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Water Quality of the North End of Cayuga Lake: 1991-2006

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SUMMARY

The Seneca County Soil and Water Conservation District (SCSWCD) has collected limnological data on the waters of the northern end of Cayuga Lake since 1991. This report updates the 1999 report (Makarewicz *et al*. 1999) with data taken by the SCSWCD from 1999 to 2006. The purpose of monitoring the northern portion of Cayuga Lake was to determine the health of the Cayuga Lake ecosystem and to determine if any temporal trends existed in Cayuga Lake water quality. The water quality of Cayuga Lake has been studied since the early 1900s when secchi disk readings were first taken. At that time, the trophic state of Cayuga Lake was classified as oligotrophic; that is, nutrient concentrations and primary production were low and transparency high. Water clarity remained approximately the same up through the early 1930s. By the late 1950s, water clarity had decreased enough to classify Cayuga Lake as mesotrophic. Total phosphorus concentrations from the 1960s were well within the mesotrophic range and remained so until the late 1960s. Chl-*a* concentration also illustrated the trend toward more productive waters in Cayuga Lake in the mid 1960s through the 1970s. By the late 1970s, the transparency of Cayuga Lake had decreased to a nearly eutrophic value. In fact, in the early 1970s, some ranked Cayuga Lake as being the most eutrophic of the Finger Lakes of upstate New York. In a 2001 report, Callinan (2001) suggested an improvement in trophic state of Cayuga Lake by characterizing the main portion of Cayuga Lake borderline between oligotrophic and mesotrophic.

Based on the sampling done by the Seneca County Soil and Water Conservation District from 1991 to 2006, an improvement in water quality of Cayuga Lake is suggested – at least at the north end where the samples were taken. Summer total phosphorus levels have significantly decreased and transparency of the northern end of the lake has significantly increased. Ambient chlorophyll levels were directly related to total phosphorus; that is chlorophyll, a measure of phytoplankton in the lake, was a function of phosphorus concentrations. As in the 1991-1998 period, the current (1999-2006) trophic status of Cayuga Lake is currently best described as mesotrophic. In conclusion, water quality of Cayuga Lake appears to have improved since the early 1970s and also within the 1991-2006 period of monitoring by the Seneca County Soil and Water Conservation District.

INTRODUCTION

Cayuga Lake, the longest of the Finger Lakes, is 435 feet deep at the deepest point off King Ferry, NY. With a length of just under 40 miles, Cayuga Lake represents a major water resource of considerable economic, recreational and aesthetic value to central New York State. As a result of the scenic lake views and the development of the wine industry in central New York, Cayuga Lake, as well as many of the other Finger Lakes, has become a destination of choice for tourists providing significant support for the local economy. Thus prevention of deterioration of water quality and maintenance of Cayuga Lake's water quality and environmental health are important to the maintenance of the tourist industry and to the public in general. A key to maintenance of water quality is having information on the current status of the lake system and comparing it with historical data to obtain trends over time. Monitoring is a process by which water samples are taken each year at the same location within the lake and analyzed for critical factors that allow determination of trends in the health of the lake. Monitoring provides the important function of documenting gradual improvements that may result from restoration efforts and remedial action plans. Similarly, monitoring provides evidence of deterioration of water quality and thus the opportunity for a management response and notification of the public of such changes.

Monitoring the water quality of Cayuga Lake has continued periodically from the early 1900s to the present. The Seneca County Soil and Water Conservation District (SCSWCD) has collected limnological data on the waters of the northern end of Cayuga Lake since 1991. This report updates the 1999 report (1991 to 1998) (Makarewicz *et al*. 1999) with data taken by the SCSWCD from 1999 to 2006. By considering nutrient and chlorophyll *a* concentrations and water clarity measurements, we reviewed the current data from Cayuga Lake with historical measurements of the lake.

METHODS

General:

Cayuga Lake was sampled once a week usually from late June or early July to September from 1999 to 2006 by personnel from the Seneca County Soil and Water Conservation District. Secchi disk measurements were taken at six different sites along the center axis of Cayuga Lake. All samples collected for water quality analysis were taken from Site #2 (Figure 1) with a Van Dorn water bottle at a depth of 1.5 m. Water depth at this site was 3.5 m. Once samples were taken, they were packed in ice and transported to SUNY College at Brockport for water quality analysis within one day. A subsample was filtered on site for soluble nutrient analysis through a 0.45-µm membrane filter. Parameters analyzed included nitrate + nitrite, total phosphorus (TP), soluble reactive phosphorus (SRP), chlorophyll-*a* (Chl-*a*), and turbidity.

Water Chemistry:

Nitrate + Nitrite: Dissolved nitrate + nitrite nitrogen analyses were performed by the automated (Technicon Autoanalyser II) cadmium reduction method (APHA 1999).

Total Phosphorus: The persulfate digestion procedure was used prior to analysis by the automated (Technicon Autoanalyser II) colorimetric ascorbic acid method (APHA 1999).

Soluble Reactive Phosphorus: Sample water was filtered through a 0.45-µm membrane filter. The filtrate was analyzed for orthophosphate using a Technicon Autoanalyzer II by the colorimetric ascorbic acid method (APHA 1999).

Turbidity: Turbidity was measured using a Turner nephelometer. The turbidimeter was calibrated with a known standard prior to measurements with routine verifications during analysis.

Chlorophyll *a*: Chlorophyll *a* was measured fluorometrically using a Turner Model 111 Fluorometer. Approximately 800 mL aliquots were filtered through glass fiber filters and extracted with 90% alkaline acetone. Extracted samples were centrifuged and measured fluorometrically (Wetzel and Likens 1994).

Secchi Disk: The secchi disk depth was determined using a black and white 20-cm disk.

Quality Assurance/Quality Control: The Water Quality Lab at SUNY Brockport is NELAC certified (ELAP #11439, EPA # NY 01449) and follows all protocols required for certification. This program includes biannual proficiency audits, annual inspections and good laboratory practices documentation of all samples, reagents and equipment. For example, multiple sample control charts (APHA 1999) are constructed for each parameter analyzed. A prepared quality control solution was placed in the analysis stream for each sampling date. If the control solution was beyond the set limits of the control chart, corrective action was taken and the samples re-run. Table 1 is a summary of a recent proficiency audit.

RESULTS and DISCUSSION

Background: A lake that is oligotrophic is biologically unproductive with high transparency and low nutrient concentrations while a eutrophic lake is biologically productive with low transparency and high nutrient concentrations. A mesotrophic lake has characteristics intermediate of oligotrophic and eutrophic. These states of a lake, oligotrophic, mesotrophic and eutrophic, are referred to as the trophic status. With time, soil particles and nutrients from the watershed are gradually added to the lake, increasing concentrations of limiting nutrients such as phosphorus. Biotic productivity increases with the higher nutrient concentrations, sedimentation of dying plankton increases, and transparency of the lake decreases accordingly. This process is natural and is called eutrophication. However, the actions of humans in a lake's watershed can increase the loss of soils and nutrients from the watershed into the lake. This cultural eutrophication accelerates the natural process often leading to deteriorating water quality. Reducing cultural effects by decreasing the rate of eutrophication and improving water quality is the goal of many environmental agencies concerned with the health of lakes.

Historical Conditions: Most of the historical limnological work (see Bloomfield 1978) on Cayuga Lake is from sites south of Aurora, New York (Fig. 1). The water quality of Cayuga Lake has been studied since the early 1900s when secchi disk readings were first taken. At that time, the trophic state of Cayuga Lake was classified as oligotrophic; that is, nutrient concentrations and primary production were low and transparency high.

