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

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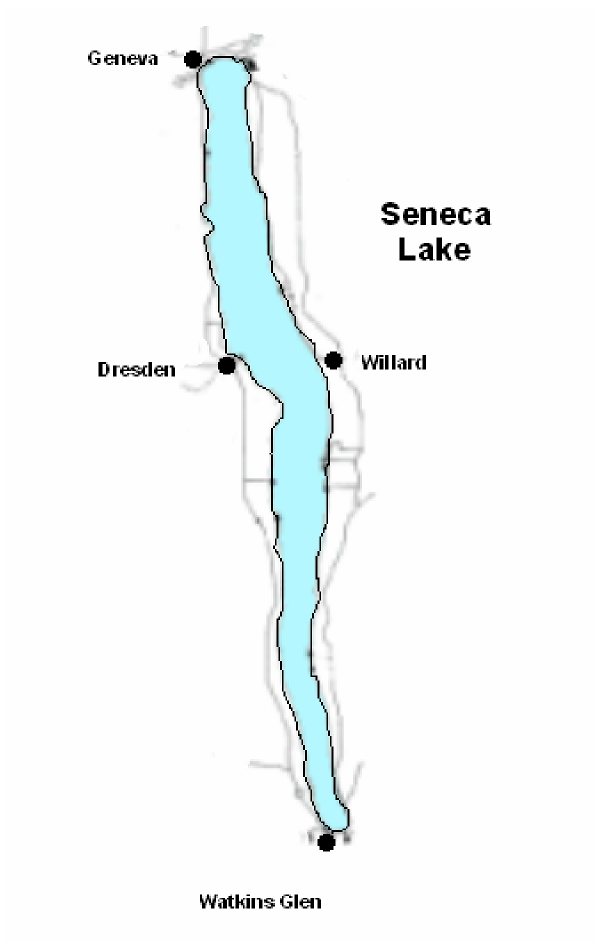
SUMMARY

The Seneca County Soil and Water Conservation District (SCSWCD) has collected limnological data on the waters of the northern end of Seneca 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 Seneca Lake was to determine the health of the Seneca Lake ecosystem and to determine if any temporal trends existed in Seneca Lake water quality. The water quality of Seneca Lake has been studied since the early 1900s when secchi disk readings were first taken. At that time, the trophic state of Seneca 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 1970s, water clarity generally decreased, indicating that the lake's trophic status was mesotrophic. Total phosphorus concentrations from the 1970s were into the mesotrophic range. Chlorophyll-*a* concentration also illustrated the trend toward more productive waters in Seneca Lake in the early to mid 1970s. Similarly, in the early 1970s, the transparency of Seneca Lake had decreased to within the eutrophic range. These low transparency values were observed into the early 1990s. Based on the sampling done by the Seneca County Soil and Water Conservation District from 1991 through 2006, an improvement in water quality of Seneca Lake is suggested – at least at the north end where the samples were taken. The trophic status of Seneca Lake is currently best described as oligotrophic. In conclusion, water quality of Seneca Lake appears to have improved since the early 1970s. However, the increase in total phosphorus levels from 2003 to 2005 represents an increase of some concern as they represent the highest values in the last 14 years.

INTRODUCTION

Seneca Lake is the deepest (618 feet) freshwater lake east of the Mississippi River outside of the Great Lakes. With a length of 38 miles, Seneca 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, Seneca Lake has become a destination of choice for tourists proving significant support for the local economy. Thus prevention of deterioration of water quality and maintenance of Seneca 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.



This report reviews data collected by the Seneca County Soil and Water Conservation District during the 1999-2006 period from the north end of Seneca Lake and is an update of data collected during the 1991-1998 period as reported by Makarewicz *et al.* (1999). By considering nutrient and chlorophyll *a* concentrations and water clarity measurements, we review the current data from Seneca Lake using the previous historical measurements of the lake.

METHODS

General:

Seneca Lake was sampled once a week usually from late June or early July to September from 1991 to 2004, and from early July to October in 2005 and 2006, by personnel from the Seneca County Soil and Water Conservation District. Water samples were collected with a Van Dorn water bottle from a depth of 1.5 m. Between 1991 and 1998 all samples collected for water quality analysis were taken from Site #3 (Fig. 1). From 1999 to 2006 water samples were collected from Site #1 (Fig. 1). Secchi disk measurements were taken at three different sites along the center axis of Seneca Lake. Once water 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

Historical Conditions: The Seneca County Soil and Water Conservation District (SCSWCD) has collected limnological data on the waters of the northern end of Seneca Lake since 1991-1998. 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 Seneca Lake was to determine the health of the of the Seneca Lake ecosystem and to determine if any temporal trends existed in Seneca Lake water quality.

The water quality of Seneca Lake has been studied since the early 1900s when secchi disk readings were first taken. At that time, the trophic state of Seneca 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 1970s, water clarity generally decreased, indicating that the lake's trophic status was mesotrophic. Total phosphorus concentrations from the 1970s were into the mesotrophic range. Chlorophyll-*a* concentration also illustrated the trend toward more productive waters in Seneca Lake in the early to mid 1970s. Similarly, in the early 1970s, the transparency of Seneca Lake had decreased to within the eutrophic range. These low transparency values were observed into the early 1990s Makarewicz *et al*. (2001). Callinan (2001) suggested an improvement in trophic state by the 1996-99 period as evidenced by marked declines in total phosphorus and chlorophyll *a* levels, and a substantial increase in water clarity. In the next few pages, we review the historical data available for several parameters often used to determine a lake's trophic status and to assess any changes in the lake over the past 50 years

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 is a lake with characteristics intermediate of oligotrophic and eutrophic. 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 human 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. .

Lake Chemistry:

<u>Phosphorus (Table 2)</u>

Total phosphorus (TP) provides an estimate of the total amount of phosphorus potentially available to aquatic plants. The Environmental Protection Agency (1974) monitored Seneca Lake as part of the National Eutrophication Survey and reported a TP range of 7-14 μg P/L in the autumn of 1972 with a mean of 9 μg P/L (Table 3). Mills (1975) observed a similar set of TP concentrations for the summer of 1973 (mean=10.9 μg P/L, range=9-12.8 μg P/L). Oglesby and Schaffner (1975) analyzed TP concentrations in all of the Finger Lakes of New York State. They reported a winter TP concentration of 17.8

µg P/L. In summer of 1994, Pawlaczyk (1995) observed a summer TP average to be 7.8 ± 1.1 µg P/L (Table 3). Callinan (2001) reported a 1996-1999 average of 7.3 µg P/L for the main portion of the lake.

