 50.7 ± 6.7 | 38.9 ± 6.8 | 21.4 ± 2.3 | 255.0 ± 42.3 | 3.3 ± 27 | 77.6 ± 25.0 | 30.1 ± 15.3 |
| Wilson | 54.2 ± 15.1 | 40.0 ± 10.1 | 25.7 ± 5.2 | 248.4 ± 52.6 | 4.4 ± 22 | 90.6 ± 19.1 | 29.0 ± 9.2 |
| Kendig | 39.1 ± 12.2 | 42.0 ± 10.7 | 19.3 ± 6.5 | 221.4 ± 35.8 | 3.0 ± 17 | 74.2 ± 20.1 | 22.5 ± 10.3 |
| Reeder | 37.1 ± 18.7 | 43.2 ± 11.2 | 24.4 ± 9.9 | 238.4 ± 45.1 | 2.4 ± 27 | 79.1 ± 25.5 | 17.4 ± 6.8 |
| Kendaia | 29.8 ± 6.6 | 37.3 ± 5.4 | 17.2 ± 6.2 | 240.0 ± 40.7 | 3.4 ± 4 | 77.4 ± 13.5 | 17.2 ± 7.9 |
| Indian | 27.5 ± 6.7 | 37.3 ± 3.9 | 15.4 ± 3.0 | 228.8 ± 35.7 | 2.2 ± 4 | 71.8 ± 9.8 | 20.8 ± 8.1 |
| Lodi Pt. | 60.9 ± 13.8 | 39.2 ± 0.1 | 32.9 ± 6.4 | 287.0 ± 103.2 | 3.6 ± 2 | 88.2 ± 11.1 | 17.2 ± 2.2 |
| Mill Cr | 8.4 ± 0.8 | 20.5 ± 2.3 | 9.3 ± 3.2 | 122.3 ± 22.6 | 1.4 ± 4 | 30.6 ± 20.3 | 8.2 ± 6.5 |
| Bullhorn | 32.2 ± 3.6 | 28.2 ± 1.6 | 18.3 ± 1.2 | 152.0 ± 14.4 | 2.1 ± 3 | 60.2 ± 6.4 | 15.2 ± 8.2 |
| Sawmill | 14.3 ± 5.0 | 21.9 ± 2.4 | 12.5 ± 7.3 | 134.5 ± 39.4 | 1.8 ± 4 | 43.8 ± 8.4 | 11.3 ± 6.4 |
| Glen Eld. | 9.6 ± 3.8 | 17.6 ± 2.2 | 6.6 ± 1.0 | 138.7 ± 56.8 | 1.1 ± 3 | 38.6 ± 10.7 | 10.3 ± 7.1 |
| Hector Falls | 18.6 ± 1.4 | 14.6 ± 0.5 | 10.4 ± 2.8 | 138.0 ± 21.1 | 1.4 ± 3 | 42.8 ± 6.0 | 11.7 ± 6.4 |
| Average Stream | 33.4 9.0 | 29.8 4.7 | 18.5 5.0 | 183.4 36.5 | 2.4 11.5 | 58.9 14.4 | 16.9 8.1 |

Wing et al. (1995) hypothesized that Seneca, and to a lesser extent Cayuga Lake, has an additional groundwater source of chloride to compliment fluvial sources because the bedrock floor of these two lakes is deep enough to intersect the Silurian beds of commercial grade rock salt located ~450-600 m below the surface. Mass-balance arguments by Halfman et al. (2006) indicate that sodium is stoichiometrically consistent with chloride, and supports the groundwater source hypothesis. Sediment pore water analyses indicated that chloride and sodium enters the lake by advection and not diffusion through the sediments. Finally, Jolly (2005, 2006) presented historical chloride concentrations for Cayuga and Seneca Lakes over the past century (Fig. 13). Chloride concentrations were ~40 mg/L in 1900, rose to ~170 mg/L by the 1960's, and subsequently decreased since 1980 to the present day concentration of ~120 mg/L in Seneca