Water clarity remained approximately the same up through the early 1930s. By the late 1950s, water clarity had decreased enough to classify Cayuga Lake as mesotrophic. Total phosphorus concentrations from the 1960s were well within the mesotrophic range and remained so until the late 1960s. Chl-*a* concentration also illustrated the trend toward more productive waters in Cayuga Lake in the mid 1960s through the 1970s. By the late 1970s, the transparency of Cayuga Lake had decreased to a nearly eutrophic value. Based on average summer secchi disk depth (3.6 m) and average summer chlorophyll levels (8.7 µg/L), Oglesby and Schaffner (1975) classified Cayuga Lake as being the most eutrophic of the Finger Lakes. More recently, the Cayuga Lake Watershed Restoration and Protection Plan (GFLRPC 2001) suggested that recent data confirm that Cayuga Lake is mesotrophic. Similarly, Callinan (2001) suggested an improvement in trophic state of Cayuga Lake by characterizing the main portion of Cayuga Lake borderline between oligotrophic and mesotrophic. However, the shallow areas at the southern end of the lake exhibited higher levels of phosphorus (Callinan 2001).

Phosphorus (Table 2)

Total phosphorus provides an estimate of the total amount of phosphorus potentially available to aquatic plants. Barlow (1969) observed yearly average TP concentrations in Cayuga Lake to range between 15 and 20 µg P/L. Peterson (1971) observed TP concentrations with a range of 9.1 to 56.7 µg P/L with a mean of 18 µg P/L during the months of June through August from 1969 to 1971. Oglesby and Schaffner (1979) analyzed TP concentrations in all of the Finger Lakes of New York State and reported a winter (1972-73) TP concentration of 21.1 µg P/L for Cayuga Lake. Epilimnetic total phosphorus concentrations from the late 1960s through the early 1970s were around 20 µg P/L. Bloomfield (1978) suggested that summer total phosphorus concentrations prior to 1978 were in the 15 to 20 µg P/L throughout the water column.

For the 1991-1998 period, the average TP was 11.4[1] μg P/L with a summer average range of 7.4 ± 1.0 to 16.6 ± 1.6 μg P/L while for the 1999 to 2006 period total phosphorus concentrations were slightly lower as the average was 10.0 μg P/L but with a smaller range of values (7.8 to 12.3 μg P/L). Callinan (2001) reported a 1996-1999 average of 9.7 μg P/L for the main portion of the lake. Based on this classification system of trophic status of a lake, it would appear that TP concentrations at the north end of Cayuga Lake are in or near the oligotrophic range (Table 6).

Considerable variability in TP concentrations existed over the 1991-2006 period (Fig. 2). Regression analysis suggested that there is a significant decrease ($p = 0.037$) in TP since 1991 (Fig. 2). However, concentrations were relatively high in 2005 and 2006 compared to the previous five years (2000 - 2004). Clearly, total phosphorus concentrations taken at the north end of the lake from 1991 to 2006 were lower than those reported from 1968, 1969-71 and 1972-73 (Table 3). Most of the samples taken prior to 1991 were from the south end of Cayuga Lake. However, data presented in the Cayuga Lake Watershed Restoration and Protection Plan (Fig. 3) provided a summer average of 'upper waters" for the late 1990s at the north end of Cayuga Lake of 12 μg P/L, which agrees surprisingly well with our 1991-1998 average of 11.7 μg P/L for the northern end of the lake. Thus a reduction in total phosphorus concentration in the lake is suggested.

Soluble reactive phosphorus provides information on the amount of phosphate ion present in the water column. Phosphate (SRP) is the form of phosphorus that is readily taken up by phytoplankton and macrophytes and is generally considered the limiting factor to plant growth in lakes in New York. Since 1991, SRP summer average concentrations ranged from a minimum of 0.9 ± 0.2 μg P/L (mean ± S.E.) in 1995 to a maximum of 4.0 ± 0.8 μg P/L in 2004 with an average concentration of 1.9 and 2.2 μg P/L for the 1991-98 and 1999-2006 study periods, respectively (Table 2). There were no significant ($p = 0.125$) upward or downward trends during the study period (Fig. 2).

[1] In the Makarewicz (1999) report, average TP concentration for the 1991 – 1998 period is listed as 11.7 μg N/L. This value represented the average of the annual summer mean and not the average of individual values for the same time period.

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Chlorophyll (Chl-*a*) (Table 2):

Chlorophyll *a* provides an estimate of algal abundance in lakes. Chlorophyll-*a* concentrations show a notable amount of variation temporally since 1991 (Fig. 4) with no discernable trend ($p = 0.471$). Hamilton (1969) in 1966 studied chlorophyll-*a* concentrations in Cayuga Lake and found concentrations averaging 5.5 µg/L until 6 July, and a mean of 1.5 µg/L from 20 July through 18 August in the surface waters. In general, average values in the 2-4 µg/L range were observed in 1966 and 1968 (Table 4) while summer means as high as 9.2 µg/L were observed in 1972 by Oglesby and Schaffner (1975). Average chlorophyll *a* concentrations dropped from the high values (>6 µg/L) observed by Oglesby and Schaffner (1975) in the late 1960s and early 1970s to an average of 3.9 µg/L and 4.1 µg/L for the 1991–1998 and 1999-2006 period, respectively. Similarly, Callinan (2001) reported a decrease at chlorophyll in the main portion of the lake in 1996-99 period (mean = 3.5 µg/L). The range of values (0.2 to 14.3 µg/L) for the 1991- 2006 period do bracket the levels observed in the 1970s (Table 4). Average concentrations for the two periods were not significantly different (1991-1998 = 3.9[2] µg/L; 1999-2006= 4.1 µg/L). A strong correlation ($r=0.61$, Fig. 5) existed between summer TP and Chl-*a* concentrations over the 1991 – 2006 period. This relationship suggests that phosphorus plays a key role in controlling algal abundance in Cayuga Lake. Lakes, such as Cayuga Lake, with chlorophyll levels in the 3 to 11 µg/L range with means near 4.7 µg/L are generally classified as mesotrophic (Table 6).

Nitrate (NO_3)(Table 2):

Figure 6 represents yearly average nitrate concentrations in Cayuga Lake from 1991 to 2006. Temporal variability in average nitrate concentration was very high and ranged from an average low of 0.04 and 0.05 mg N/L in 1995 and 1999, respectively, to an average maximum nitrate concentration of 0.66 mg N/L in 1992. Average

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[2] In the Makarewicz (1999) report, average chlorophyll concentration for the 1991 – 1998 period is listed as 4.0 µg /L. This value represented the average of the annual summer mean and not the average of individual values for the same time period.

concentrations in the 1991-1998 (0.27 mg N/L[3]) and 1999- 2006 periods (0.25 mg N/L) were similar (Table 2). No obvious trend over time was observed (Fig. 6, p = 0.494). During the summer of 1968, nitrate concentrations at the southern end of the lake below 0.50 mg/L were observed by Barlow (1969).

Turbidity (Table 2):

Table 2 provides yearly average turbidity readings of samples taken from Cayuga Lake from 1992 to 2006 (turbidity was not measured in 1991). Minimum summer yearly turbidity was observed in 1995 at 0.52 ± 0.08 NTU. Maximum yearly turbidity measurements occurred in 2003 at 4.10 ± 0.42 NTU. Mean annual turbidity for the 1991-1998 and 1999-2006 periods were 1.54[4] (±0.34) and 1.84 (±0.17) NTU (Table 2). Average values are generally over the 1 NTU standard required for non-filtration of drinking water in New York State.

Secchi Disk (Lake Clarity) (Table 2):

Our early knowledge of Cayuga Lake's water quality dates from the early 1900s. Birge and Juday (1921) observed a transparency reading of 6.1 m in the early 1918 while Burkholder (1931) observed a similar transparency reading (5.6 m) in the early 1930s (Table 5). By the early 1950s and into the 1970s, transparency appeared to decrease as the mean range reported by Henson *et al*. (1961) in the 1950s was 3.5 to 4.5m. By 1991, average values at Site 5 was reduced to 1.8 m but increased progressively and dramatically increased over the next 16 years (Table 2) to as high as 5.08 m - a value within the range reported in 1950-52 but not near the historical highs from the early 1900s. Callinan (2001) reported an average secchi disk reading of 4.0 m in the main portion of the lake from 1996-99.

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[3] In the Makarewicz (1999) report, average nitrate concentration for the 1991 – 1998 period is listed as 0.29 mg N/L. This value represented the average of the annual summer means and not the average of individual values for the same time period.

