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Changes in mid-summer water temperature and clarity across the Great Lakes between 1968 and 2002

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ABSTRACT

In recent decades, three important events have likely played a role in changing the water temperature and clarity of the Laurentian Great Lakes: 1) warmer climate, 2) reduced phosphorus loading, and 3) invasion by European Dreissenid mussels. This paper compiled environmental data from government agencies monitoring the middle and lower portions of the Great Lakes basin (lakes Huron, Erie and Ontario) to document changes in aquatic environments between 1968 and 2002. Over this 34-year period, mean annual air temperature increased at an average rate of 0.037 °C/y, resulting in a 1.3 °C increase. Surface water temperature during August has been rising at annual rates of 0.084 °C (Lake Huron) and 0.048 °C (Lake Ontario) resulting in increases of 2.9 °C and 1.6 °C, respectively. In Lake Erie, the trend was also positive, but it was smaller and not significant. Water clarity, measured here by August Secchi depth, increased in all lakes. Secchi depth increased 1.7 m in Lake Huron, 3.1 m in Lake Ontario and 2.4 m in Lake Erie. Prior to the invasion of Dreissenid mussels, increases in Secchi depth were significant ($p < 0.05$) in lakes Erie and Ontario, suggesting that phosphorus abatement aided water clarity. After Dreissenid mussel invasion, significant increases in Secchi depth were detected in lakes Ontario and Huron.

Introduction

Two important abiotic factors in lakes that affect most organisms are water temperature and water clarity. Water temperature influences growth, survival, and distribution of many aquatic species (Holland, 1993; Jackson et al., 2001; King et al., 1999; Kocovsky and Carline, 2001). Water clarity influences light transmission which may alter the thermal structure of a lake (Fee et al., 1996) and has important consequences for photosynthesis and vertical distribution of biota (MacIsaac, 1996; Nalepa et al., 1996; Scherer, 1976). Higher trophic levels may be influenced when primary production shifts deeper to unfavorable temperatures or out of reach of some fish. With this deepening, vulnerability to predation can be reduced as refuges are lost while the improved visibility may alter predator–prey interactions (Aksnes and Giske, 1993; Eiane et al., 1997; Mazur and Beauchamp, 2003). Fisheries can also be impacted as spatial distributions of fish shift in response to changing environmental conditions (Buijse et al., 1992; Ryan et al., 1999).

The Laurentian Great Lakes of North America contain over one-fifth of the world's fresh water and provide a wide variety of habitats for numerous aquatic species (Dann, 1994). By the early 1970s, severely degraded waterways and declining fisheries throughout the Great Lakes were raising concerns of anthropogenic impacts on the ecosystem. The Great Lakes Water Quality Agreement (GLWQA) first signed in 1972, initiated commitments from the US and Canada to restore and maintain the chemical, physical, and biological integrity of the Great Lakes (IJC, 1972). In 1978, revisions to the GLWQA set phosphorus concentration and loading targets for each lake (IJC, 1978). Phosphorus abatement programs put in place as a result of this agreement reduced phosphorus loadings throughout the Great Lakes (Neilson et al., 1995). Through the mid-1980s, primary and secondary productivity declined in most areas with resulting improvements in water clarity (Neilson et al., 1995).

Beginning in the late 1980s, filtering of the water column by zebra mussels *Dreissena polymorpha* and their deeper-living relatives, quagga mussels *D. bugensis*, may have further increased water clarity (Fahnenstiel et al., 1995; Mills et al., 1999; Wilson et al., 2006). In Lake Erie, zebra mussels were first observed in 1988 (Leach, 1993) but rapidly colonized the lake by 1989–90 (Griffiths et al., 1991). Substantial reductions in chlorophyll and total phosphorus reported for Lake Erie and Saginaw Bay during late 1980s to early 1990s coincided with the invasion of *Dreissena* spp. and a causal mechanism was inferred (Nicholls et al., 1999). While building a phosphorus budget for Saginaw Bay, Lake Huron, Johengen et al. (1995) found zebra mussels to be a considerable phosphorus sink, which was also confirmed by enclosure experiments (Heath et al., 1995). Recently, there has been a shift from *D. polymorpha* to *D. bugensis* in deeper areas of Lake Erie (Barbiero and Tuchman, 2004). Similarly, an east–west gradient, with *D. bugensis* dominant in

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the west and *D. polymorpha* in the east, has been found in southern Lake Ontario (Mills et al., 1999). Given the possible water clearing actions of these mussels, such shifts in the *Dreissena* spp. have implications for water clarity in deeper parts of the lakes. Filtration by zebra mussels has also been found to have differing impacts on nearshore and offshore waters in Lake Erie (Makarewicz et al., 1999) and in shallow embayments in Lake Ontario (Bailey et al., 1999).

Temperature is another dimension of the Great Lakes environment that has probably changed in recent decades, given recent trends in atmospheric temperature (IPCC, 2001). Increases in water temperature for some areas of the Great Lakes have been reported (e.g., Austin and Colman, 2007; Casselman, 2002; Jones et al., 2006; McCormick and Fahnenstiel, 1999), suggesting that effects of global warming are already apparent.

Although many studies (e.g., Bailey et al., 1999; Barbiero and Tuchman, 2004; Dobson et al., 1974; Fahnenstiel et al., 1995; Fee et al., 1996; Hall et al., 2003; Johengen et al., 1995; Makarewicz et al., 1999) have reported on recent environmental changes in the Great Lakes, each of these studies covered either limited time periods or limited spatial areas. A broad-scale, long-term account of changes in water clarity and temperature in the Laurentian Great Lakes is lacking. The purpose of this paper is to fill this gap by documenting the changes that have occurred in several Great Lakes since 1968.

To provide comprehensive coverage of this large area, we obtained environmental data from Canadian and US government agencies that have been active in monitoring the Great Lakes. For logistical reasons, we focused our data acquisition effort on the middle and lower portions of the Great Lakes basin (i.e., lakes Huron, Erie, and Ontario). Our collated dataset included temperature observations (air temperature, surface water temperature, and depth profiles of water temperature) and water clarity observations (Secchi depth). We used these data to describe trends in air temperature, surface temperature, and water clarity within each lake from 1968 to 2002. Our analysis of water clarity changes also investigated the extent to which increasing water clarity due to phosphorus abatement was exacerbated by the invasion of Dreissenid mussels.

Methods

Sources of data

For lakes Huron, Erie, and Ontario, we compiled climate and limnological data from the following government agencies: Fisheries and Oceans Canada, Environment Canada, the Ontario Ministry of Natural Resources, the US National Oceanic and Atmospheric Administration National Data Buoy Center, the US National Weather Service, the US Great Lakes Environmental Research Laboratory, the US Environmental Protection Agency STORET database, the US Great Lakes National Program Office, and the Michigan Department of Natural Resources. Observations were consolidated in a database containing data from approximately 15,000 sites sampled during May to October between 1968 and 2002. Samples included observations of air temperature, surface water temperature, water temperature profiles, Secchi depth, light extinction, and turbidity.