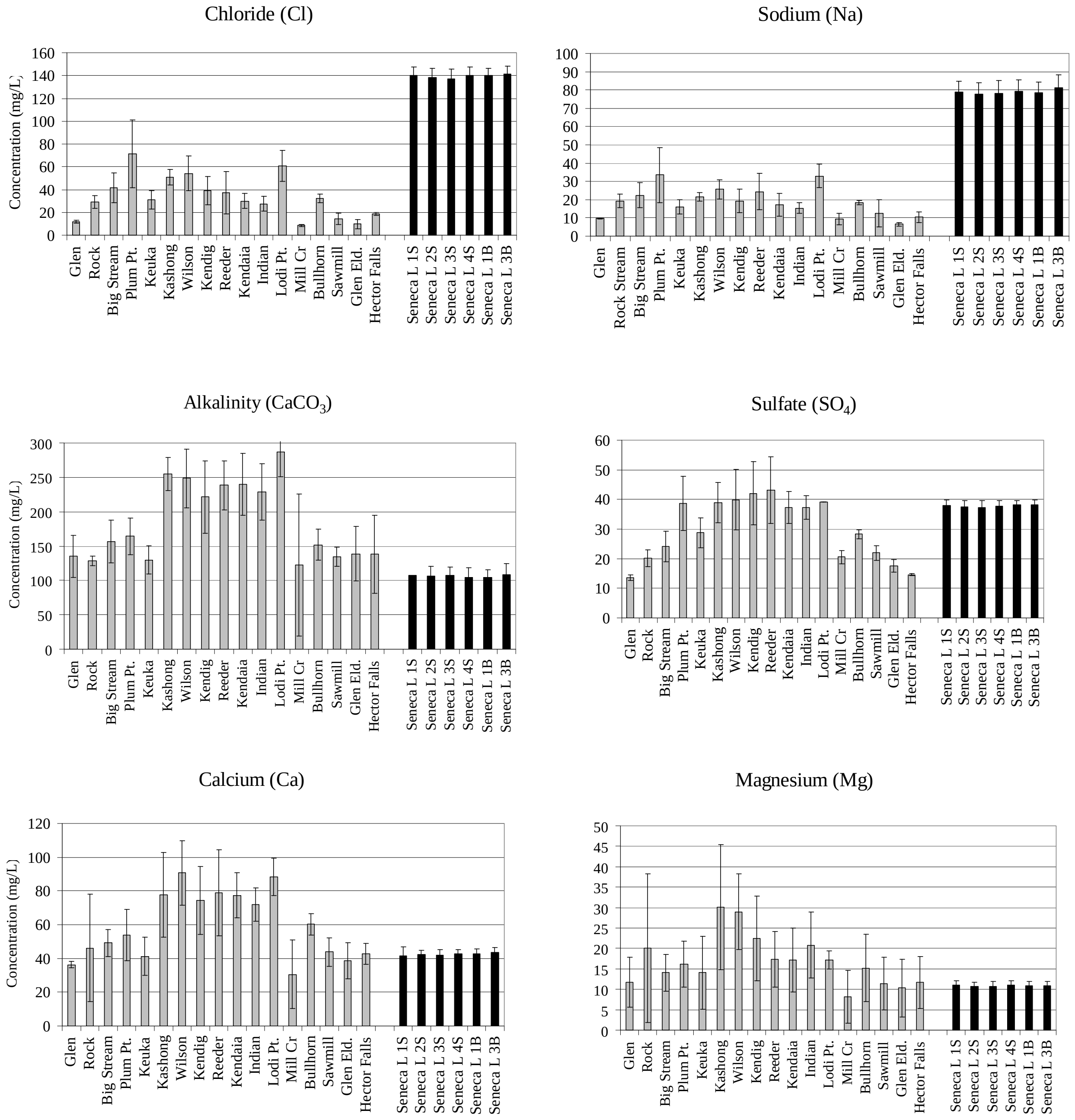


Fig. 12. Major ion mean concentrations in Seneca Lake and its major tributaries (Halfman et al., 2006).