[4] In the Makarewicz (1999) report, average turbidity concentration for the 1991 – 1998 period is listed as 1.49 NTU. This value represents the average of the summer means and not the average of individual values for the same time period.

From 1991 to 1998, transparency increased from ~2 m to ~4.6 m. From 1999 to 2006, transparency dropped and was in the 3 to 4 m range except in 2000 when the highest average value (5.08 m) was recorded. In general, transparency within the water column of Cayuga Lake has significantly ($p = 0.001$) improved over the past 16 years (Fig. 7). Similarly, Callinan (2001) reported a modest increase in water clarity since the 1970s. The increase in transparency reported here corresponds with the decrease in total phosphorus (Fig. 2) during this same period but interestingly not with any changes in turbidity or chlorophyll *a*. The correlation between secchi disk readings and chlorophyll *a* ($r = 0.23$) and turbidity ($r = 0.04$) was very low. An average secchi disk reading for the north end of Cayuga Lake of 3.78 m (1999-2006) suggests mesotrophic conditions (Table 6). Similarly, lakes with a secchi disk transparency ranging from 1.5 to 8.1 m and an average of 4.2 m are generally considered to be mesotrophic (Vollenweider in Wetzel 2001).

Carlson's Trophic Status Index (TSI) (Table 7):

Carlson's TSI is used to assess the trophic state of a given lake by analyzing TP concentrations and summer Chl-*a* concentrations and by measuring summer secchi disk depth. This index is one of several that can be used to evaluate the trophic status of a lake; that is, what is the overall productivity of the lake. TSI values less than 30 are considered oligotrophic and from 50 to 70 are considered eutrophic by Wetzel (2001). Carlson (2007) suggests that values in the 40 to 50 range are mesotrophic. Based on the average Chl-*a* and summer TP concentrations and secchi disk readings for the entire 1999-2006 period, Carlson's TSI was 37.2 for TP, 43.4 for chlorophyll *a* , and 41.1 for secchi disk (Table 7). Based on these data, a mesotrophic status is suggested for the north end of Cayuga Lake. This conclusion is reinforced by considering the general relationship of lake productivity with phosphorus, transparency and chlorophyll (Table 6). Chlorophyll, phosphorus, transparency, and the TSI observed during the 1991-98 period also suggest a mesotrophic status for Cayuga Lake.

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Table 1. Results of the semi-annual New York State Environmental Laboratory Assurance Program (ELAP Lab # 11439, EPA # NY 01449, SUNY Brockport) Non-Potable Water Chemistry Proficiency Test, January 2007. Score Definition: 4 (Highest) = Satisfactory, 3 = Marginal, 2 = Poor, 1 = Unsatisfactory.).

Analyte	**Mean/Target**	**Result**	**Score**
Residue			
Solids, Total Suspended	37.7 mg/L	36.1 mg/L	4
Organic Nutrients			
Kjeldahl Nitrogen, Total	14.4 mg/L	14.17 mg/L	4
Phosphorus, Total	2.86 mg/L	2.77 mg/L	4
Inorganic Nutrients			
Nitrate (as N)	14.3 mg/L as N	14.41 mg/L as N	4
Nitrite (as N)	1.85 mg/L as N	1.94 mg/L as N	4
Orthophosphate (as P)	2.70 mg/L as P	2.83 mg/L as P	4
Minerals II			
Sodium, Total	36.4 mg/L	36.33 mg/L	4

Table 2. Average summer values for total phosphorus (TP), nitrate, soluble reactive phosphorus (SRP), chlorophyll *a* (Chl *a*), turbidity (Turb) and transparency (secchi disk), Cayuga Lake. Values (mean ± Standard error) are the average for Site 2 except for secchi disk which is from Site 5. The range for a summer is in parentheses. *Not measured. ND=Non-detectable.

	Nitrate (mg N/L)	SRP (µg P/L)	TP (µg P/L)	Chl *a* (µg/L)	Turbidity (NTU)	Secchi Disk (cm) (SITE 5)
1991	0.18 ± 0.08 (ND - 0.50)	1.9 ± 0.4 (0.1 - 3.4)	15.5 ± 2.0 (9.7 - 24.8)	6.3 ± 0.7 (3.3 - 9.7)	*	196 ± 35 (120 - 280)
1992	0.66 ± 0.06 (0.42 - 0.93)	2.4 ± 0.5 (0.5 - 5.5)	9.9 ± 1.1 (3.4 - 14.0)	3.5 ± 0.3 (2.0 - 4.6)	0.67 ± 0.11 (0.42 - 1.24)	260 ± 32 (160 - 350)
1993	0.23 ± 0.10 (ND - 0.64)	2.8 ± 0.3 (2.0 - 4.2)	16.6 ± 1.6 (12.5 - 23.5)	5.3 ± 1.0 (3.4 - 11.0)	1.70 ± 0.22 (0.93 - 2.68)	231 ± 15 (210 - 275)
1994	0.19 ± 0.08 (ND - 0.61)	1.9 ± 0.5 (0.6 - 4.4)	9.1 ± 2.5 (2.5 - 24.8)	1.6 ± 0.4 (0.3 - 3.5)	1.47 ± 0.55 (0.21 - 5.40)	282 ± 42 (120 - 340)
1995	0.04 ± 0.02 (ND - 0.19)	0.9 ± 0.2 (0.6 - 1.7)	7.4 ± 1.0 (4.0 - 10.9)	1.7 ± 0.2 (0.8 - 2.5)	0.52 ± 0.08 (0.20 - 0.91)	375 ± 34 (220 - 440)
1996	0.57 ± 0.36 (0.07 - 2.73)	2.0 ± 0.5 (0.6 - 3.9)	13.1 ± 1.4 (7.6 - 17.4)	6.0 ± 1.0 (3.6 - 10.2)	1.36 ± 0.25 (0.50 - 2.10)	414 ± 36 (325 - 500)
1997	0.13 ± 0.07 (ND - 0.49)	1.2 ± 0.4 (ND - 3.1)	10.4 ± 0.7 (8.2 - 13.9)	2.0 ± 0.3 (1.1 - 3.2)	3.09 ± 1.95 (0.22 - 18.60)	467 ± 11 (450 - 500)
1998	0.17 ± 0.07 (ND - 0.52)	2.1 ± 0.9 (0.6 - 7.4)	11.5 ± 3.5 (4.5 - 38.7)	5.8 ± 1.4 (1.3 - 14.3)	1.60 ± 0.37 (0.38 - 3.74)	292 ± 49 (150 - 400)
1999	0.05 ± 0.02 (0.01 - 0.26)	2.0 ± 0.4 (0.6 - 4.5)	11.2 ± 1.5 (6.7 - 21.2)	3.8 ± 0.7 (1.3 - 7.7)	2.20 ± 0.46 (0.71 - 5.32)	342 ± 32 (200 - 400)
2000	0.28 ± 0.08 (0.01 - 0.72)	2.3 ± 0.3 (1.3 - 4.0)	8.2 ± 1.0 (3.7 - 12.4)	2.8 ± 0.5 (1.1 - 5.3)	0.71 ± 0.24 (0.27 - 2.57)	508 ± 33 (400 - 600)
2001	0.21 ± 0.09 (ND - 0.80)	1.1 ± 0.4 (ND - 2.9)	9.8 ± 0.5 (6.7 - 11.5)	6.7 ± 1.0 (3.1 - 11.2)	1.64 ± 0.29 (0.64 - 3.48)	341 ± 34 (220 - 500)
2002	0.13 ± 0.06 (ND - 0.47)	1.8 ± 0.5 (0.6 - 5.0)	10.3 ± 0.4 (8.3 - 11.9)	4.9 ± 0.7 (0.8 - 6.8)	2.87 ± 0.46 (0.88 - 4.50)	337 ± 38 (240 - 460)
2003	0.34 ± 0.06 (0.07 - 0.63)	2.1 ± 0.5 (0.6 - 3.9)	9.8 ± 1.7 (1.2 - 17.0)	4.8 ± 0.8 (1.1 - 9.4)	4.10 ± 0.42 (2.79 - 6.23)	403 ± 30 (360 - 460)
2004	0.49 ± 0.06 (0.20 - 0.71)	4.0 ± 0.8 (1.6 - 8.0)	7.8 ± 0.8 (5.5 - 13.0)	1.3 ± 0.3 (0.2 - 3.1)	1.04 ± 0.24 (0.23 - 2.42)	350 ± 150 (200 - 500)
2005	0.11 ± 0.05 (0.02 - 0.47)	2.7 ± 0.7 (ND - 7.1)	12.3 ± 1.5 (7.3 - 23.0)	3.4 ± 0.8 (0.5 - 7.5)	1.04 ± 0.24 (0.43 - 2.47)	*
2006	0.43 ± 0.07 (0.08 - 0.75)	1.8 ± 0.4 (ND - 4.0)	10.6 ± 0.7 (6.9 - 13.3)	4.8 ± 1.2 (0.7 - 10.0)	1.32 ± 0.26 (0.32 - 2.55)	350 (350 - 350)
1991-1998	0.27 ± .05 (ND-2.73)	1.9 ± 0.2 (ND-7.4)	11.4 ± 0.8 (2.5-38.7)	3.9 ± 0.3 (0.3-14.3)	1.54 ± 0.34 (0.20-18.60)	320± 18 (120-500)
1999-2006	0.25 ± 0.03 (ND-0.80)	2.2 ± 0.2 (ND-8.0)	10.0 ± 0.4 (1.2-23.0)	4.1 ± 0.3 (0.2-11.2)	1.84 ± 0.17 (0.23-6.23)	378 ± 19 (200-600)
1991-2006	0.26 ± 0.03 (ND - 2.73)	2.1 ± 0.1 (ND - 8.0)	10.7 ± 0.4 (1.2 - 38.7)	4.0 ± 0.2 (0.2 - 14.3)	1.71 ± 0.18 (0.20 - 18.60)	346 ± 13 (120 - 600)