Air temperature

To describe climatic changes during recent decades, we used air temperature data reported by Environment Canada weather stations on the shoreline of each lake. These stations reported daily mean, minimum, and maximum air temperature. For each weather station, we calculated a monthly mean if the station reported air temperature for at least 28 days in a month. From these data we calculated annual means for each station if there were 12 monthly means in a given year. Because of the highly unusual weather that occurred following the eruption of Mt. Pinatubo, temperature data from 1992 were ignored. Stations were selected as representative for a lake if the station had annual means for at least 26 of the 34 years, producing a list of 14 stations. From these we selected seven stations as representative of specific lakes (Fig. 1). Linear regression analysis was used to describe trends in mean annual air temperature.

Limnological data

Our analyses focused on Secchi depth and surface water temperature (top 5 m of the water) because these measures provided the widest spatial and temporal coverage across all lakes and basins. Surface water temperature and Secchi depth from each lake were organized into basins (Fig. 1) because these variables can vary spatially within a lake. Lake Erie was divided into three basins: Western, Central, and Eastern (as in Barbiero and Tuchman, 2004; Charlton et al., 1993). Lake Ontario was divided into four basins: Western, Eastern, Outlet basin, and the Bay of Quinte. The outlet basin, covering the easternmost portion of the lake, has also been referred to as the Kingston basin (Kerr and LeTendre, 1991). Lake Huron was divided into seven basins: the middle portion or main basin was divided into Northern, Central, and Southern basins; the more northern portion was divided into the North Channel and Georgian Bay; and Saginaw Bay was divided into the inner and outer bays, separating the shallow eutrophic zone from the deeper oligotrophic area adjacent to the main basin (Beeton et al.,

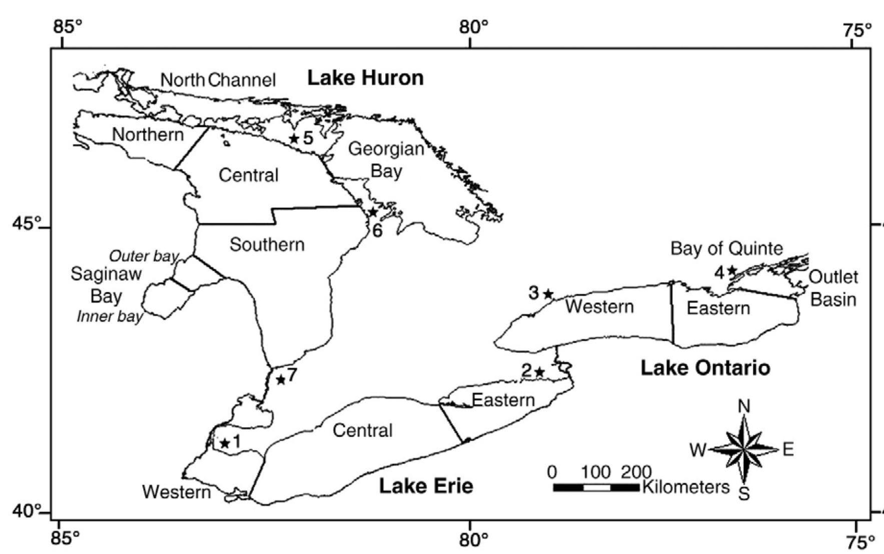

Fig. 1. Map of lakes Huron, Erie, and Ontario showing basin divisions used in this study. Climatological stations (Table 2) used are marked by a star.

1967; Johengen et al., 2000; Nalepa et al., 1995). We excluded Outer Saginaw Bay in our analysis as it represented a transitional zone.

This spatial organization of the data resulted in 13 basins for which we describe changes in water temperature and Secchi depth (Fig. 1, Table 1). We divided basins into two types (shallow and deep), based on mean depth criterion of 10 m. The samples we obtained within a basin did not always cover the entire extent of its depths. In the shallow basins (Erie—Western, Huron—Inner Saginaw Bay, and Ontario—Bay of Quinte), most of the data were collected at sites shallower than 10 m, so we excluded the few observations from deeper sites. In the deep basins (Table 1), most of the data were collected at sites deeper than 10 m, so we excluded shallower observations.

Water temperature and transparency undergo annual cycles so our analysis of long-term trends was based on observations collected at the same time of year. To identify an appropriate time period, we classified observations according to week (1–52) and calculated weekly means from sites sampled within each basin. These results indicated that most basins were sampled throughout the ice-free season, but the amount of coverage was highly variable among basins. The highest sampling frequency occurred during August. We therefore used August data to document changes in water temperature and Secchi depth. For water temperatures, we ignored data from 1992 as we did with the air temperature data.

Sampling intensity varied among years causing the precision of these indices to be highly variable (see Appendix). We therefore used a precision criterion to filter data. Precision was measured as the relative standard error of estimated means (RSE = standard error/mean); we rejected indices for years when RSE exceeded 15% or the number of observations was less than three. This procedure had little effect on the water temperature dataset because RSEs were typically low (<5%). In contrast, higher variability in Secchi depth and smaller sample sizes led to less precise estimates. Consequently, our dataset for Secchi depth is less complete than temperature (Table 1).

Additional filtering of data was done by examining pairwise correlations among basins within each lake. Correlations were typically high, so instances of low correlations suggested data problems. This process identified one temperature outlier (Ontario—Western 1988) and two Secchi depth outliers (Erie—Eastern 1974, Huron—Central 2002) that were excluded.

Analyses of changes in water temperature and clarity

Analyses of water temperature data first examined whether there were temporal trends in August surface water temperature. We used observations from the top 5 m to measure surface temperature. This depth criterion was deemed suitable because the depth of the thermocline (if it existed) was always much greater than 5 m. Linear regression analysis (mean surface temperature versus year) was used to describe trends and test significance within each basin. Analysis of covariance was then used to test whether slopes varied among basins within a lake and, when slopes were not significantly different, to calculate a common slope. These results were used to test for a significant effect at the lake level.

We also examined trends in water temperature at various depths. The lack of temperature profile data across the 34-year time span severely restricted our ability to describe trends in basins and lakes. Our analysis was based on a single basin (Ontario—Western) for which sufficient data were available. To describe temperature-at-depth, we classified sampling depths into 5-m intervals and calculated mean August temperature for each year. We then used linear regression analysis (mean temperature-at-depth versus year) to describe trends.

Analyses of water clarity first examined whether there were temporal trends in August Secchi depth. The regression methods described above for surface water temperature were used to test for trends in each basin and to describe trends at the lake level. Additional analyses were performed to test whether effects of phosphorus reduction and Dreissenid mussel invasion could be separated. To do so, we organized the Secchi depth data into three time periods: Period 1 denoting pre-phosphorous control, Period 2 denoting post-phosphorous control prior to mussel establishment, and Period 3 denoting post-mussel establishment. Period 1 began in 1968, the first common year of data for all lakes. Period 2 began in 1982 when phosphorus levels in each lake became stable following phosphorous abatement (Neilson et al., 1995). The starting date for Period 3 differed among lakes because zebra mussels were established by 1989 in Lake Erie (Griffiths et al., 1991) and by 1993 in lakes Huron (Nalepa et al., 1995) and Ontario (Haynes, 1997).