Since 1991, concentrations of TP in Seneca Lake never surpassed the NYSDEC Ambient Water Quality Guideline of 20 µg/L. Average total phosphorus concentration for the study period (1991 to 2006) was 8.5 µg P/L with summer average concentrations ranging from a minimum of 5.3 ± 1.0 µg P/L in 1994 and 1995 to a maximum of 13.3 ± 1.5 µg P/L in 2005 (Table 3). Vollenweider (in Wetzel 1995) suggested that lakes, such as Seneca Lake, with a total phosphorus value near 8 µg P/L with a range of 3.0 to ~18 µg P/L are oligotrophic (Table 4).

Although averages presented in Figure 2 suggest that total phosphorus concentrations at in the lake have not changed significantly over the past 40 years, annual data from 1991 to 2006 suggests otherwise (Fig. 3). TP concentration was around the 10 µg P/L from 1991 to 1993, dropped significantly in 1994 and 1995 to ~ 5, and hovered in the 6 to 8 µg P/L range from 1996 to 2003. After 2003, average summer TP levels increased above 11 µg P/L with the highest TP level observed in 14 years in 2005 at 13.3 µg P/L (Fig. 3). In general, regression analysis suggested a significant ($p = 0.005$) trend of increasing TP. It does not seem likely that the increased TP observed was due to the change in the sampling site in 1999. Although site 1 is in shallower water compared to site 3, TP levels in 1999, 2000, 2001, 2002 and 2003 at site 1 were comparable to the previous seven years at site 3. Also, transparency of the water (secchi disk) that was taken at all three sites suggests that transparency at sites 1, 2 and 3 was generally not significantly different from each other during a year. This suggests that the changes observed in TP are due to overall changes in the lake and not due to the change in sites sampled. As discussed earlier, monitoring data provides trend data. It provides information on is the lake getting better or worse. It does not provide any information on the cause of the increase in total phosphorus.

Soluble reactive phosphorus (SRP) represents a soluble fraction of phosphorus, phosphate ion 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 0.8 $\pm$ 0.1 µg P/L (mean $\pm$ S.E.) in 1995 to a maximum of 3.4 ± 0.7 µg P/L in 2004 with an average concentration of 2.1 µg P/L for the study period (Table 2). There were no obvious trends during the study period of 1993 to 2006 (Fig. 3). However, concentrations of SRP weakly mimic the temporal trends observed in total phosphorus. That is, SRP concentrations were generally higher in the 2004-2006 period (2.5 – 3.4) than the 1994-2003 period (0.8-2.7 µg P/L).

Chlorophyll-*a* (Tables 2 and 5)

Chlorophyll *a* provides an estimate of algal abundance in lakes. Generally in phosphorus-limited lakes, algal abundance increases with increasing levels of phosphorus in the water column. Chl- *a* concentration in the summer of 1972 ranged from 0.2 µg/L to 10.4 µg/L, with the minimum being in May and the maximum being in July 1972 (EPA 1974). A 1973 synoptic survey (Bloomfield 1978) reported Chl-*a* concentrations of 3 - 5.5 µg/L. Oglesby and Schaffner (1975) analyzed summer chlorophyll-*a* concentration in all of the Finger Lakes of New York State and observed an average summer concentration of 7.1 µg/L for Seneca Lake. In 1995, Pawlaczyk (1995) observed summer average Chl-*a* concentration to be 1.21 µg/L, which would be classified as oligotrophic (Wetzel 1995)(Table 5). Callinan (2001) reported a 1996-1999 average of 2.4 µg /L for the main portion of the lake.

From 1991 to 1996, Chl-*a* concentrations in the north end of Seneca Lake were variable and ranged from an average summer minimum of 2.0 ± 0.2 µg/L in 1995 to a maximum of 5.0 ± 0.6 µg/L in 1992 (Table 2, Fig. 4). The average chlorophyll-*a* concentration for the study period was 3.2 µg/L. There appeared to be a general downward trend in chlorophyll *a* levels at the north end of the lake (Fig. 4). Minimum levels have not changed much over the past 14 years. However, maximum average levels are not as high as they were in early 1990s (Fig. 4). Lakes, such as Seneca Lake, with a chlorophyll levels in the 0.3 to 4.5 µg/L, are generally classified as oligotrophic or nutrient poor (Table 4).

Nitrate (NO_3) (Table 2):

Figure 5 represents yearly average nitrate concentrations in Seneca Lake from 1991 to 2006. Considerable temporal variability in nitrate concentration was observed but with no obvious patterns over time with perhaps one exception. Since 2002, there appears to be a steady decline in nitrate concentration from a high of 0.39 mg/L in 2002 to a low of 0.32 in 2006. In general, nitrate + nitrite ranged from a minimum of 0.26 ± 0.02 mg N/L in 1991 to a maximum of 0.39 ± 0.03 mg N/L in 1994 and 2002 (Table 2). Average concentration for the study period was 0.34 mg N/L.

Turbidity (Table 2):

Figure 6 illustrates yearly average turbidity readings of samples taken from Seneca Lake from 1992 to 2006 (turbidity was not measured in 1991). Minimum mean yearly turbidity was observed in 2002 at 0.53 ± 0.06 NTU. Maximum mean yearly turbidity occurred one year later in 2003 at 3.87 ± .39 NTU. Mean annual turbidity for the study period was 0.98 NTU (Table 2) which is below the 1 NTU standard required for non-filtration of drinking water in New York State.

Transparency (Secchi Disk)(Table 2)

Our early knowledge of Seneca Lake's water quality dates from the early 1900s. Birge and Juday (1921) observed secchi disk readings averaging 8.3 m in 1910. Similarly high transparency readings (9.1 m) were observed by Muenscher (1928)(Table 6). By 1973, the transparency of the lake had decreased dramatically. Oglesby and Schaffner (1975) observed a summer average of 3.6 m in Seneca Lake in the early 1970s. Bloomfield (1978) reported a transparency range of 2-4.5 m, also for the early 1970s (Fig. 7). By the 1996-99 period, Callinan (2001) reported an average secchi disk reading of 6.0 m in the main portion of the lake. The increase in transparency likely occurred by 1994. From 1991 through 1993, average transparency readings were 3.9 m in the northern portion of the lake (Fig. 6). In 1994, the average secchi disk reading jumped to over 6 m (Fig. 6). In general, Seneca Lake water transparency since 1992 (generally greater than 8 m) has become remarkably similar to transparency observed in the early 1900s. Makarewicz *et al.* (1999) has attributed this to zebra mussels which were first observed in 1991 in Seneca Lake and were widespread throughout the lake by 1993.