Table 3. Historical comparisons of total phosphorus (µg P/L) concentrations in Cayuga Lake. The mean is the average for the period while the range represents the minimum and maximum value during the period.

Year	**Mean**	**Range**	**Period**	**Author**
1968	20	15-20	Summer	Barlow (1969)
1969-71	18	9.1- 56.7	June –August	Peterson (1971)
1972-73	21.1	NA	Winter	Oglesby and Schaffner (1979)
1991-1998	11.4	2.5-38.3	June-September	Makarewicz et al. (1999)
1998-1999	12.0	NA	Summer	GFLRPC (2001)
1996-1999	9.7	NA	May -October	Callinan (2001)
1999 -2006	10.0	1.2 -23.0	June-September	This Study

Table 4. Historical comparisons of chlorophyll *a* (µg/L) concentrations in Cayuga Lake. NA=Not available. The mean is the average for the period while the range represents the minimum and maximum value during the period.

Year	**Mean**	**Range**	**Period**	**Author**
1966	2.82	1.5- 5.5	May-August	Hamilton (1969)
1968	3.9	NA	Epilimnion, summer	Barlow (1969)
1969-1971	4.0	NA	Euphotic zone	Peterson (1971)
1968	6.1	NA	Upper 10m	Oglesby and Schaffener (1975)
1972	9.2	NA	Upper 10m	Oglesby and Schaffener (1975)
1996-1999	3.5	NA	May – October epilimnion	Callinan (20010
1991-1998	3.9	1.6 - 14.3	June-September	Makarewicz *et al*. (1999)
1999-2006	4.1	0.2 - 11.2	June-September	This Study

Table 5. Historical comparisons of transparency (secchi disk) in Cayuga Lake. Data for 1991–1998 is for Sites 5 and 6. NA=Not available. The mean is the average for the period while the range represents the minimum and maximum value during the period.

Year	**Mean (m)**	**Range**	**Period**	**Author**
1918	6.1	-	Week in August and September	Birge and Juday (1921)
1930	5.6	4.0–7.0	Summer	Burkholder (1931)
1950-52	3.5-4.5	1.7-7.0	Summer	Henson *et al*. (1961)
1970-74	NA	2.0-4.5	June-September	Bloomfield (1978)
1996-98	4.0	NA	May - October	Callinan (2001)
1991-98	3.20	1.2-5.0	June-September	Makarewicz *et al.* (1999)
1999-2006	3.78	2.0 – 6.0	June-September	This study

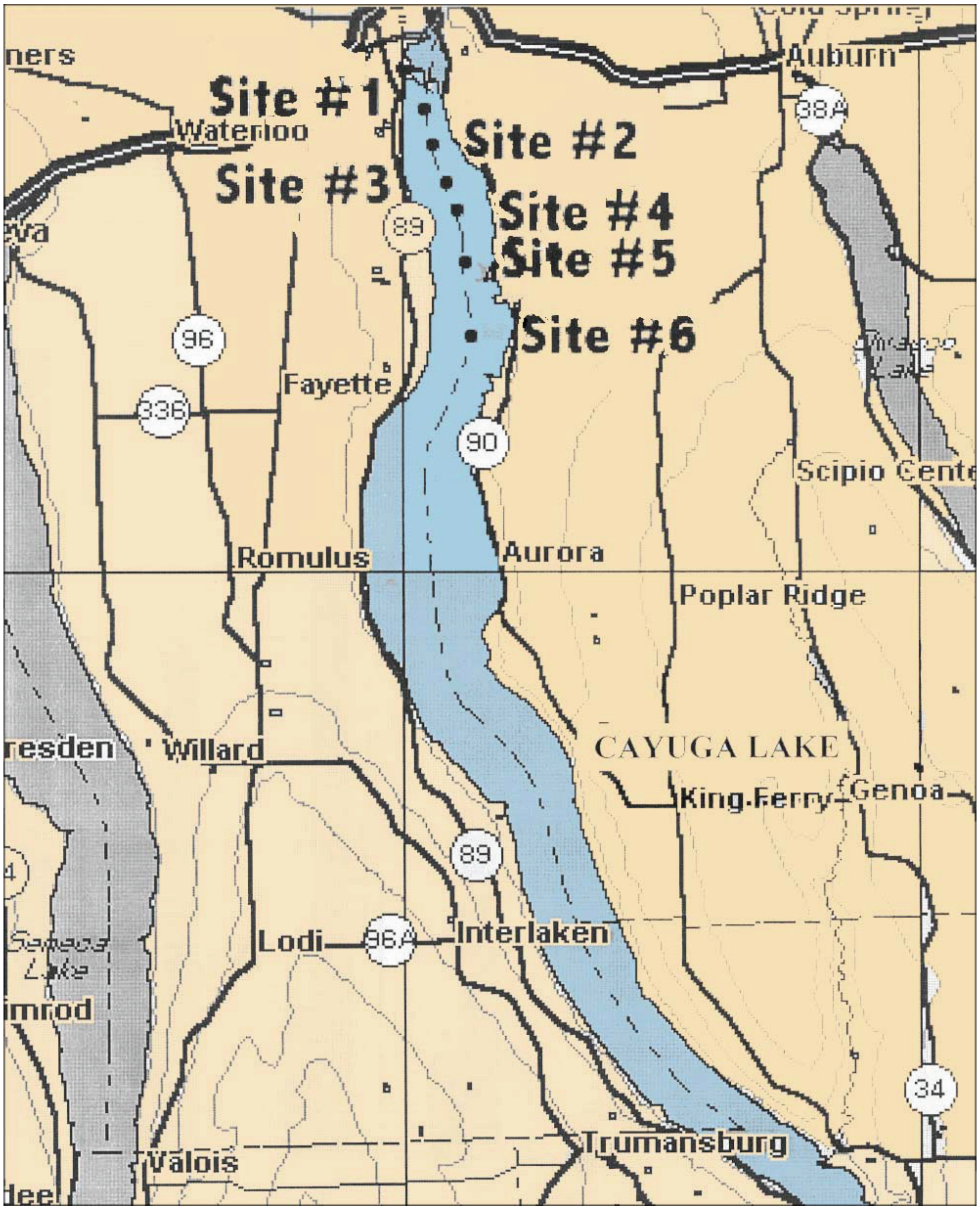
Table 6 . General relationship of lake productivity in relation to phosphorus, nitrogen, transparency and chlorophyll *a.* Adapted from Wetzel (1983, 2001).