An increase in water clarity between Periods 1 and 2 was expected due to reduced phosphorus input. Because phosphorus levels were stable by the end of Period 2, an increase in water clarity after Period 2 would be an evidence of a mussel invasion effect. Analyses of variance were conducted to test whether Secchi depth differed between Periods 1 and 2 and between Periods 2 and 3. In these analyses, a logarithmic transformation of Secchi depth was used because variance in Secchi depth increased with the mean.

Results

Air temperature

Mean annual air temperature between 1968 and 2002 ranged from 5.0 °C in the north (Gore Bay, Manitoulin Island, Lake Huron) to

Table 1
Summary of data by basin, after applying a precision filter, showing the number of years for which August surface water temperature and Secchi depth means were calculated for each basin.

Lake and basin	Basin attributes				Water temperature			Secchi depth		
	Basin type	Area (km^2)	Mean depth (m)	Max depth (m)	Years	Mean	Standard deviation	Years	Mean	Standard deviation
Erie										
Western	Shallow	4837	6	15	9	24.58	1.93	7	1.1	0.4
Central	Deep	15,061	19	30	21	23.33	1.11	19	5.8	1.5
Eastern	Deep	5836	24	68	16	23.13	0.84	13	5.7	1.2
Ontario										
Western	Deep	10,342	70	200	31	20.06	1.57	26	3.1	1.2
Eastern	Deep	6895	95	230	29	21.45	1.12	21	3.3	1.2
Outlet Basin	Deep	1724	20	40	26	21.71	0.83	16	3.2	1.0
Bay of Quinte	Shallow	103	5	20	24	22.38	1.09	5	1.9	0.9
Huron										
Northern	Deep	6918	70	140	15	19.09	1.88	7	7.8	1.3
Central	Deep	20,221	65	220	17	17.89	1.83	12	8.3	1.3
Southern	Deep	6386	55	170	17	19.47	1.65	14	8.5	1.0
North Channel	Deep	5321	14	60	15	17.57	1.63	5	6.6	0.8
Georgian Bay	Deep	15,964	30	160	13	18.71	1.46	13	8.5	1.4
Saginaw Bay—Inner	Shallow	1480	4	10	13	19.82	1.57	6	1.5	0.3

Annual means and samples size are documented in the Appendix (website link).

Table 2
Linear regression of mean annual air temperature (°C) versus year for key climatological stations.

Station	ID	Lake association	No. of years	Intercept	Slope	(SE)	R^2	P-value
Windsor	1	Erie	31	8.8	0.038	(0.014)	0.21	<0.05
Port Colborne	2	Erie	22	8.1	0.042	(0.017)	0.24	<0.05
Toronto	3	Ontario	31	8.6	0.033	(0.014)	0.17	<0.05
Trenton	4	Ontario	31	6.5	0.030	(0.013)	0.14	<0.05
Gore Bay	5	Huron	26	4.6	0.053	(0.019)	0.24	<0.05
Wiarton	6	Huron	29	5.6	0.037	(0.017)	0.15	<0.05
Sarnia	7	Huron	28	7.6	0.030	(0.018)	0.10	0.10
All stations				7.1	0.037	(0.006)	0.81	<0.01

Year is relative to 1968. Results for 'All stations' report a common slope and mean intercept based on analysis of covariance. Station locations are shown in Fig. 1 labeled by ID.

9.5 °C in the south (Windsor, Lake Erie). Regression of mean annual air temperature versus year gave positive slopes at all stations (Table 2). Trends were significant ($p<0.05$) at all stations except Sarnia ($p=0.10$). Analysis of covariance indicated that slopes were not significantly different from each other and implied a common slope of 0.037 °C/y (SE = 0.006), indicating that air temperature increased 1.3 °C between 1968 and 2002.

Water temperature

Regression of August surface temperature versus year revealed a positive slope for all basins (Fig. 2, Table 3). The magnitude of this trend and its significance varied among lakes. The smallest temperature change occurred in Lake Erie. Although a positive slope was estimated in each of the three basins, none of these trends were significant. Slopes were not significantly different among basins and analysis of covariance produced a common slope of 0.025 °C/y (SE = 0.011) that was also non-significant ($p=0.18$).

The next largest change in water temperature occurred in Lake Ontario where trends were significant ($p<0.05$) in 3 of 4 basins. Slopes were not significantly different among basins and analysis of covariance revealed a common slope of 0.048 °C/y (SE = 0.011), or an increase of 1.6 °C over the 34-year period.

The largest change in temperature occurred in Lake Huron where trends were significant in 3 of 6 basins. Slopes were not significantly different among basins and analysis of covariance gave a common slope of 0.084 °C/y (SE = 0.013) equivalent to an increase in water temperature of 2.9 °C.

Trends in temperature-at-depth were examined only in the Western basin of Lake Ontario because insufficient data existed for other basins. Regression analysis suggested that warming trends (i.e., slope estimates in Table 4) similar in magnitude to the surface trend extended as deep as 20 m (Fig. 3a). From 20 to 35 m, the estimate of warming trend declined rapidly, but trends were not statistically significant. However, at depths of 35–50 m, a small (i.e., 0.02 °C/y) but significant trend existed. These regression results were used to produce temperature profiles that contrast the beginning (1968) and end (2002) of our time series (Fig. 3b). Over the 34-year period, the implied increase in epilimnetic temperature is approximately 2.7 °C; the implied increase at a depth of 40 m is approximately 0.7 °C.

Table 3
Linear regression of August surface water temperature (°C) versus year.

Lake and basin	No. of years	Intercept	Slope	(SE)	R^2	P-value
Erie						
Western	9	23.0	0.072	(0.079)	0.11	0.40
Central	21	23.1	0.014	(0.024)	0.02	0.57
Eastern	16	22.8	0.024	(0.021)	0.08	0.29
All basins	21	23.2	0.025	(0.011)	0.20	0.18
Ontario						
Western	31	19.0	0.064	(0.025)	0.15	<0.05
Eastern	29	20.9	0.035	(0.019)	0.11	0.07
Outlet Basin	26	21.2	0.038	(0.017)	0.17	<0.05
Bay of Quinte	24	21.3	0.054	(0.021)	0.24	<0.05
All basins	34	20.6	0.048	(0.011)	0.44	<0.01
Huron						
Northern	15	16.5	0.136	(0.028)	0.65	<0.01
Central	17	16.5	0.073	(0.038)	0.19	0.08
Southern	17	17.7	0.088	(0.031)	0.35	<0.05
North Channel	15	16.2	0.082	(0.032)	0.34	<0.05
Georgian Bay	13	17.4	0.067	(0.036)	0.24	0.09
Saginaw Bay—Inner	13	18.3	0.076	(0.040)	0.25	0.08
All basins	19	17.2	0.084	(0.013)	0.46	<0.01

Year is relative to 1968. Results for 'All basins' report a common slope and mean intercept based on analysis of covariance.