Figure 6 displays yearly average secchi disk readings during the summer months of 1991 to 2006. From 1991 to 2006, average secchi disk readings between sites 1, 2 and 3 were generally not significantly different (Fig. 8) in any given year. Secchi disk depth or transparency of the lake depth ranged from 125 cm (Site #1 on 3 August 1992) to 12 m (Sites #1, #2 and #3 on 18 September 2001). The data suggests that the transparency or clarity of the lake increased between 1991 to 1995 from a low of about 3 m or less in 1992 to over 8 m in 1995. Between 1995 and 2002, with the exception of 1996 and 1999, the transparency averaged above 8 m (Fig. 6 and 8). In general, transparency of the north end of the lake significantly ($p = 0.001$) increased during the study period. That is, the lake became remarkably clearer during the 1990s analogous to readings taken back in 1910 and 1928 (Fig. 7). Since 2002, average transparency has decreased to less than 8 m (Fig. 6). This corresponds with the increase in total phosphorus during this same period but interestingly not with any changes in turbidity or chlorophyll *a*. Nevertheless, lakes with a secchi disk transparency ranging from 5.4 to 28.3 m and average of 9.9 m are generally considered to be oligotrophic.

The decrease in lake transparency that has occurred after 2002 does not correspond directly with an increase in chlorophyll-*a* concentrations (algae). Regression analysis suggests that only 3% of the variability observed in the transparency readings was accounted for by variability in chlorophyll concentrations. Turbidity, which is a measure of organic and inorganic particles in the water, accounted for 10% of the variability (Fig. 9) in the secchi disk readings. Neither regression is strong but the decrease in secchi disk readings (Transparency) appears to be related to an increase in inorganic particles (soil?) in the water.

Carlson's Trophic Status Index (TSI):

Carlson's TSI is used to assess the trophic state of a given lake by analyzing summer TP concentrations and 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. Based on the average Chl-*a* and summer TP concentrations and secchi disk readings for the entire 1991-2006 period, Carlson's total TSI was generally less than 40 (Table 7) suggesting an oligotrophic status for the lake even though the Chl-*a* value is just within the mesotrophic classification range. The conclusion of an oligotrophic status was reinforced by considering the general relationship of lake productivity with phosphorus, transparency and chlorophyll (Table 4). Chlorophyll and total phosphorus concentrations and transparency readings observed during the 1991-2006 period also indicate an oligotrophic status for Seneca Lake. This is particularly evident for epilimnetic total phosphorus.

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LITERATURE CITED

APHA (American Public Health Association). 1999. *Standard Methods for the Examination of Water and Wastewater*. Washington, D.C.

Birge, E.A. and Juday, C. 1921. A limnological study of the Finger Lakes of New York. Bulletin of the Bureau of Fisheries. pp. 525 - 609.

Bloomfield, J.A. 1978. *Lakes of New York State*. Vol. I. Academic Press, New York.

Callinan, C.W. 2001. Water Quality of the Finger Lakes. NYSDEC. Division of Water, Albany, NY. 150pp.

EPA Region II Working Paper No. 170. 1974. Report on Seneca Lake Schuyler County, New York. National Eutrophication Survey. pp 6 - 9.

Makarewicz, J.C., R.J. Ward and T. Lewis. 1999. Water Quality of Seneca Lake. Seneca Soil and Water Conservation District. 20pp. Available from Drake Memorial Library. SUNY Brockport, Brockport, NY.

Mills, E.L. 1975. Phytoplankton composition and comparative limnology of four Finger Lakes with emphasis on lake typology. Ph. D. Thesis, Cornell University, Ithaca, New York.

Muenscher, W.C. 1928. Plankton studies of Cayuga, Seneca, and Oneida Lakes. *In* "A Biological Survey of the Oswego River System," Suppl. 17th Annu. Rep., 1927,

Chapter VII, pp. 140-157. New York State Conservation Department, Albany, New York.
Oglesby R.T, and Schaffner W.R. 1975. The response of lakes to phosphorus in "Nitrogen and Phosphorus: Food Production, Waste and Environment." (K. S. Porter ed.) Pp. 25 - 60. Ann Arbor Science Publication, Ann Arbor Michigan. 1975.
Pawlaczyk, P.A. 1995. Comparison of two methods of water sample storage for determination of total phosphorus levels and season al changes in total phosphorus in seven Finger Lakes and Waneta Lake in New York State. Pg. 26. Independent study with NYSDEC (Avon) and SUNY Brockport.
Wetzel, R. G. 1983. *Limnology*. W. B. Saunders Company, Philadelphia. 765p.

Wetzel, R.G. 1995. *Limnology: Lakes and River Ecosystems.* Academic Press. NY 1006pp.

Wetzel, R.G. and G.E. Likens. 1994. *Limnological Analyses*. Springer Verlag, NY. 391 pp.

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) in Seneca Lake. Values from 1991-1998 are the average for Site #3. Values from 1999-2006 are the average for Site #1 except for secchi disk which are from Site 3.The standard error is in parentheses. *Not measured.

Year	**Nitrate (mg N/L)**	**SRP (µg P/L)**	**TP (µg P/L)**	**Chl-*a* (µg/L)**	**Turb (NTU)**	**Secchi Disk (m)**
1991	0.26 (0.02)	3.0 (0.6)	9.1 (2.0)	2.4 (0.5)	*	4.9(.55)
1992	0.38 (0.01)	2.7 (0.6)	9.7 (1.1)	5.0 (0.6)	0.79 (0.12)	3.1 (.34)
1993	0.32 (0.01)	2.4 (0.8)	10.5 (2.1)	4.1 (1.3)	0.65 (0.12)	3.9 (.50)
1994	0.39 (0.01)	0.9 (0.3)	5.3 (0.9)	2.6 (0.4)	0.70 (0.12)	6.8 (.50)
1995	0.31 (0.01)	0.8 (0.1)	5.3 (1.1)	2.0 (0.2)	0.58 (0.08)	8.9 (.33)
1996	0.34 (0.03)	1.9 (0.5)	8.7 (1.7)	4.0 (1.3)	0.75 (0.14)	6.3 (.29)
1997	0.36 (0.01)	1.1 (0.5)	6.1 (0.6)	3.3 (0.6)	1.30 (0.19)	8.4 (.60)
1998	0.35 (0.02)	2.4 (0.7)	8.2 (0.7)	3.4 (0.6)	0.84 (0.15)	9.4 (.50)
1999	0.32 (0.03)	2.2 (0.4)	7.2 (0.9)	2.3 (0.3)	0.68 (0.10)	6.7 (50)
2000	0.34 (0.05)	2.7 (0.5)	8.7 (0.9)	3.9 (0.6)	0.61 (0.09)	9.3 (49)
2001	0.29 (0.04)	1.7 (0.5)	7.3 (1.3)	3.0 (0.5)	0.58 (0.08)	9.9 (55)
2002	0.39 (0.04)	2.2 (0.7)	5.9 (0.7)	2.7 (0.5)	0.53 (0.06)	9.0 (26)
2003	0.37 (0.02)	1.2 (0.4)	8.3 (1.4)	3.7 (0.9)	3.87 (0.39)	6.4 (88)
2004	0.37 (0.03)	3.4 (0.7)	11.9 (1.1)	4.0 (0.6)	1.11 (0.16)	6.7 (52)
2005	0.34 (0.02)	3.1 (1.4)	13.3 (1.5)	2.5 (0.4)	0.82 (0.14)	7.5 (89)
2006	0.32 (0.01)	2.5 (0.6)	11.0 (1.7)	2.3 (0.5)	0.90 (0.15)	7.5 (65)
Average	0.34	2.1	8.5	3.2	0.98	7.2