	Epilimnetic Total Phosphorus (µg P/L)	**Annual Total Phosphorus (µg P/L)**	**Chl *a* (µg/L)**	**Secchi Disk (m)**
Oligotrophic	5-10	3.0-17.7	0.3- 4.5	5.4-28.3
Mesotrophic	10-30	10.9-95.6	3-11.0	1.5-8.1
Eutrophic	30-100	16.0-386	3-78.0	0.8-7.0
Hypereutrophic	>100	750-1200	100-150	0.4-0.5
Cayuga Lake (91-98)	11.4	NA	3.9	3.2
Cayuga Lake (99-06)	10.0	NA	4.1	3.78

Table 7. Values for Carlson's Trophic Status Index (TSI) from 1991 to 2006 for Site 2, Cayuga Lake.

	Carlson's TSI		
	TP Site 2	Chl-*a* Site 2	Secchi Disk Site 5
1991	43.7	48.6	50.3
1992	37.2	42.9	46.2
1993	44.6	47.0	47.9
1994	36.0	35.5	45.1
1995	33.0	35.5	41.0
1996	41.3	48.1	39.5
1997	37.9	37.4	37.8
1998	39.3	47.8	44.6
1999	39.0	43.7	42.3
2000	34.5	40.8	36.6
2001	37.1	49.2	42.3
2002	37.8	46.2	42.5
2003	37.1	46.0	39.9
2004	33.7	33.1	41.9
2005	40.3	42.6	NA
2006	38.2	45.9	41.9
1991-1999 Average	39.1	42.9	44.0
1999-2006 Average	37.2	43.4	41.1

Figure 1. Location and depth (m) of sampling sites on Cayuga Lake, 1991-2006.



Site 1: N 42° 54.482' W 076° 44.533'	Water Depth: 3.6 m
Site 2: N 42° 54.177' W 076° 44.367'	Water Depth: 3.5 m
Site 3: N 42° 53.714' W 076° 44.131'	Water Depth: 3.5 m
Site 4: N 42° 52.537' W 076° 43.508'	Water Depth: 3.5 m
Site 5: N 42° 51.898' W 076° 43.418'	Water Depth: 3.5 m
Site 6: N 42° 50.628' W076° 43.337'	Water Depth: 3.5 m

Figure 2. Average summer total phosphorus and soluble reactive concentrations, Cayuga Lake. The error bars correspond to the standard error.

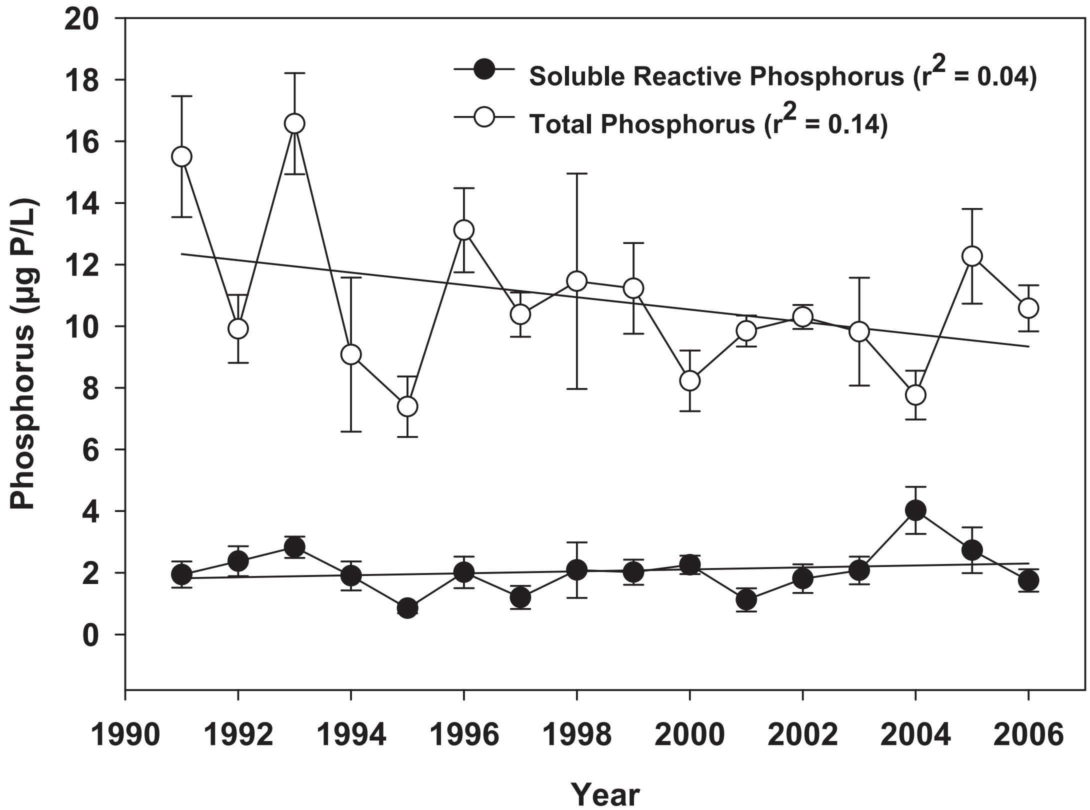


Figure 3. Summer total phosphorus concentrations for Cayuga Lake, 1996-2000. adapted from GFLRPC (2001).

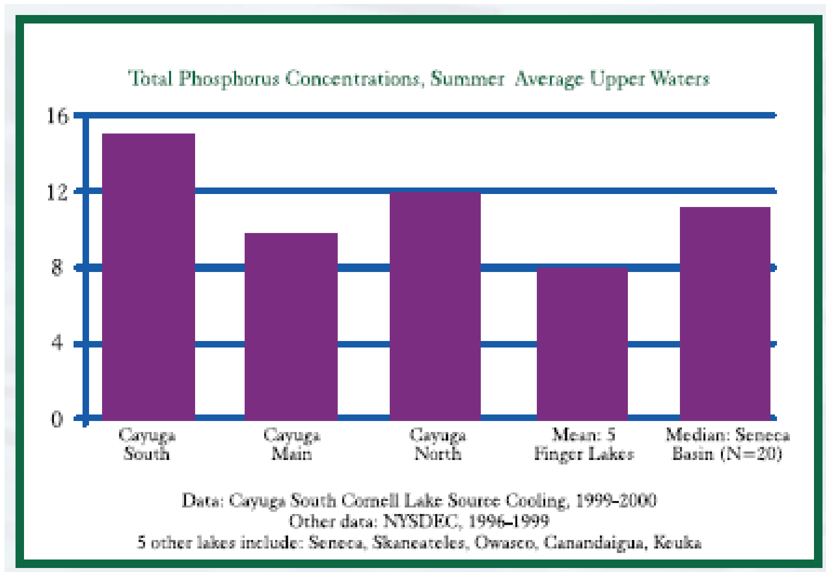


Figure 4. Chlorophyll *a* concentrations for the north end of Cayuga Lake. Error bars represent the standard error.