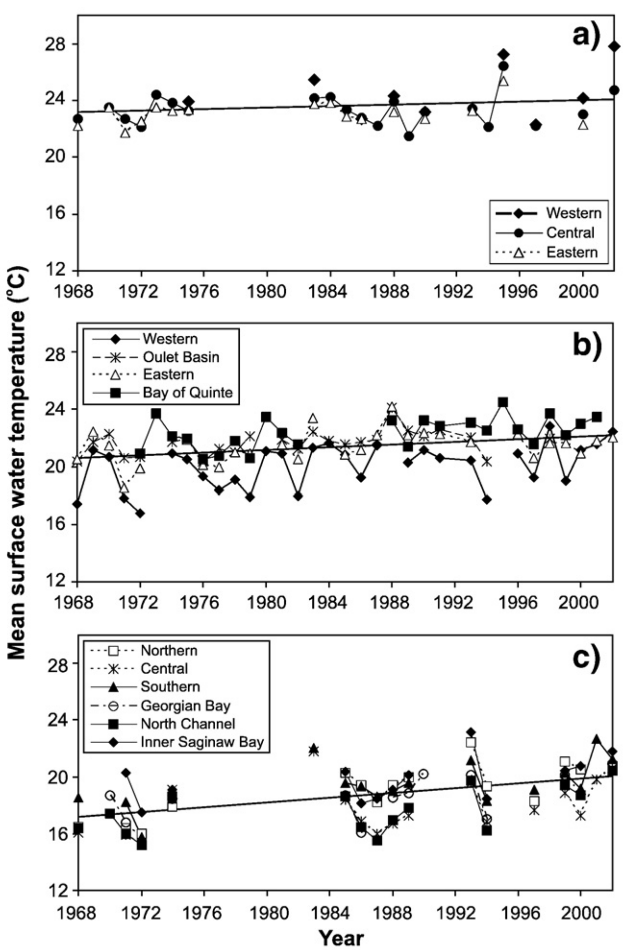

Fig. 2. Trends in August surface water temperature (°C) in lakes (a) Erie, (b) Ontario, and (c) Huron. Solid lines describe the lake trend (Table 3).

Table 4
Linear regression of August temperature-at-depth (°C) versus year for the Western basin of Lake Ontario.

Depth	No. of years	Intercept	Slope	(SE)	R^2	P-value
0–5	32	18.9	0.061	(0.027)	0.15	<0.05
5–10	27	16.6	0.077	(0.043)	0.11	0.09
10–15	27	13.3	0.092	(0.049)	0.12	0.07
15–20	27	10.1	0.084	(0.056)	0.08	0.14
20–25	27	7.9	0.038	(0.042)	0.03	0.37
25–30	27	6.3	0.014	(0.028)	0.01	0.61
30–35	27	4.9	0.022	(0.015)	0.08	0.15
35–40	26	4.6	0.024	(0.008)	0.29	<0.01
40–45	26	4.3	0.017	(0.007)	0.19	<0.05
45–50	26	4.3	0.019	(0.008)	0.20	<0.05
50–55	27	4.2	0.008	(0.006)	0.07	0.20

Year is relative to 1968. Temperature-at-depth was averaged over 5-m depth intervals.

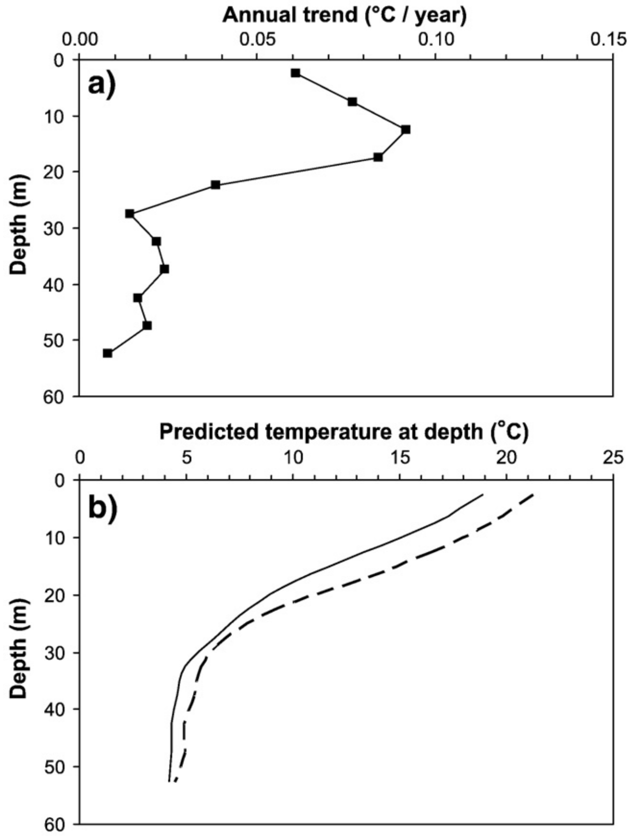

Fig. 3. (a) Trends in water temperature-at-depth for the Western basin of Lake Ontario. Each point is the estimated slope (°C/y) from the linear regression of mean water temperature versus year for a specific depth interval (e.g., 0–5, 5–10, etc.). (b) Regression-based estimates of temperature-at-depth for 1968 (solid line) and for 2002 (dotted line) in the Western basin of Lake Ontario.

Water clarity

Regression of mean Secchi depth versus year revealed a positive slope in all except one basin, but only in Lake Ontario were these trends significant in all basins (Fig. 4, Table 5). In Lake Erie, the trend was significant in the well-sampled Central basin, but not in the Eastern or Western basins. Failure to detect a significant effect in other basins may have been due to the smaller sample size (see Appendix). The pattern of change in the Eastern basin matched the Central basin prior to 1986, but there are few observations from the Eastern basin after this year. When data from both basins are combined, the common slope is 0.070 (SE = 0.021, $p<0.01$), implying a significant trend in water clarity within the deep basins of Lake Erie. The ANOVA results (Table 5) indicate that a significant change in Secchi depth occurred between Periods 1 and 2 in the Central basin, suggesting that phosphorus controls had an effect. There is no significant difference between Periods 2 and 3, indicating that a further increase in Secchi depth was not detected after the arrival of Dreissenid mussels. In the shallow Western basin, water clarity is much lower. The small sample size (9 years) prohibits detailed analysis of trends, but the data available are consistent with the conclusion that water clarity peaked prior to the arrival of mussels.