Table 3. Historical comparisons of total phosphorus (µg P/L) concentrations in Seneca Lake.

Year	Mean	Range	Period	Author
1972	9	7-14	Autumn	EPA (1974)
1973	10.9	9.0-12.8	July and August	Mills (1975)
1994	7.8	1.1	Summer	Pawlacyzk (1995)
1996-1999	7.3	NA	May -October	Callinan (2001)
1991-2002	7.7	5.3-10.5	June-September	This study
2003-2006	11.1	8.3-13.3	July-October	This study

Table 4. General relationship of lake productivity in relation to phosphorus, nitrogen, transparency and chlorophyll *a*. Adapted from Wetzel (1983). Seneca Lake's values are from site 3 prior to 2000 and from site 1 after 1999. NA=Not Applicable.

	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
Seneca Lake (1991-2006)	8.5	NA	3.2	7.2

Table 5. Historical comparisons of chlorophyll *a* (µg/L) concentrations in Seneca Lake. NA=Not available.

Year	**Mean**	**Range**	**Period**	**Author**
1972	5.33	0.2-10.4	Spring/Summer	EPA (1974)
1973	NA	3.0-5.5	Sampled once in April, June and August	Bloomfield (1978)
1969-72	7.1	NA	Upper 10m	Oglesby and Schaffener (1975)
1995	1.21	NA	July-October	Pawlaczyk (1995)
1996-1999	2.4	NA	May – October epilimnion	Callinan (2001)
1991-2006	3.2	2.0-5.0	June-September	This Study

Table 6. Historical comparisons of transparency (secchi disk) in Seneca Lake

Year	**Mean**	**Range**	**Period**	**Author**
1910	8.3	One reading	Week in August	Birge and Juday (1921)
1928	9.1	Not available	Summer	Muenscher (1931)
1969-72	3.6	Not available	Summer	Oglesby (1975)
1970-74	Not available	2.0-4.5	June-September	Bloomfield (1978)
1991-1993	3.9	3.1-4.8	June-September	This study
1996-98	6.0	NA	May - October	Callinan (2001)
1994-2002	8.4	6.3-9.9	June-September	This study
2002-2006	7.0	6.4-7.5	July-October	This study

Table 7. Values for Carlson's Trophic Status Index (TSI) fro 1991 to 2006 for site 3 (1991 to 1998) and site 1 (1999 to 2006).

	Carlson's TSI		
year	TP	Chl-*a*	Secchi
1991	36.1	39.0	37.4
1992	36.9	46.5	43.5
1993	38.0	44.5	40.4
1994	28.2	39.9	32.4
1995	28.3	37.5	28.4
1996	35.3	44.1	33.5
1997	30.3	42.2	29.4
1998	34.5	42.6	27.8
1999	32.5	38.8	32.5
2000	35.4	44.0	27.8
2001	32.8	41.2	27.0
2002	29.9	40.3	27.0
2003	34.6	43.3	33.2
2004	39.8	44.2	32.5
2005	41.5	39.7	30.9
2006	38.7	38.6	31.0
Mean	34.6	41.7	32.2
S.E.	1.0	0.7	1.2

Figure 1. Location of sampling sites on Seneca Lake, 1991-2006.

Site 1 - N 42° 51.720' W 076° 57.487' Water depth = 14 m
Site 2 - N 42° 50.469' N 076° 57.486' Water depth = 113 m
Site 3 - N 42° 45.904' N 076° 56.692' Water depth = 150 m (estimated)

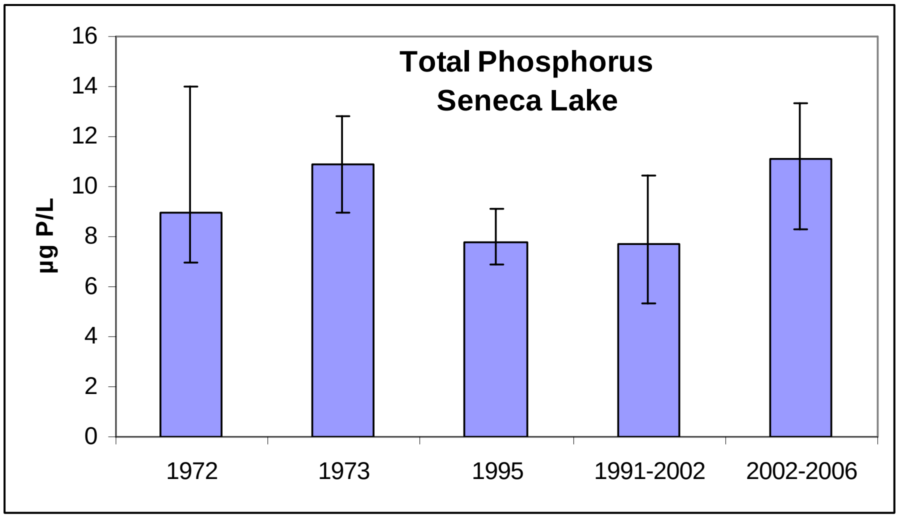

Figure 2. Historical total phosphorus values for Seneca Lake. Error bars represent the range of values observed. Sources of the data are listed in Table 3.