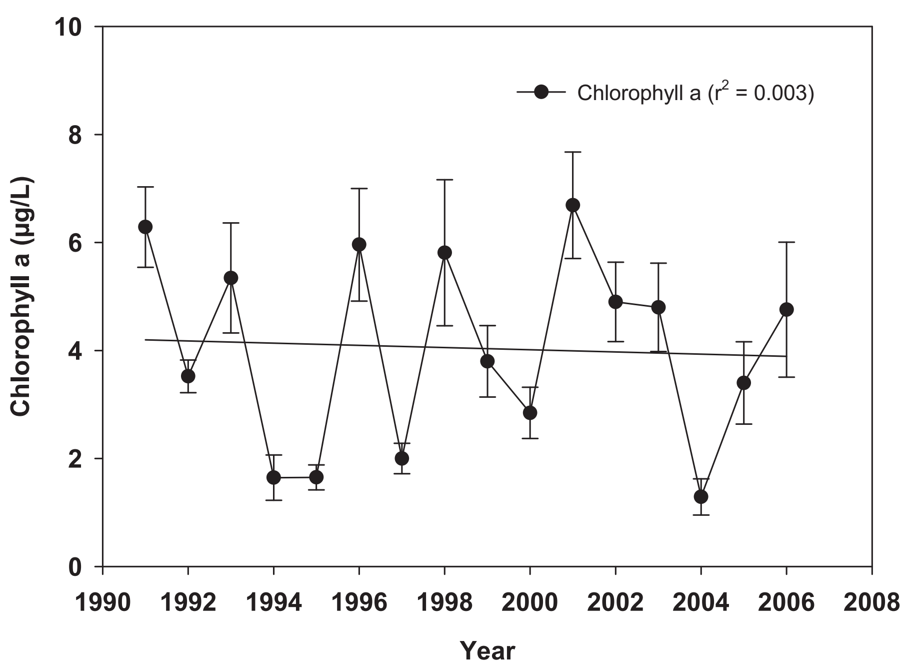


Figure 5. Relationship between total phosphorus and (site 2) and chlorophyll *a* (site 2) concentrations at the north end of Cayuga Lake (1991 - 2006).

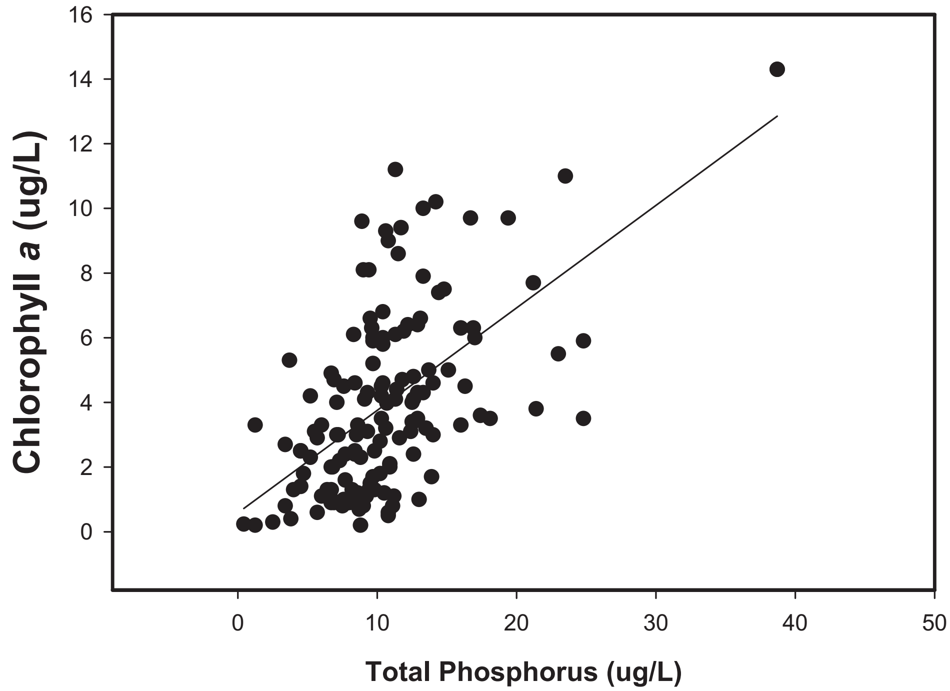


Figure 6. Average nitrate concentrations in Cayuga Lake from 1991 to 2006. The error bars correspond to the standard error.

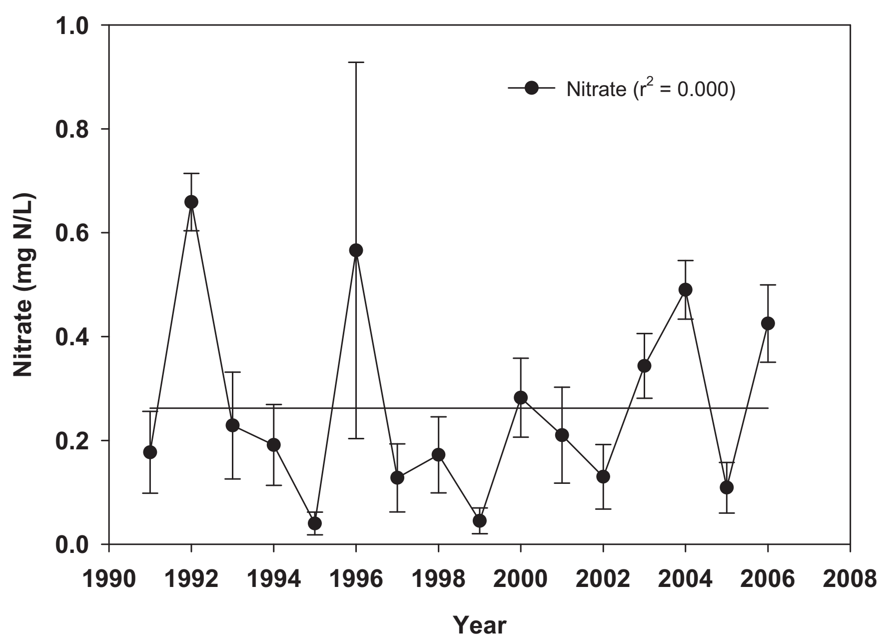
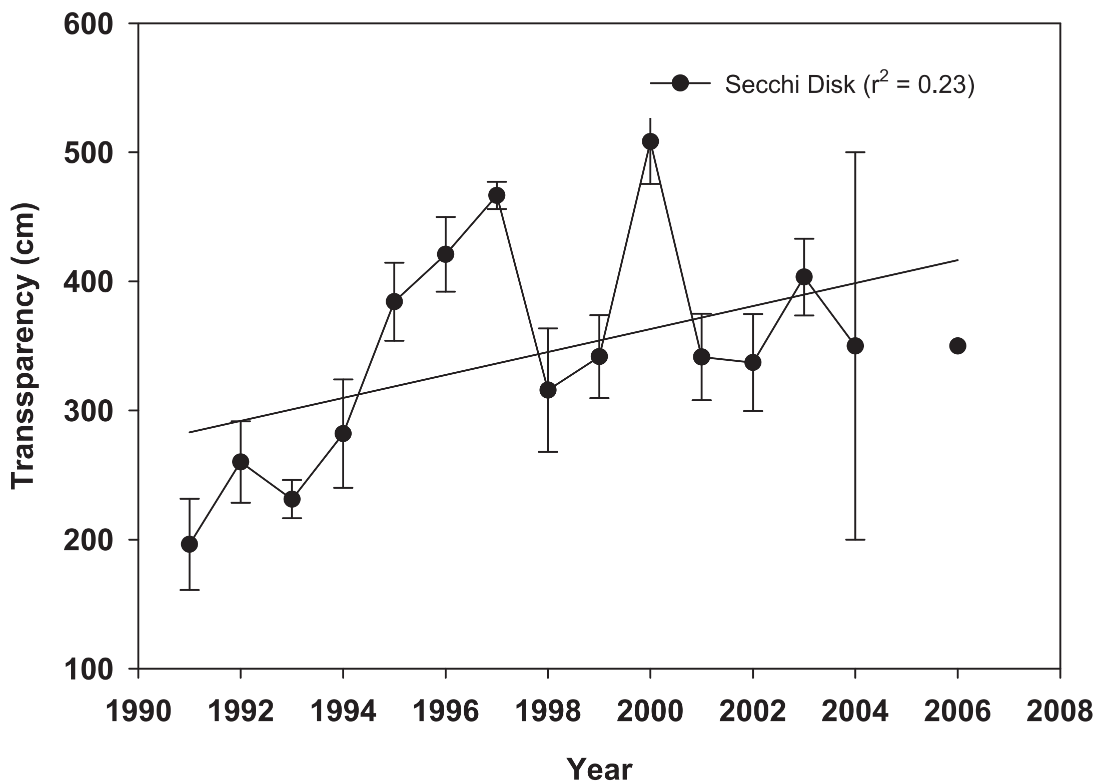


Figure 7. Transparency values (mean±S.E.) for Cayuga Lake since 1991. For 1991-1998, values are the average of Sites 5 and 6. For 1999 to 2006, values represent the average for Site 5. Only one reading was taken 2006 at Site 5.