In Lake Ontario, water clarity differed little among the deep basins (Western, Eastern, and Outlet) and the pattern of change over years was similar (Fig. 5). Each deep basin displayed similar inter-annual variation and regression analysis produced virtually identical estimates of a positive trend. Here, analysis of covariance revealed a common slope of 0.091 m/y (SE = 0.011, $p<0.01$). In contrast to Lake Erie, it appears that most of this change occurred after mussel invasion (1993). Water clarity fluctuated between 2 and 4 m from 1968 to 1993. Water clarity in excess of 4 m has been observed mainly in more recent years. Changes in Secchi depth between Periods 1 and 2 were not significant in any basin, although the change was significant when data were combined across the deep basins of the lake. On the other hand, changes in Secchi depth after mussel invasion (Periods 2–3) were significant in all basins. Regression results for the shallow basin (Bay of Quinte) indicated a stronger trend (slope = 0.125 m/y, SE = 0.037), but this trend describes changes since 1984 because data from the earlier period were not available. Results (Fig. 4) suggest that this trend is driven mainly by changes after 1993 when mussels arrived in Lake Ontario. This conclusion is supported by the ANOVA results (Table 5) that compare water clarity in the pre-invasion period (1982–1993) to the post-invasion period (post 1993).

In Lake Huron, estimated slopes for Secchi depth were generally positive but a significant trend existed only in the Southern basin. Georgian Bay deviates from other basins because the highest values were observed near the start of the time series (i.e., 1970 and 1971) and the slope estimate is negative (albeit non-significant). Slopes for other deep basins were similar and analysis of covariance implied a common slope of 0.049 (SE = 0.015, $p<0.01$). Comparisons among periods for the deep basins (excluding Georgian Bay) indicated no significant change prior to the arrival of mussels (Periods 1–2 in Table 5), but a significant effect after mussel arrival (Periods 2–3). Georgian Bay also showed an increase in Secchi depth after mussel invasion. Data from Inner Saginaw Bay (see Appendix) show that Secchi depth was

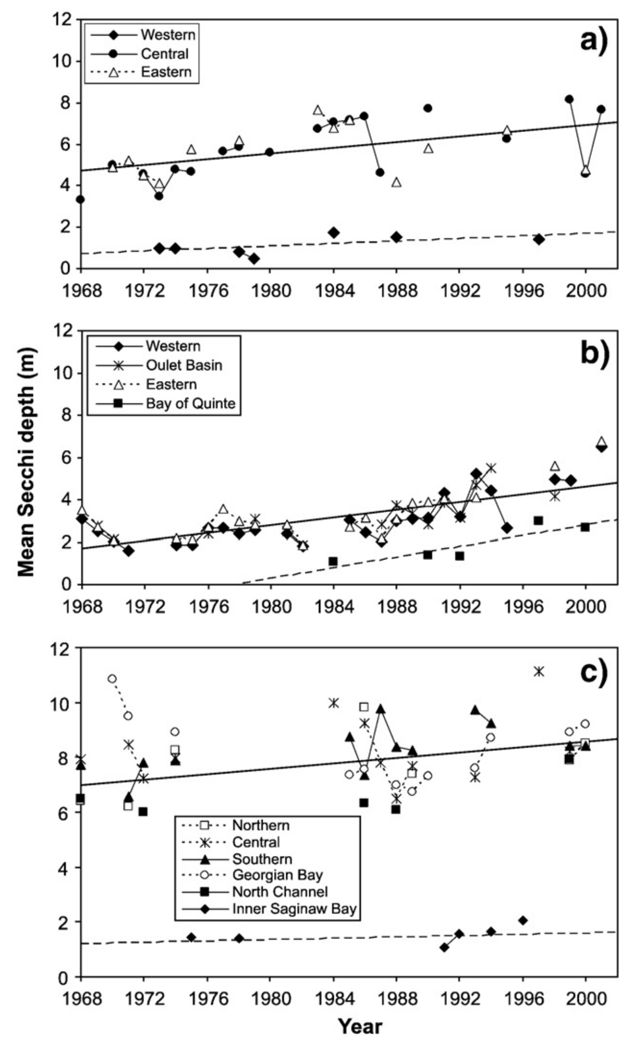

Fig. 4. Trends in August Secchi depth (m) in lakes (a) Erie, (b) Ontario, and (c) Huron. Solid lines describe the deep basin trend in each lake (Table 5). Dashed lines describe the trends for shallow basins.

Table 5
Linear regression of August mean Secchi depth (m) versus year by basin.

Lake and basin	No. of years	Intercept	Slope	(SE)	R^2	*P*-value	ANOVA *P*-values Periods 1–2	Periods 2–3
Erie								
Western*	7	0.7	0.031	(0.019)	0.34	0.17	0.08	0.31
Central	19	4.4	0.092	(0.026)	0.42	<0.01	<0.05	0.90
Eastern	13	5.2	0.032	(0.035)	0.07	0.38	0.26	0.57
Deep basins	25	4.7	0.070	(0.021)	0.27	<0.01	<0.01	0.81
Ontario								
Western	26	1.6	0.094	(0.017)	0.57	<0.01	0.06	<0.01
Eastern	21	1.9	0.093	(0.020)	0.53	<0.01	0.40	<0.05
Outlet Basin	16	1.8	0.083	(0.020)	0.54	<0.01	0.13	<0.05
Bay of Quinte*	5	−1.2	0.125	(0.037)	0.79	<0.05	NA	<0.01
Deep basins	51	1.7	0.091	(0.011)	0.55	<0.01	<0.05	<0.01
Huron								
Northern	7	7.0	0.051	(0.036)	0.29	0.21	0.30	0.85
Central	12	7.8	0.031	(0.038)	0.06	0.44	0.77	0.74
Southern	14	7.3	0.063	(0.020)	0.46	<0.01	0.08	0.62
North Channel	5	6.0	0.041	(0.027)	0.43	0.23	0.67	0.12
Georgian Bay	13	8.8	−0.012	(0.041)	0.01	0.78	<0.01	<0.01
Saginaw Bay—Inner*	6	1.2	0.012	(0.016)	0.19	0.39	0.42	0.22
Deep basins	36	7.0	0.049	(0.015)	0.43	<0.01	0.07	<0.05

Year is relative to 1968. Results for 'Deep basins' report a common slope and mean intercept based on analysis of covariance on the data from deep basins. Georgian Bay was excluded from the 'deep basins' analysis (see text for explanation). An asterisk (*) indicates a shallow basin.

shallower than the deep basins of the lake. The trend is also positive here but there are few observations and the effect is not significant.

Summary of changes

Changes in each lake are summarized in Fig. 5. This summary used the regression results to calculate start (i.e., 1968) and end (i.e., 2002) values of water temperature and Secchi depth. Fig. 5 plots the change against initial value. The graphs demonstrate that changes are inversely related to initial state. The largest change in temperature (Fig. 5a) occurred in Lake Huron, the coldest lake, where water temperature increased from 17.2 to 20.1 °C (i.e., +2.9 °C). In Lake Ontario, water temperature increased from 20.6 to 22.2 °C (i.e., +1.6 °C). Although the change in temperature was not significant in Lake Erie, we show the estimated change of 23.2 to 24.1 °C (i.e., +0.9 °C) for comparison with other lakes. A similar pattern was observed for Secchi depth. The largest change (+3.1 m) occurred in Lake Ontario (i.e. 1.7 to 4.8 m) where water clarity was lowest in 1968. In Lake Erie, water clarity increased 2.4 m (4.7 to 7.1 m). In Lake Huron, the clearest lake, Secchi depth increased only 1.7 m (7.0 to 8.6 m).