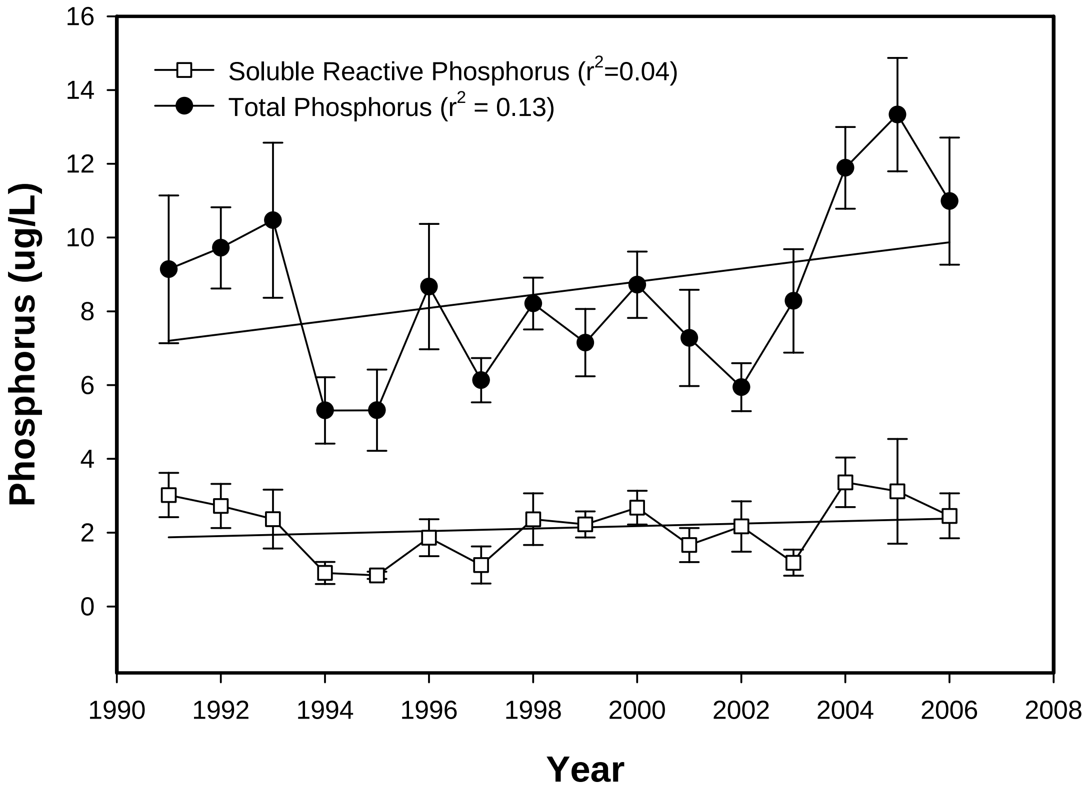

Figure 3. Temporal trends in average phosphorus fractions (mean $\pm$ S.E.) at the north end of Seneca Lake.

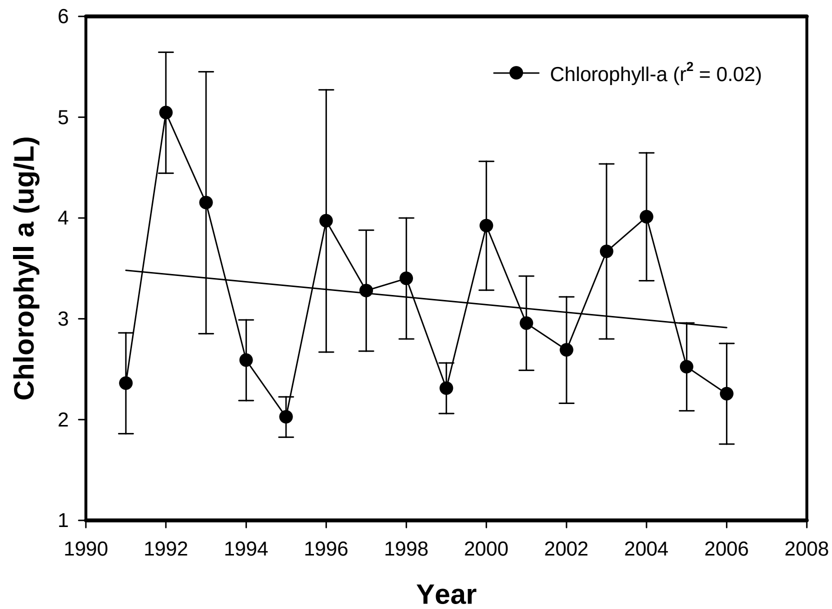

Figure 4. Average chlorophyll *a* (mean ± S.E.) concentrations at the north end of Seneca Lake.

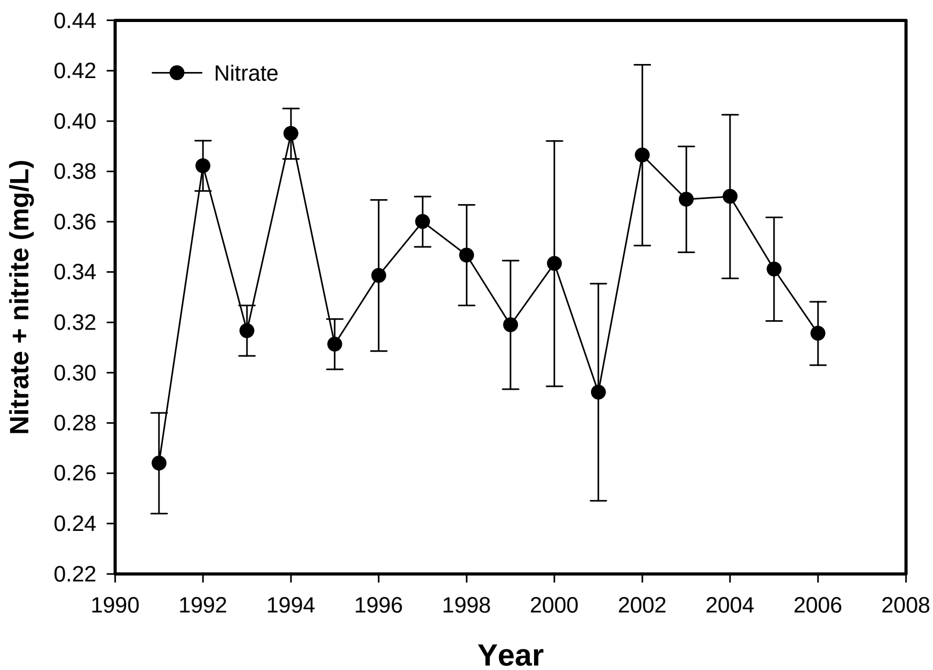

Figure 5. Average nitrate concentrations in Seneca Lake from 1991 to 2006. The error bars correspond to the standard error.