Lake. Similar trends with peak concentrations of 120 mg/L were detected in Cayuga Lake. These historical trends are unique as chloride data from Canadice, Hemlock and Skaneateles Lakes steadily increased from below 10 mg/L to above 30 mg/L from 1920 to the present day. The other lake trends are interpreted to reflect the increased use of road salt on our major roadways (Sukeforth and Halfman, 2006). The historical data still requires a groundwater source for the excess chloride and sodium, however it dictates that the flux of salt varied during the past century. Perhaps the change in groundwater sources is related to changes in solution salt mining activities under the watershed. However, mining activity data are currently unavailable to support this speculation, and earthquake activity may have opened and later closed avenues for the salt to flow from the bedrock through the overlying sediments into the lake.

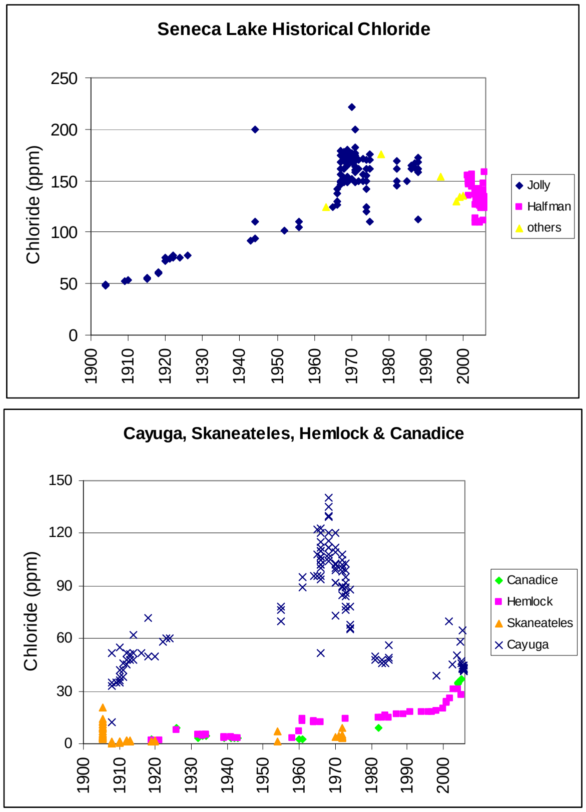


Fig. 13. Historical chloride concentrations in Seneca and Cayuga Lakes (Jolly, 2005 and 2006), and in Canadice, Hemlock and Skaneateles Lakes (Sukeforth and Halfman, 2006)

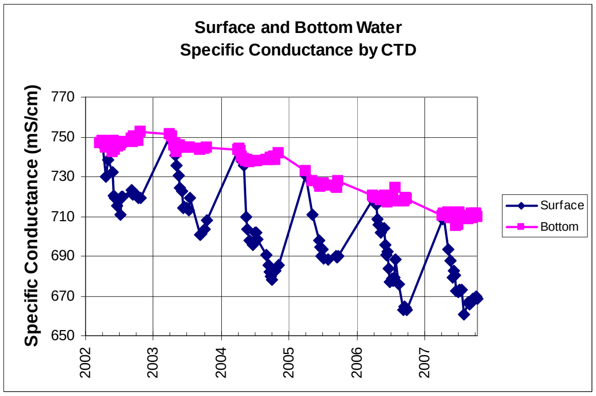


Fig. 14. Surface and bottom water average specific conductance data from available CTD profiles (Dye and Halfman, 2007).