Discussion

A number of studies have examined changes in water temperature and clarity across the Great Lakes, but these studies either covered limited time periods (e.g., Dobson et al., 1974; Hall et al., 2003; Johengen et al., 1995; Makarewicz et al., 1999) or limited spatial areas (e.g., Barbiero and Tuchman, 2004; Fee et al., 1996; Makarewicz et al., 1999). This is the first published study that covers a broad historical time frame, 1968–2002, and examines changes in both water temperature and clarity across the basins of lakes Huron, Erie, and Ontario. Our results confirm conjecture that substantial increases in water temperature and water clarity have occurred in the Great Lakes over the last three decades. We also found that the degree of change is highly variable among lakes.

The exchange of heat between the atmosphere and water is a major determinant of water temperature. Water temperature may be the same across geographic areas (Benson et al., 2000) but can also vary within a lake depending on basin size or differ between nearshore and offshore areas (Finlay et al., 2001). Basins within a lake can differ because air temperature, local meteorological conditions, and basin morphometry all influence water temperature (Leon et al., 2005). So it is not surprising that mean August surface water temperature varied among lakes and among basins within lakes (Table 1). Trends were difficult to detect at the basin level because temperature fluctuated widely (Fig. 2, Table 3), but when data from all basins within each lake were combined, highly significant ($p<0.01$) trends were observed in lakes Huron and Ontario.

Trends in surface water temperature were more prominent in colder lakes (Fig. 3, Table 3). In the two coldest lakes (i.e., Huron and Ontario), average warming rates were 0.084 °C/y and 0.048 °C/y; in Lake Erie (the warmest lake) the warming rate was lower (0.025 °C/y). Because Lake Erie was the least sampled lake, the temperature trend was measured less precisely than in other lakes. Our estimate of the trend is not statistically different than zero, yet it is closer to the rate of atmospheric warming (i.e., 0.037 °C/y) than it is to zero, so one cannot discount the hypothesis that warming rate in Lake Erie matched the rate of atmospheric warming. In contrast, the water temperature increased faster than air temperature in the other two lakes.

Austin and Colman (2007) reported similar trends in the Great Lakes from 1979 to 2006. For the northern lakes (Superior, Huron, and Michigan), summer (July–September) surface temperature increased more rapidly than air temperature. In Lake Erie, the increase in surface water temperature was approximately equal to the increase in air temperature, but not significantly different from zero. Water temperature

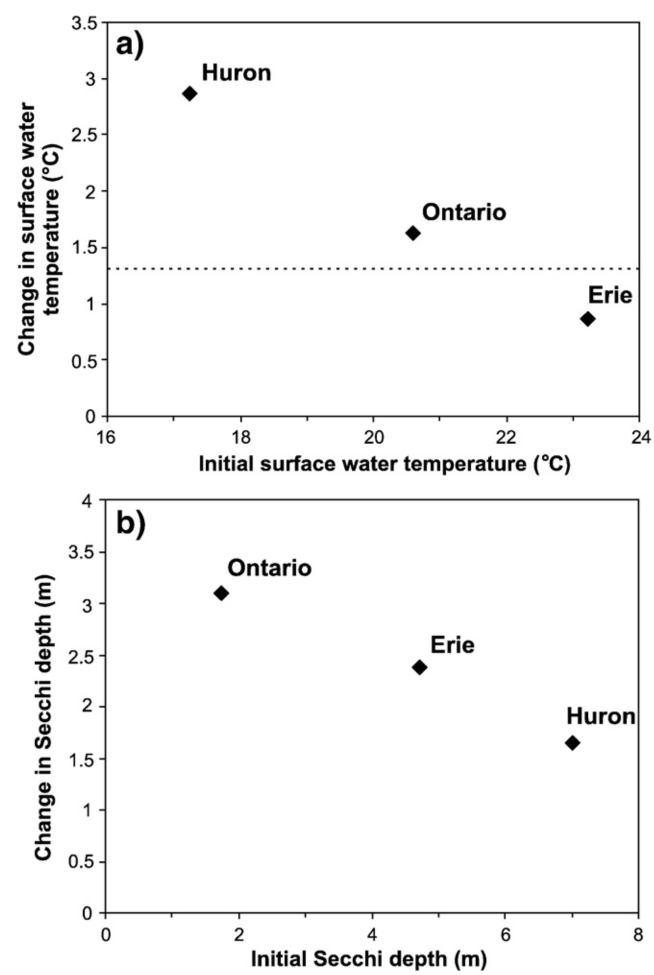

Fig. 5. Summary of changes in each lake based on the regression results (Tables 3 and 5). (a) Estimated change in surface water temperature from 1968 to 2002 plotted against initial temperature in each lake; Lake Erie results were not significant but the estimate is shown here for comparison with the other lakes. Dashed line is the estimated change in air temperature. (b) Estimated change in Secchi depth of deep basins from 1968 to 2002 plotted against initial Secchi depth.

increased most rapidly (i.e., 0.12 °C/y) in Lake Superior (the coldest of the Great Lakes), followed by Lake Huron (0.088 °C/y) and Lake Michigan (0.065 °C/y). The discrepancy between air and water temperature changes was attributed to earlier stratification (Austin and Colman, 2007). An earlier start to the stratified period increases the duration of time over which the lake warms during summer months allowing a higher maximum temperature. Consequently, if duration of the stratified period increases with air temperature the trend in surface temperature will tend to exceed air temperature. If this effect was more pronounced in colder lakes, it would explain the higher rate of warming in these lakes.

When describing changes in water clarity, measured here by August Secchi depth, we differentiated between deep and shallow basins. Mean Secchi depth (Table 1) ranged from 1–2 m in shallow basins and was always less than in deep basins. Mean Secchi depth in deep basins was approximately 3 m in Lake Ontario, 6 m in Lake Erie, and 8 m in Lake Huron. Shallow basins were not very useful in describing trends during the past 34 years, because they were sampled infrequently (i.e., 5–7 years). We therefore focused on the deep basin results to describe changes in each lake (Fig. 5). The largest change occurred in Lake Ontario, where Secchi depth increased 3.1 m, followed by Lake Erie (+2.4 m). In Lake Huron (excluding Georgian Bay), the change in Secchi depth was less (+1.7 m). Georgian Bay was excluded from our analysis of lake trends because the pattern of change differed from other basins in the lake (Fig. 5).

We identified time periods in each lake when the effects of phosphorus abatement programs and establishment of Dreissenid mussels likely dominated over other effects on water clarity. Phosphorus concentrations have a direct impact on water clarity and this was a major reason for initiation of 1970s phosphorus abatement programs which were enacted to reduce concentrations across the Great Lakes. In lakes Erie and Ontario, water clarity increased during the period of phosphorus abatement, but in Lake Huron a significant effect was not detected.

Phosphorus concentrations in Lake Erie often exceeded target levels during Period 1 (1968–1981), but were generally lower during the 1990s (Neilson et al., 2003). Although targets were not always met, our results suggest that mean concentrations were reduced sufficiently after 1981 to cause a significant increase in water clarity (Table 5).