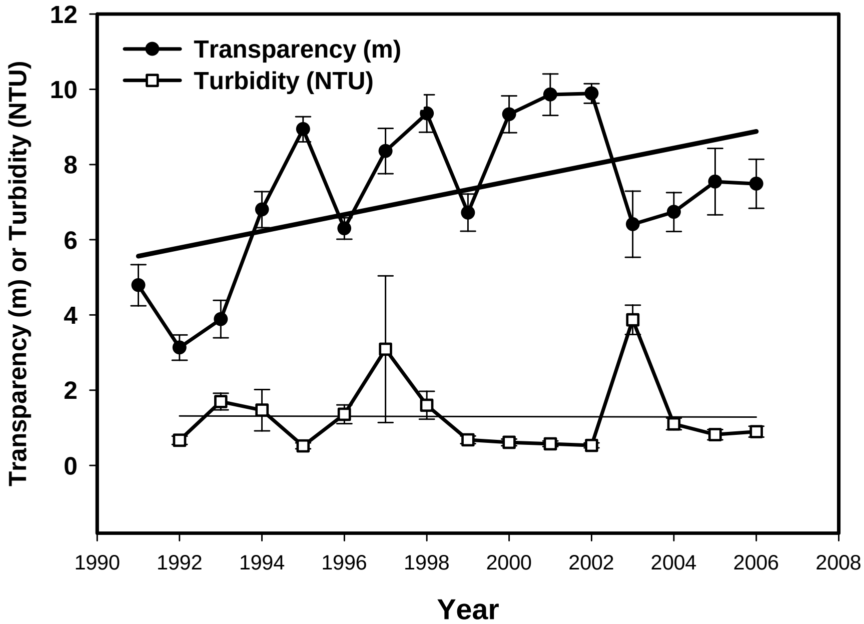

Figure 6. Temporal trends in secchi disk readings (Transparency) and turbidity in the north end of Seneca Lake.

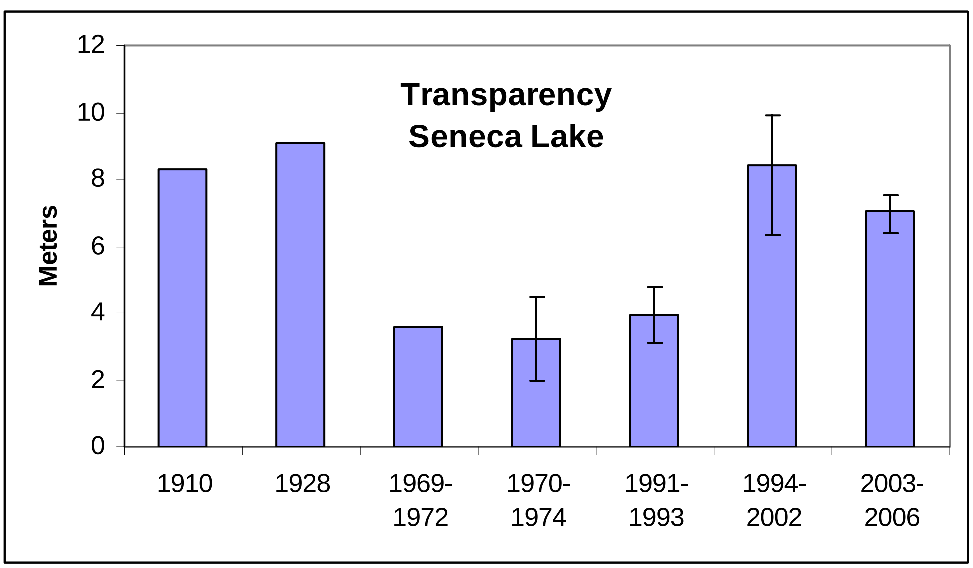

Figure 7. Historical transparency values for Seneca Lake. Error bars represent the range of values observed. Sources of these data are listed in Table 5.

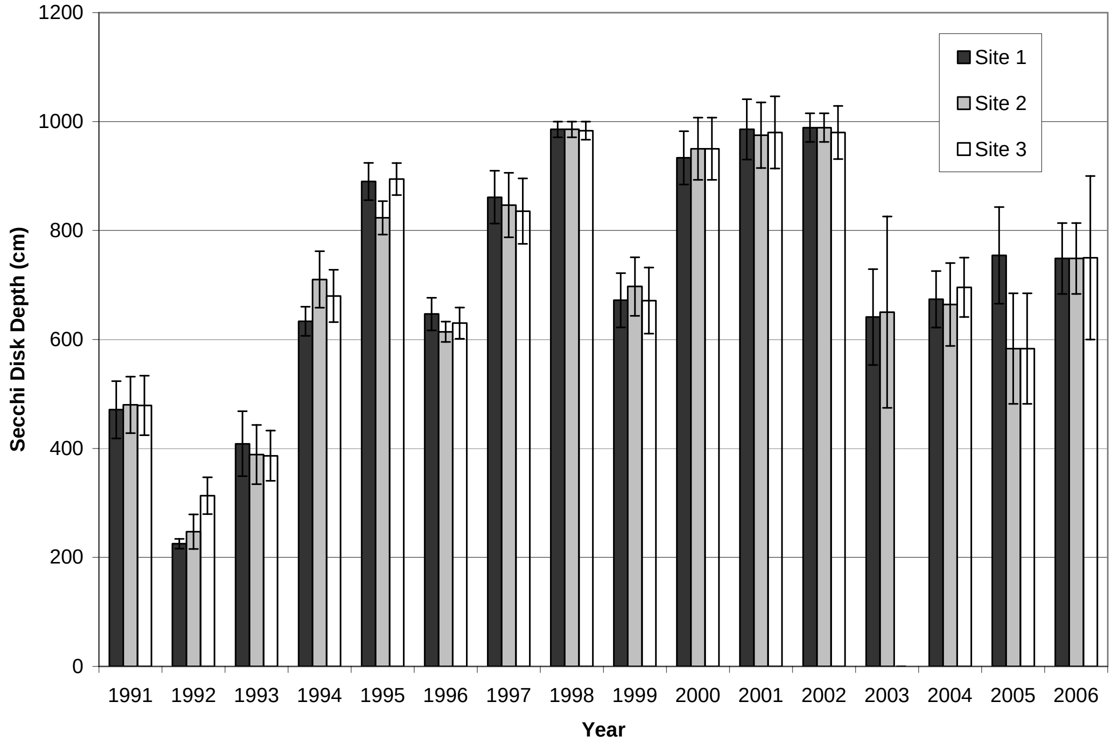

Figure 8. Average summer transparency (secchi disk) measurements for Seneca Lake. All error bars represent plus or minus the standard error.