Appendix. Cayuga Lake data: 1991 to 2006. See text for locations. Chemistry data from Site 2. TP = Total phosphorus, SRP = Soluble reactive phosphorus, Chl *a* = Chlorophyll *a*. A secchi disk value of 350 cm from sites 1, 2 and 3 indicates the bottom. ND = no data.

Cayuga Lake							Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Date	Year	Nitrate (mg N/L)	SRP (µg P/L)	TP (µg P/L)	Chl (µg/L)	Turbidity (NTU)	Secchi disk (cm)	Secchi disk (cm)	Secchi disk (cm)	Secchi disk (cm)	Secchi disk (cm)	Secchi disk (cm)
7/2/1991	1991	0.5	2.4	16	3.3	ND	110	180	200	195	160	
7/9/1991	1991	0.36	2.2	19.4	9.7	ND	120	140	175	225	225	140
7/16/1991	1991	0.31	2.7	11.3	6.1	ND	115	165	180	155	280	205
7/30/1991	1991	0.0	2	12.9	6.4	ND	85	220	175	165	120	195
8/12/1991	1991	0.0	0.8	9.7	5.2	ND	ND	ND	ND	ND	ND	ND
8/27/1991	1991	0.01	0.1	14.4	7.4	ND	ND	ND	ND	ND	ND	ND
9/10/1991	1991	0.06	3.4	24.8	5.9	ND	ND	ND	ND	ND	ND	ND
7/7/1992	1992	0.61	2.8	10.3	4.5	1.24	90	210	190	140	180	190
7/14/1992	1992	0.45	1.2	12.9	4.3	0.88	250	ND	ND	ND	ND	ND
7/21/1992	1992	0.42	2.9	8.5	3	0.54	250	350	ND	ND	ND	ND
7/28/1992	1992	0.67	0.5	3.4	2.7	0.61	300	250	300	260	250	270
8/4/1992	1992	0.93	1.9	6.8	2	0.57	400	400	350	375	350	385
8/11/1992	1992	0.82	1.2	12.6	4.1		300	320	350	210	160	140
8/18/1992	1992	0.74	5.5	10.3	3.5	0.42	230	330	340	300	300	280
8/25/1992	1992	0.72	2.8	14	3	0.45	350	330	300	330	320	360
9/1/1992	1992	0.57	2.6	10.4	4.6	ND	190	295	260	140	ND	ND
9/15/1992	1992	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
6/29/1993	1993	0.64	2	16	6.3	2.68	130	180	200	140	275	375
7/13/1993	1993	0.49	4.2	12.6	3.4	1.93	150	200	230	150	210	150
7/20/1993	1993	0.39	4	21.4	3.8	1.45	190	210	260	ND	ND	ND
7/27/1993	1993	0.08	2.6	23.5	11	2.08	150	190	180	ND	ND	ND
8/17/1993	1993	0.0	2.3	13.7	5	1.26	170	180	240	220	220	260
8/24/1993	1993	0.0	2	16.3	4.5	1.56	200	ND	ND	ND	ND	ND
8/30/1993	1993	0.0	2.7	12.5	3.4	0.93	150	230	220	220	220	230
7/11/1994	1994	0.55	4.4	7.7	2.4	2.01	300	280	270	250	330	380

Appendix (continued). Cayuga Lake data: 1991 to 2006.

7/21/1994	1994	0.01	3.4	24.8	3.5	2.24	ND	ND	ND	ND	ND	ND
8/8/1994	1994	0.11	1.8	6.7	2	1.14	ND	350	ND	ND	ND	ND
8/16/1994	1994	0.0	3.1	6	1.1	0.3	350	350	350	360	120	120
8/29/1994	1994	0.61	0.6	3.4	0.8	0.26	350	400	450	380	340	240
9/6/1994	1994	0.22	0.6	3.8	0.4	0.21	330	320	340	470	280	400
9/12/1994	1994	0.17	1.7	2.5	0.3	0.4	340	350	350	520	340	400
9/19/1994	1994	0.04	0.9	8.7	0.8	1.3	325	ND	ND	ND	ND	ND
9/27/1994	1994	0.01	0.6	18.1	3.5	5.4	ND	ND	ND	ND	ND	ND
7/11/1995	1995	0.19	0.6	6.7	0.9	0.68	320	340	330	ND	440	280
7/18/1995	1995	0.03	0.6	9.4	1.3	0.37	320	340	330	400	ND	ND
8/1/1995	1995	0.01	0.6	4	1.3	0.45	320	340	330	350	440	400
8/7/1995	1995	0.0	0.6	7.5	0.8	0.52	320	340	330	350	420	400
8/15/1995	1995	0.03	1.5	10.9	2	0.6	320	340	330	350	440	420
8/21/1995	1995	0.03	0.6	10.9	2.1	0.91	320	340	330	320	360	340
8/28/1995	1995	0.02	0.6	4.5	2.5	0.2	320	340	330	320	220	260
9/11/1995	1995	0.01	1.7	5.2	2.3	0.43	320	340	330	320	370	600
7/3/1996	1996	2.73	1.6	16.7	9.7	ND	300	300	260	480	430	500
7/17/1996	1996	0.38	3.9	17.4	3.6	1.95	250	200	240	450	500	600
8/14/1996	1996	0.25	2.3	14.2	10.2	0.94	350	250	190	400	450	400
8/22/1996	1996	0.19	0.6	14	4.6	0.5	270	350	350	ND	ND	ND
8/28/1996	1996	0.15	1.4	12.6	4.8	1.41	300	310	320	310	325	320
9/11/1996	1996	0.07	3.7	7.6	4.5	2.1	330	230	210	220	400	520
9/24/1996	1996	0.19	0.6	9.3	4.3	1.28	330	330	330	ND	ND	ND
7/8/1997	1997	0.49	0.0	8.2	1.3	2.3	330	340	350	450	450	460
7/15/1997	1997	0.43	0.0	8.6	1.2	0.49	350	350	350	400	450	450
7/23/1997	1997	0.17	1.4	8.4	2.5	0.22	350	350	350	400	ND	ND
8/6/1997	1997	0.0	0.6	9.8	1.3	0.59	350	350	350	400	ND	ND
8/13/1997	1997	0.01	2.5	13.5	3.2	1.47	350	350	350	400	450	450
8/20/1997	1997	0.05	0.6	9.2	1.1	1.17	ND	ND	ND	ND	ND	ND
9/1/1997	1997	0.0	0.6	11.6	2.9	1.25	350	350	350	400	450	450
9/8/1997	1997	0.0	3.1	13.9	1.7	1.75	350	350	350	400	500	500
9/15/1997	1997	0.0	2	10.2	2.8	18.6	350	350	350	400	500	500

Appendix (continued). Cayuga Lake data: 1991 to 2006.