Phosphorus concentrations in Lake Ontario dropped consistently after 1970 and target levels were met by the 1990s (Neilson et al., 2003). This reduction of phosphorous levels is associated with an increase in the water clarity in the deep basins of the lake (Table 5). We did not have sufficient data to describe the change in the shallow Bay of Quinte, but at least one other study of the bay suggests that phosphorous controls improved water clarity in the bay (Robinson, 1986).

Phosphorus concentrations in Lake Huron have always been below or slightly above the GLWQA target level (Chapra and Robertson, 1977; Neilson et al., 2003), so we would not expect large changes in water clarity as a result of the phosphorus abatement program. Small changes may have occurred, but small changes would be difficult to detect given the small number of observations on Lake Huron (Fig. 4c).

Much has been written about changes in water clarity within the Great Lakes after colonization by Dreissenid mussels in the early 1990s. We detected a significant increase in water clarity during this time period in lakes Ontario and Huron, but not in Lake Erie (Table 5). Our ability to detect an increase within Lake Erie was limited due to poor sampling, but there is no indication that water clarity surpassed the level attained prior to mussel invasion. Similar findings were noted by Barbiero and Tuchman (2004) who found no evidence of a Dreissenid mussel effect in Lake Erie. However, they noted an increase in water clarity in eastern Lake Erie during the spring and hypothesized that calcium uptake by Dreissenid mussels may have reduced whitening events in that basin. Dreissenid mussels may have had an impact on spatial scales smaller than the basins we used. For instance, in Hatchery Bay, western Lake Erie, Secchi depth increased 100% following establishment of zebra mussels (Holland, 1993).

Water clarity following the establishment of Dreissenid mussels increased in all Lake Ontario basins. This effect after reductions in phosphorous levels was also observed by Nicholls et al. (2001). One reason we may have found a stronger effect here is that high densities of both zebra mussels and quagga mussels occur across Lake Ontario (Mills et al., 1999; Wilson et al., 2006) with quagga mussels having a stronger impact on deeper waters. French et al. (2007) noted an exponential increase in quagga mussels in Lake Michigan from 2001 to 2003 which may indicate the possibility of similar changes in water clarity in its deeper basins.

In the deep basins of Lake Huron (except Georgian Bay), filtering by zebra mussels and the deeper residing quagga mussels likely facilitated the more than 1 m increase in Secchi depth. For Inner Saginaw Bay, we observed a small (yet insignificant) increase in Secchi depth (1 m) following zebra mussel establishment. Fahnenstiel et al. (1995) noted a doubling of Secchi depth during 1974 to 1993 and a significant increase in Secchi depths after 1991 which could be attributed to zebra mussel establishment. Qualls et al. (2007) also found no trend in Secchi depth following zebra mussel invasion in Green Bay, Lake Michigan. They suggested that zebra mussels had not yet impacted water clarity in the bay. However, they also found a reduction in chlorophyll *a* concentration in the bay and hypothesized that zebra mussels may have selectively filtered algal material and not suspended sediments leading to an undetectable change in water clarity.

In summary, the Laurentian Great Lakes form an interconnected body of fresh water but each lake has unique environmental conditions. Global warming is changing the duration and extent of ice cover across the lakes (Assel et al., 2003; Magnuson et al., 2000), with greatest impact on the larger cooler lakes Superior, Huron, and Ontario, and likely Lake Michigan. This warming is also extending the growing season for cool and warm water fishes. Much has already been written on the effects of climate change on fish of the Great Lakes (e.g., Jansen and Hesslein, 2004; Meisner et al., 1987; Magnuson et al., 1997; Smith, 1991). Here we have shown that the rate of change has not been the same across all lakes or basins during the past 34 years.

While changes in water clarity occurred in all lakes following phosphorus abatement programs enacted in the 1970s, the amount of change varied among lakes. In the late 1980s and early 1990s, Dreissenid mussel invasion further changed the water clarity in the lakes, but again, the amount of change varied among lakes. The largest effects were on lakes where water clarity was lowest in 1968.

Differences in water clarity and seasonal cycles between and within the lakes have been noted in the past (Dobson et al., 1974). Here we have combined data from several sources to obtain uniquely large spatial and temporal coverage that further supports these differences among lakes. We have also shown that water clarity in shallow basins is different from that in their associated main basins but similar to clarity in other shallow basins across the lakes. This pattern points to the importance of watershed inputs to these basins rather than to offshore effects.

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Appendix

Data used in this analysis organized by lake, basin, period, and year.