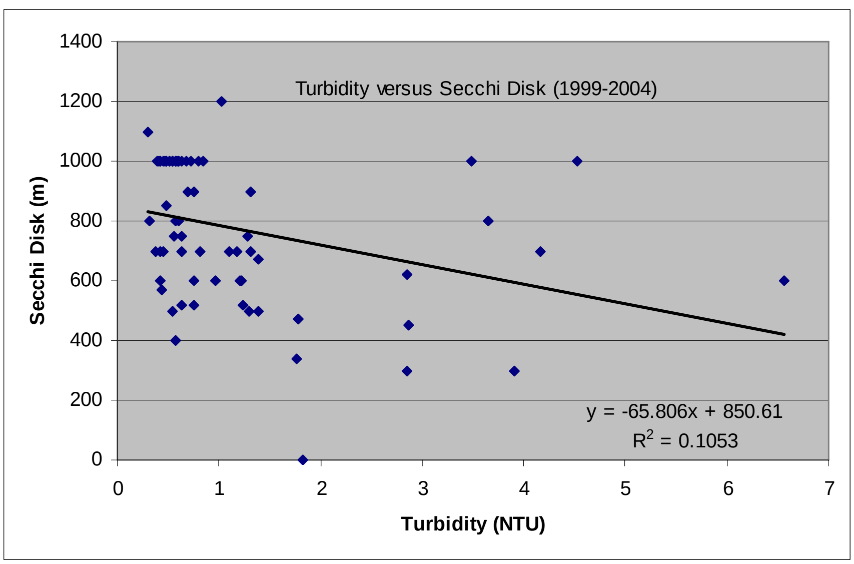

Figure 9. Relationship between secchi disk and turbidity readings from 1994 to 2006 in Seneca Lake at site 1.

Appendix. Seneca Lake data: 1991 to 2006. See text for locations. Chemistry data from site 3 from 1991 to 1998. After 1998 chemistry data from site 1. TP = Total phosphorus, SRP = Soluble reactive phosphorus, Chl *a* = Chlorophyll *a*. nd = no data.

Seneca Lake Date	Nitrate mg/L	SRP µg/L	TP µg/L	Chl-a µg/L	Turbidity NTU	Secchi Disk (cm) Site 1	Site 2	Site 3
7/23/1991	0.28	5.3	11.5	2.8	nd	200	190	180
8/2/1991	0.22	3.4	6.2	3.8	nd	300	300	310
8/15/1991	0.26	2.4	6.3	2.7	nd	600	560	580
9/3/1991	0.25	1.7	16.1	1.5	nd	510	620	610
9/17/1991	0.31	2.3	5.6	1	nd	650	610	610
7/7/1992	0.34	1.1	7.5	3.5	0.36	200	400	500
7/14/1992	0.36	1.2	11.4	3.9	0.5	nd	nd	360
7/21/1992	0.42	2.9	9.3	5.4	0.93	220	220	200
7/28/1992	0.45	4.3	5	6.9	0.95	220	200	250
8/4/1992	0.43	3.6	7.3	7.3	1.16	125	140	170
8/11/1992	0.39	0.2	8.8	3.2	nd	200	210	300
8/18/1992	0.36	5.5	9.9	2.3	1.06	340	300	390
8/25/1992	0.32	2.8	16	5.2	0.54	270	260	300
9/15/1992	0.37	2.9	12.3	7.7	nd	nd	nd	nd
6/29/1993	0.33	2	15.4	10.1	1.1	320	300	300
7/13/1993	0.31	1.3	3.6	2.3	0.47	330	400	410
7/20/1993	0.36	5.9	15.6	3.6	0.9	nd	nd	290
8/17/1993	0.3	1	13.7	5.5	0.53	nd	nd	320
8/24/1993	0.3	2.7	7.4	1	0.65	460	510	480
8/30/1993	0.3	1.3	7.1	2.4	0.27	740	710	700
7/11/1994	0.44	0.6	5.3	1.4	0.77	660	750	850
7/21/1994	0.4	2.7	10.3	3.4	0.37	650	740	800
8/8/1994	0.46	0.0	7.4	0.8	1.17	600	570	500
8/22/1994	0.36	0.6	3.4	3	0.54	nd	nd	510
8/29/1994	0.37	0.6	2.7	4.1	0.38	nd	nd	510
9/6/1994	0.38	0.6	5.7	2.5	1.29	660	770	850
9/12/1994	0.39	1.6	2.5	3.1	0.53	710	880	730
9/19/1994	0.36	0.5	5.2	2.4	0.58	nd	nd	700
7/11/1995	0.34	0.6	1.24	1.8	0.46	900	840	900
7/18/1995	0.35	0.6	6.2	3.3	0.44	nd	nd	800
8/1/1995	0.28	1.5	2.5	1.3	0.38	740	800	850
8/7/1995	0.35	0.6	3.8	1.3	0.35	900	800	800
8/15/1995	0.26	0.6	8.7	2.8	0.64	900	700	900
8/21/1995	0.29	0.6	10.9	2.1	1.03	1000	900	900
9/11/1995	0.3	1.3	5.2	1.9	0.76	nd	nd	900
9/18/1995	0.32	0.6	4	1.7	0.59	nd	nd	1100
7/17/1996	0.4	1.9	7.6	1.1	0.35	650	650	650
8/14/1996	0.33	0.6	17.4	4	0.78	620	620	570