7/6/1998	1998	0.33	4.5	4.5	1.4	1.31	350	350	350	400	400	400
7/13/1998	1998	0.52	0.6	6	3.3	1.31	350	350	350	400	400	400
7/20/1998	1998	0.51	0.6	6.4	1.3	1.83	350	350	350	400	400	500
8/3/1998	1998	0.09	0.6	6.9	4.7	0.38	350	350	350	400	460	500
8/24/1998	1998	0.01	0.6	12.2	6.4	1.1	ND	350	ND	ND	ND	ND
8/31/1998	1998	0.0	1.8	9.4	8.1	0.81	350	350	350	125	150	150
9/14/1998	1998	0.0		10	4.7	0.84	ND	ND	ND	ND	ND	ND
9/21/1998	1998	0.04	7.4	38.7	14.3	3.12	200	200	200	200	200	200
9/28/1998	1998	0.05	0.6	9	8.1	3.74	200	200	200	200	200	ND
6/29/99	1999	0.26	1.4	15.1	5.0	2.33	200	ND	ND	ND	ND	ND
7/6/99	1999	0.08	0.6	21.2	7.7	5.32	200	150	200	ND	ND	ND
7/20/99	1999	0.01	1.3	13.1	6.6	1.98	320	180	260	220	200	270
7/27/99	1999	0.01	3	12.5	4.0	2.93	250	250	250	250	300	350
8/10/99	1999	0.01	0.8	6.7	1.3	0.74	325	325	325	400	400	400
8/24/99	1999	0.01	4.5	7.2	3.0	1.83	300	300	250	ND	ND	ND
8/31/99	1999	0.04	0.6	12.9	3.5	3.58	300	200	200	440	370	360
9/8/99	1999	0.01	2.7	8.8	2.3	0.87	300	300	200	400	400	400
9/14/99	1999	0.01	2.3	7.7	1.6	0.71	300	300	280	400	380	ND
9/21/99	1999	0.01	3	7.1	3.0	1.66	350	350	ND	ND	ND	ND
7/6/2000	2000	0.72	1.9	10.2	1.8	2.57	ND	ND	ND	ND	ND	ND
7/11/2000	2000	0.52	1.9	9.7	1.7	0.53	350	350	400	400	500	400
7/17/2000	2000	0.39	3.0	12.4	3.1	0.27	350	350	400	500	600	600
7/27/2000	2000	0.14	2.7	9.2	1.1	0.83	350	350	400	370	450	450
8/2/2000	2000	0.11	1.3	9.8	2.5	0.42	350	350	400	600	ND	ND
8/16/2000	2000	0.17	1.3	9.1	4.1	0.33	350	350	350	ND	ND	ND
8/24/2000	2000	0.15	1.6	4.7	1.8	0.30	350	350	350	600	600	670
9/13/2000	2000	0.01	2.6	3.7	5.3	0.74	350	350	350	350	500	550
9/26/2000	2000	0.33	4.0	5.2	4.2	0.38	350	350	350	400	400	400
7/9/2001	2001	0.46	1.5	9.3	3.1	0.95	350	350	350	250	300	ND
7/18/2001	2001	0.31	2.2	11.3	11.2	0.64	350	350	350	500	ND	ND
8/2/2001	2001	0.06	0.0	9.5	6.6	1.51	320	320	260	300	500	ND
8/8/2001	2001	0.25	0.0	6.7	4.9	0.74	240	350	310	310	220	300

Appendix (continued). Cayuga Lake data: 1991 to 2006.

8/14/2001	2001	0.01	2.9	8.6	3.3	1.69	200	310	320	150	400	400
8/22/2001	2001	0.80	0.0	10.3	4.2	1.97	180	300	350	310	300	180
8/29/2001	2001	0.0	2.3	11.5	8.6	1.61	220	350	240	140	320	240
9/5/2001	2001	0.0	0.6	10.8	9.0	3.48	200	250	200	180	ND	ND
9/12/2001	2001	0.0	0.6	10.6	9.3	2.17	300	270	300	300	350	390
7/10/2002	2002	0.43	1.5	11.1	0.8	ND	350	300	350	ND	ND	ND
7/15/2002	2002	0.47	1.2	9.5	1.5	ND	310	220	320	460	460	500
7/25/2002	2002	0.11	0.6	8.3	6.1	0.88	350	350	350	460	460	550
8/1/2002	2002	0.07	5.0	9.6	6.3	2.03	280	300	240	350	400	420
8/7/2002	2002	0.0	1.4	10.4	5.8	3.50	260	220	310	350	ND	ND
8/13/2002	2002	0.0	3.0	11.9	6.2	4.50	300	230	240	260	260	220
8/21/2002	2002	0.0	0.6	10.4	6.8	3.63	300	240	300	220	290	350
8/28/2002	2002	0.09	1.3	9.7	5.9	2.30	250	300	210	210	240	220
9/4/2002	2002	0.0	1.7	11.8	4.7	3.25	250	250	240	280	250	320
7/8/2003	2003	0.63	2.2	11.2	1.1	5.22	350	350	ND	ND	ND	ND
7/14/2003	2003	0.50	0.6	17.0	6.0	5.46	280	300	ND	ND	ND	ND
7/22/2003	2003	0.24	1.2	11.7	9.4	6.23	270	270	ND	ND	ND	ND
7/29/2003	2003	0.36	3.9	4.5	2.5	3.22	280	320	320	340	390	300
8/5/2003	2003	0.51	3.2	7.1	4.0	2.86	270	350	300	360	ND	ND
8/13/2003	2003	0.41	3.5	8.4	4.6	3.99	330	330	340	400	ND	ND
8/20/2003	2003	0.24	0.6	16.9	6.3	4.12	350	350	250	300	360	300
9/2/2003	2003	0.07	2.9	10.4	6.0	3.01	350	350	350	ND	ND	ND
9/10/2003	2003	0.13	0.6	1.2	3.3	2.79	350	350	300	400	460	300
7/12/2004	2004	0.20	2.8	13.0	1.0	2.42	350	350	350	ND	ND	ND
7/20/2004	2004	0.40	8.0	9.0	0.8	2.00	350	350	350	400	ND	ND
7/28/2004	2004	0.58	5.0	5.7	2.9	0.72	350	350	350	ND	ND	ND
8/11/2004	2004	0.58	1.6	8.8	0.2	1.14	350	350	350	400	ND	ND
8/17/2004	2004	0.49	2.0	5.7	0.6	0.57	350	350	350	400	500	520
8/24/2004	2004	0.40	4.7	6.6	1.1	1.18	350	350	350	350	ND	ND
8/31/2004	2004	0.35	2.4	5.5	3.1	0.52	350	350	350	350	200	160
9/8/2004	2004	0.70	2.7	8.0	0.9	0.62	350	350	350	350	ND	ND
9/22/2004	2004	0.71	7.0	7.6	1.0	0.23	350	350	ND	ND	ND	ND

Appendix (continued). Cayuga Lake data: 1991 to 2006.

7/6/2005	2005	0.47	1.9	10.8	0.5	0.73	350	350	350	350	ND	ND
7/19/2005	2005	0.14	0.0	10.8	0.6	0.65	350	350	350	350	ND	ND
8/10/2005	2005	0.02	0.0	7.3	2.2	0.43	350	350	350	ND	ND	ND
8/17/2005	2005	0.13	7.1	8.4	2.4	0.50	350	350	350	350	ND	ND
8/23/2005	2005	0.13	3.0	13.3	4.3	0.48	350	350	350	350	ND	ND
9/6/2005	2005	0.02	3.1	10.6	3.2	1.34	350	350	350	350	ND	ND
9/14/2005	2005	0.03	1.9	11.4	4.4	0.86	350	350	350	ND	ND	ND
9/28/2005	2005	0.02	4.7	14.8	7.5	2.47	350	350	350	ND	ND	ND
10/4/2005	2005	0.02	2.9	23.0	5.5	1.88	350	350	ND	ND	ND	ND
7/11/2006	2006	0.73	1.9	ND	ND	ND	ND	ND	ND	ND	ND	ND
7/18/2006	2006	0.46	2.2	8.7	0.7	1.58	350	350	350	350	350	350
7/26/2006	2006	0.61	2.4	10.5	1.2	0.32	350	350	350	350	ND	ND
8/8/2006	2006	0.28	2.1	12.6	2.4	0.53	350	350	350	350	ND	ND
8/15/2006	2006	0.29	1.5	9.7	6	1.78	350	350	350	350	ND	ND
8/23/2006	2006	0.08	0.6	8.9	9.6	2.23	350	350	350	350	ND	ND
9/5/2006	2006	0.12	0.6	13.3	10	2.55	350	350	350	ND	ND	ND
9/19/2006	2006	0.75	4.0	11.3	4.1	0.82	350	350	350	ND	ND	ND
9/27/2006	2006	0.39	0.0	13.3	7.9	1.33	ND	ND	ND	ND	ND	ND
10/10/2006	2006	0.54	2.2	6.9	0.9	0.74	350	350	350	ND	ND	ND