Dye and Halfman (2007) investigated the recent decrease in salinity in Seneca Lake (Fig. 14). CTD profiles from the past eight years revealed that surface and bottom water specific conductance were the same during the early spring and late fall when the lake was isothermal. Epilimnetic specific conductance decreased through the year during thermal stratification, then rose at the end of the year during fall overturn and subsequent mixing of the entire water coloumn. The decrease reflects the input of less saline tributary water. Bottom water remained unchanged until overturn, and then concentrations decreased slightly. Surface and bottom water chloride and sodium ion concentrations revealed similar trends. It indicates that the extra source of chloride and sodium to the lake has reduced, if not turned off, since the 1970s, and the lake is progressively becoming more dilute from the input of “fresher” tributary water. The variability nicely depicts the time it takes to first “pollute” and later “cleanse” a lake of chloride and sodium and could be used to model conservative pollutants.

Sulfate, alkalinity, calcium and magnesium comprise the other major ions in the lake with mean lake concentrations of 40, 105, 42 and 11 mg/L, respectively (Halfman et al., 2006). Similar mass-balance arguments indicate that the fluvial inputs of sulfate, like chloride and sodium, are insufficient to supply the sulfate in the lake. It suggests that sulfate also has an additional groundwater source, perhaps originating from the underlying gypsum-rich ($CaSO_4 \cdot H_20$), Bertie Formation. The calcium and magnesium data indicate that Seneca Lake water is moderately hard, with total hardness concentrations of 140 - 150 mg/L ($CaCO_3$). Lake water is not as hard as the local groundwater, however. Calcium, magnesium and alkalinity concentrations are smaller in the lake than the tributaries in the watershed, opposite to the chloride, sodium and sulfate distribution (Halfman et al., 2006). The tributary to lake decrease is interpreted to reflect the utilization of calcium, magnesium and alkalinity in the lake primarily during the precipitation of fine-grained, calcium carbonate ($CaCO_3$) from the water column during algal blooms when the lake is calm and very warm. Calcium and bicarbonate ions are also required to precipitate calcium carbonate shells for zebra mussels, clams, snails and other shelled animals. Preliminary calculations suggest that zebra mussels remove approximately 30% of the calcium precipitated on the lake floor, however these calculations are based on crude estimates of zebra mussel populations (Halfman et al., 1999; Halfman et al., 2006).

The pH of Seneca Lake varied from 8.0 to 9.0. Thus, acid rain has had a minimal impact on the acidity of the lake. The difference between Seneca Lake and the acid rain impaired lakes in the Adirondack relates to the variability in buffering capacity (i.e., the ability to neutralize acids) of their respective watersheds. Acid rain reacts with and is neutralized by lime-rich soils, limestone bedrock, and lakes are buffered by carbonate ($CO_3^{2-}$) and bicarbonate ($HCO_3^-$) ions in the water. Limestone is abundant in the glacial tills and bedrock under the northern portion of the watershed, and the lake is alkaline, i.e., the water is rich in bicarbonate. Thus, acid precipitation is neutralized before it impacts the pH of Seneca Lake. The lakes in the Adirondacks are less fortunate, especially in the high peaks region.

## CONCLUSIONS & RECOMMENDATIONS:

Seneca Lake is a borderline mesotrophic ecosystem. None of the water quality parameters are life threatening at the present time. The trends over the past two decades reveal significant impacts by zebra and quagga mussels, especially in the 1990s. Nutrient loading has impaired water quality over the past five years. Nutrients and other loadings from the watershed (e.g., suspended sediments) will degrade water quality in the lake into the future if not addressed in a meaningful and sustainable manner. Identified sources of nutrients and other pollutants include a wastewater treatment facility, and runoff from onsite wastewater systems, agricultural activities, soil erosion, fertilized lawns, roadside ditches and construction activities.

Due to the variety of the pollutant sources, remediation efforts should be multifaceted to improve water quality in Seneca Lake and its tributaries.