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

8/22/1996	0.31	0.6	9.6	7.6	0.75	730	600	600
8/28/1996	0.23	3.3	6.7	9.6	0.54	520	550	560
9/1/1996	0.3	4.3	4.3	3.3	0.82	nd	nd	nd
10/1/1996	0.38	1.1	10.4	0.8	1.49	nd	nd	nd
10/8/1996	0.42	1.2	4.7	1.4	0.52	nd	nd	750
7/8/1997	0.37	0.0	4.5	2	1.43	800	900	850
7/15/1997	0.41	0.0	4.5	3.4	2.15	1000	1000	1000
7/23/1997	0.39	0.8	3.5	1.3	0.51	1000	1000	1000
8/6/1997	0.35	0.0	5.9	2.9	0.79	1000	1000	1000
8/13/1997	0.31	4.9	8.6	3.2	1.51	650	500	500
8/20/1997	0.37	0.6	7	0.7	0.84	800	750	720
9/1/1997	0.33	0.0	7.2	5.2	2.13	800	720	700
9/8/1997	0.36	2.1	7.3	7	1.18	750	750	750
9/15/1997	0.35	1.7	6.7	3.8	1.2	1000	1000	1000
7/6/1998	0.42	7.2	10.7	0.9	1.25	900	900	900
7/13/1998	0.42	1.3	8.7	7.4	0.68	>1000	>1000	>1000
7/20/1998	0.39	1.6	7.6	2.9	1.55	1000	1000	nd
8/3/1998	0.33	1.3	12	1.6	0.32	1000	1000	1000
8/24/1998	nd	nd	nd	nd	nd	nd	nd	nd
8/31/1998	0.35		7.8	2.3	0.32	1000	1000	1000
9/14/1998	0.3	3.1	4.6	4.7	0.43	>1000	>1000	>1000
9/21/1998	0.25	2.2	7.2	2.7	1.02	nd	nd	nd
9/28/1998	0.31	1.6	7.3	4.2	1.32	1000	1000	1000
10/5/1998	0.35	0.6	8	3.9	0.71	650	650	650
6/29/99	0.42	1.4	7.9	3.3	0.55	500	nd	nd
7/6/99	0.38	0.6	11.6	1.6	0.76	600	nd	nd
7/20/99	0.41	1.5	4.6	2.0	0.44	570	600	600
7/27/99	0.39	3.3	4.6	2.4	1.3	500	600	600
8/10/99	0.3	2.4	10.7	2.0	0.42	600	600	600
8/24/99	0.29	3.8	7.7	3.9	0.82	700	700	700
8/31/99	0.34	2.9	3.7	2.0	0.42	700	680	500
9/8/99	0.21	3	9.3	2.7	1.18	700	700	700
9/14/99	0.21	0.6	7.7	1.3	0.48	850	1000	1000
9/21/99	0.24	2.7	3.7	1.9	0.46	1000	nd	nd
7/6/2000	0.47	2.2	7.9	1.4	0.60	1000	1000	1000
7/11/2000	0.44	2.2	8.5	1.2	0.40	1000	1000	1000
7/17/2000	0.49	3.0	6.7	7	0.57	1000	1000	1000
7/27/2000	0.32	3.4	10.4	3.9	0.57	1000	1000	1000
8/2/2000	0.30	1.3	9.8	4.5	0.46	700	600	600
8/16/2000	0.38	1.3	14.6	6.2	1.31	700	nd	nd
8/24/2000	0.38	1.3	7.2	4.2	0.48	1000	1000	1000
9/13/2000	0.31	4.6	8.2	3.2	0.52	1000	1000	1000
9/26/2000	0.0	4.8	5.2	3.7	0.61	1000	1000	1000
7/9/2001	0.38	2.1	5.2	0.6	0.35	nd	nd	nd
8/2/2001	0.01	0.0	5.4	3.1	0.38	700	nd	nd
8/8/2001	0.47	1.5	4.6	3.2	0.51	1000	1000	nd
8/14/2001	0.21	2.2	7.7	2.9	0.80	1000	750	800
8/22/2001	0.29	0.0	6.5	2.0	0.73	1000	900	900

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

8/29/2001	0.26	1.3	7.9	5.4	0.54	1000	1000	1000
9/5/2001	0.31	3.9	17.2	3.1	0.39	1000	1000	1000
9/12/2001	0.34	0.6	4.6	1.9	1.02	1200	1200	1200
9/18/2001	0.36	3.4	6.4	4.4	0.47	nd	nd	nd
7/10/2002	0.62	5.7	7.3	1.9	nd	1000	1000	nd
7/15/2002	0.44	1.0	6.1	2.4	nd	1000	1000	nd
7/25/2002	0.35	0.2	5.2	2.3	0.42	1000	1000	1000
8/1/2002	0.36	5.7	10.2	2.9	0.60	800	800	800
8/7/2002	0.45	1.9	3.8	6.5	0.85	1000	1000	1000
8/13/2002	0.32	1.4	4.6	2.7	0.54	1000	1000	nd
8/21/2002	0.29	1.4	6.8	3.1	0.47	1000	1000	nd
8/28/2002	0.39	0.6	4.6	1.3	0.30	1100	1100	1100
9/4/2002	0.26	1.7	4.9	1.1	0.55	1000	1000	1000
7/8/2003	0.45	1.9	4.9	2.0	6.56	600	nd	nd
7/14/2003	0.47	0.6	11.1	1.6	4.52	1000	1000	nd
7/22/2003	0.38	0.0	6.5	1.6	3.49	1000	nd	nd
7/29/2003	0.40	0.0	13.1	6.6	3.65	800	nd	nd
8/5/2003	0.37	2.8	13.5	6.1	4.16	700	nd	nd
8/13/2003	0.29	1.5	5.9	0.8	2.85	300	nd	nd
8/20/2003	0.33	0.6	6.7	3.8	3.90	300	nd	nd
9/2/2003	0.30	2.6	11.6	8.0	2.87	450	450	nd
9/10/2003	0.33	0.6	1.2	2.5	2.85	620	500	nd
7/12/2004	0.61	2.1	10.9	3.5	1.28	750	750	750
7/28/2004	0.33	2.3	12.5	5.4	1.39	500	500	500
8/11/2004	0.35	6.5	17.8	1.4	1.32	900	900	900
8/17/2004	0.28	0.0	10.7	4.7	1.78	470	300	nd
8/24/2004	0.30	3.8	10.3	6.3	1.21	600	700	700
8/31/2004	0.36	2.1	8.8	1.6	0.63	700	700	700
9/8/2004	0.32	4.5	17.0	4.9	1.39	670	nd	nd
9/22/2004	0.40	5.7	8.7	6.1	0.64	520		520
9/29/2004	0.38	3.3	10.3	2.2	0.31	800	800	800
7/6/2005	0.45	2.2	8.1	2.3	1.10	700	nd	nd
7/19/2005	0.42	2.8	16.2	2.8	1.76	340	nd	nd
8/10/2005	0.25	0.0	7.0	4.1	0.97	600	600	600
8/17/2005	0.36	0.0	8.6	4.3	0.58	400	400	400
8/23/2005	0.33	1.8	9.4	3.6	0.64	750	750	750
9/6/2005	0.33	0.0	7.1	1.7	0.59	1000	nd	nd
9/14/2005	0.33	13.7	31.1	2.3	0.68	1000	nd	nd
9/28/2005	0.30	4.2	14.8	0.6	0.42	1000	nd	nd
10/4/2005	0.30	3.4	17.7	1.0	0.63	1000	nd	nd
7/11/2006	0.36	0.0	5.7	0.7	0.76	520	520	nd
7/18/2006	0.31	2.2	10.5	3.8	1.23	520	520	nd
7/26/2006	0.31	1.2	12.3	4.6	1.22	600	600	600
8/23/2006	0.23	1.9	13.3	0.9	0.76	900	900	900
9/5/2006	0.32	1.4	9.9	3.7	0.69	900	900	nd
9/19/2006	0.32	5.6	8.6	2.3	0.48	1000	1000	nd
9/27/2006	0.35	4.7	23.2	1	1.82	nd	nd	nd
10/10/2006	0.34	3.7	6.9	2.5	0.56	750	750	nd

10/16/2006	0.30	1.4	8.5	0.8	0.58	800	800	nd