***Municipal Wastewater Facilities:*** Wastewater treatment facilities should evaluate the treatment and removal of nutrients from their effluent. Those with minimal phosphorus removal should add appropriate tertiary treatment systems. Selection of the best method must balance the effectiveness of the removal process with its costs. Any additional treatment procedure adds to the capital and operating costs of running the facility, costs that will be passed on to the users of each facility.

***Other Industrial Facilities:*** Current permitted discharges should be evaluated to assess the impact on the lake and its ecosystem. For example, more research is required to determine the source and fate of chloride and sodium salts in the lake from mining activities and application of road salt. Its variability over the past century is perplexing but intellectually useful to understand and model.

***Agricultural BMPs:*** Various "best management practices" (BMPs) are available to reduce the nonpoint source contributions from the agricultural sector, both crop farming and animal husbandry. Implemented BMPs can include contour plowing, installation of settling ponds, buffer vegetation strips, minimal tillage farming, manure digesters, and others. Steps should be taken to investigate which are practices most effective for this watershed and which mechanisms must be in place so that the entire economic burden is not placed solely on the farmer. In some cases education is critical to gain acceptance and follow through with adaptation of these practices. Perhaps the ongoing, USDA funded-research on various BMPs in the Conesus watershed by SUNY Brockport, County Soil and Water, and colleagues, will shed light on practical systems to use in the Owasco watershed.

***Watershed Inspector:*** A watershed inspector, staff and office should be established in this watershed with enough support and authority to protect and preserve Seneca Lake as a potable water source. This is a significant challenge because funding and jurisdiction is at odds with traditional town, county and state agencies and boundaries. We recommend that the inspector's office work in conjunction with existing County Soil and Water Offices, Seneca Lake Area Partners in Five Counties (SLAP-5), Cornell Cooperative Extension Offices, concerned citizens and the Finger Lakes Institute to promote and implement best management practices that reduce nutrient loading from agricultural landscapes; initiate an onsite system inspection program and lawn care fertilizer and herbicide reduction seminars for lakefront property owners; mitigate the impact of construction and roadside ditch drainage activities; and, update watershed protection legislation for the entire Seneca Lake Watershed. Taken together, these steps would reduce nutrient loading to and increase water quality in the lake. Sufficient funding is essential. One model to support the Inspector, and related staff and operations budget, would be a tax on water users. If levied at a few dollars per user per year, the tax would provide a viable operational budget to support the program. In fact, an inspector's office might save the water users money in the long run, by reducing the cost of filtering algae and suspended sediment from the water before it is delivered to the consumer.

***Education:*** Education is also critical for local residents to understand the need for properly functioning onsite wastewater treatment systems and environmentally friendly (less fertilized) lawns to help reduce the seepage and runoff of nutrients to the lake. The education starts at primary and secondary levels but should also include the average homeowner, government officials, and environmental protection associations. The Finger Lakes Institute has an active K-12 outreach program that utilizes our 65-ft research vessel on Seneca Lake and various exercises that teachers can bring into their classrooms. It is currently underutilized by the numerous secondary programs throughout the watershed. FLI sponsors a successful community outreach program as well.

***Stream and Lake Monitoring:*** Finally, water quality monitoring of selected streams and lake sites should continue into the future. At a minimum, both peak flow and base flow fluxes must be quantified for phosphates, total suspended solids and nitrates, and encompass samples from the seven tributaries utilized in this study. This minimal effort will evaluate the effectiveness of the nutrient reduction strategies in the largest tributaries to the lake but does not assess the entire watershed and other critical pollutants. We suggest that a monitoring program should include the other major tributaries in the watershed, year round sampling, and add analyses for herbicides, pesticides, heavy metals, organic compounds like PCBs and DDT, human and concentrated animal healthcare products like antibiotics, estrogens and other hormones, and coliform bacteria because protection of our water supply is worth the cost. Lake sites should also be monitored for the same list of parameters.  The Finger Lakes Institute plans to continue its monitoring of the lake and watershed in the years to come.  The nature of the FLI monitoring program and its diversity of analyses, however depends on funding.

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