Lake	Basin	Period	Year	Usage Flag secchi	N secchi	Mean secchi	Mean log secchi	Stdev secchi	Stdev log secchi	SE secchi	SE log secchi	RSE Secchi	Usage Flag temperature	N surface water temperature	Mean surface water temperature	Stdev surface water temperature	SE Surface water temperature	RSE Water temperature
Erie	Central	1	1968	1	16	3.313	1.117	1.401	0.418	0.350	0.104	0.106	1	51	22.689	0.915	0.128	0.006
Erie	Central	1	1970	1	17	4.971	1.566	1.280	0.299	0.310	0.072	0.062	1	105	23.478	0.867	0.085	0.004
Erie	Central	1	1971	0	10	3.650	1.129	2.015	0.640	0.637	0.202	0.175	1	60	22.688	0.629	0.081	0.004
Erie	Central	1	1972	1	30	4.547	1.469	1.152	0.348	0.210	0.064	0.046	1	183	22.147	1.400	0.103	0.005
Erie	Central	1	1973	1	15	3.453	1.166	1.335	0.402	0.345	0.104	0.100	1	84	24.382	0.819	0.089	0.004
Erie	Central	1	1974	1	21	4.762	1.322	2.741	0.789	0.598	0.172	0.126	1	78	23.869	0.391	0.044	0.002
Erie	Central	1	1975	1	32	4.650	1.413	1.983	0.556	0.351	0.098	0.075	1	150	23.261	0.799	0.065	0.003
Erie	Central	1	1977	1	3	5.667	1.731	0.577	0.105	0.333	0.061	0.059						
Erie	Central	1	1978	1	12	5.875	1.666	2.057	0.574	0.594	0.166	0.101						
Erie	Central	1	1979	0	8	4.563	1.373	1.972	0.666	0.697	0.235	0.153						
Erie	Central	1	1980	1	5	5.600	1.713	0.894	0.152	0.400	0.068	0.071						
Erie	Central	2	1983	1	12	6.750	1.896	1.138	0.177	0.329	0.051	0.049	1	10	24.160	0.317	0.100	0.004
Erie	Central	2	1984	1	15	7.033	1.908	2.150	0.304	0.555	0.079	0.079	1	10	24.260	0.965	0.305	0.013
Erie	Central	2	1985	1	6	7.167	1.965	0.753	0.107	0.307	0.044	0.043	1	9	23.322	0.944	0.315	0.013
Erie	Central	2	1986	1	3	7.333	1.990	0.577	0.077	0.333	0.045	0.045	1	6	22.800	0.310	0.126	0.006
Erie	Central	2	1987	1	4	4.625	1.522	0.750	0.161	0.375	0.081	0.081	1	6	22.177	0.498	0.203	0.009
Erie	Central	2	1988	0	4	4.875	1.400	3.119	0.746	1.560	0.373	0.320	1	6	23.933	0.524	0.214	0.009
Erie	Central	3	1989	0	2	11.000	2.389	2.121	0.194	1.500	0.137	0.136	1	4	21.450	0.751	0.375	0.017
Erie	Central	3	1990	1	8	7.688	2.024	1.510	0.187	0.534	0.066	0.069	1	10	23.220	0.308	0.098	0.004
Erie	Central	3	1991	0	2	6.750	1.903	1.061	0.158	0.750	0.112	0.111						
Erie	Central	3	1993	0	1	7.000	1.946						1	4	23.450	0.058	0.029	0.001
Erie	Central	3	1994										1	6	22.167	0.103	0.042	0.002
Erie	Central	3	1995	1	12	6.250	1.751	2.094	0.483	0.605	0.139	0.097	1	81	26.412	0.706	0.078	0.003
Erie	Central	3	1996	0	4	5.400	1.588	2.238	0.567	1.119	0.284	0.207						
Erie	Central	3	1997	0	6	2.470	0.836	1.089	0.389	0.444	0.159	0.180	1	4	22.250	0.289	0.144	0.006
Erie	Central	3	1998	0	2	1.021	0.015	0.151	0.148	0.107	0.105	0.104						
Erie	Central	3	1999	1	3	8.167	2.085	1.756	0.215	1.014	0.124	0.124						
Erie	Central	3	2000	1	15	4.567	1.484	1.266	0.272	0.327	0.070	0.072	1	89	23.005	0.495	0.052	0.002
Erie	Central	3	2001	1	3	7.633	2.031	0.586	0.075	0.338	0.044	0.044						
Erie	Central	3	2002	0	4	4.875	1.445	2.250	0.693	1.125	0.347	0.231	1	33	24.713	1.330	0.232	0.009
Erie	Eastern	1	1968	0	6	2.250	0.569	1.508	0.822	0.616	0.336	0.274	1	27	22.206	1.608	0.310	0.014
Erie	Eastern	1	1970	1	16	4.875	1.504	1.766	0.446	0.441	0.111	0.091	1	96	23.486	1.137	0.116	0.005
Erie	Eastern	1	1971	1	16	5.219	1.576	1.897	0.436	0.474	0.109	0.091	1	84	21.770	1.019	0.111	0.005
Erie	Eastern	1	1972	1	27	4.515	1.487	0.910	0.205	0.175	0.039	0.039	1	126	22.579	0.963	0.086	0.004
Erie	Eastern	1	1973	1	15	4.120	1.364	1.271	0.352	0.328	0.091	0.080	1	90	23.510	0.798	0.084	0.004
Erie	Eastern	1	1974	0	18	7.528	2.006	1.206	0.170	0.284	0.040	0.038	1	64	23.285	0.591	0.074	0.003
Erie	Eastern	1	1975	1	16	5.775	1.733	1.059	0.221	0.265	0.055	0.046	1	92	23.350	0.893	0.093	0.004
Erie	Eastern	1	1978	1	7	6.214	1.820	0.809	0.130	0.306	0.049	0.049						
Erie	Eastern	1	1979	0	1	5.000	1.609											
Erie	Eastern	2	1983	1	22	7.636	2.025	0.941	0.126	0.201	0.027	0.026	1	101	23.736	0.559	0.056	0.002
Erie	Eastern	2	1984	1	19	6.789	1.879	1.828	0.282	0.419	0.065	0.062	1	47	23.804	0.928	0.135	0.006
Erie	Eastern	2	1985	1	11	7.191	1.956	1.432	0.191	0.432	0.058	0.060	1	31	22.839	0.583	0.105	0.005
Erie	Eastern	2	1986	0	2	5.000	1.604	0.707	0.142	0.500	0.100	0.100	1	2	22.700	0.000	0.000	0.000
Erie	Eastern	2	1987	0	3	3.833	1.320	1.041	0.262	0.601	0.151	0.157						
Erie	Eastern	2	1988	1	3	4.167	1.426	0.289	0.068	0.167	0.039	0.040	1	7	23.171	0.776	0.293	0.013
Erie	Eastern	3	1990	1	15	5.833	1.693	1.848	0.439	0.477	0.113	0.082	1	35	22.706	1.023	0.173	0.008
Erie	Eastern	3	1991	0	2	6.750	1.909	0.354	0.052	0.250	0.037	0.037						
Erie	Eastern	3	1993	0	1	6.000	1.792						1	2	23.300	0.000	0.000	0.000
Erie	Eastern	3	1995	1	9	6.689	1.890	1.011	0.158	0.337	0.053	0.050	1	45	25.407	0.735	0.110	0.004
Erie	Eastern	3	1998	0	2	5.750	1.741	1.061	0.186	0.750	0.131	0.130						
Erie	Eastern	3	1999	0	1	5.000	1.609											
Erie	Eastern	3	2000	1	5	4.800	1.557	0.837	0.172	0.374	0.077	0.078	1	45	22.276	0.346	0.052	0.002

Erie	Eastern	3	2001	0	1	9.300	2.230											
Erie	Western	1	1970	0	1	1.800	0.588											
Erie	Western	1	1972	0	2	1.250	0.203	0.354	0.287	0.250	0.203	0.200						
Erie	Western	1	1973	1	11	0.988	−0.059	0.340	0.313	0.103	0.094	0.104						
Erie	Western	1	1974	1	3	1.000	0.000	0.000	0.000	0.000	0.000	0.000						
Erie	Western	1	1975	0	1	1.000	0.000						1	7	23.943	1.632	0.617	0.026
Erie	Western	1	1978	1	96	0.800	−0.355	0.491	0.503	0.050	0.051	0.063						
Erie	Western	1	1979	1	37	0.465	−1.006	0.389	0.662	0.064	0.109	0.137						
Erie	Western	1	1980	0	1	1.300	0.262											
Erie	Western	2	1982	0	3	0.900	−0.139	0.265	0.326	0.153	0.188	0.170						
Erie	Western	2	1983	0	2	1.500	0.405	0.000	0.000	0.000	0.000	0.000	1	2	25.500	0.000	0.000	0.000
Erie	Western	2	1984	1	4	1.750	0.549	0.289	0.166	0.144	0.083	0.082						
Erie	Western	2	1986	0	1	2.000	0.693						1	4	22.700	0.000	0.000	0.000
Erie	Western	2	1987	0	2	1.500	0.347	0.707	0.490	0.500	0.347	0.333						
Erie	Western	2	1988	1	3	1.500	0.405	0.000	0.000	0.000	0.000	0.000	1	2	24.300	0.000	0.000	0.000
Erie	Western	3	1989	0	1	2.500	0.916											
Erie	Western	3	1990	0	3	3.000	1.059	1.000	0.348	0.577	0.201	0.192	1	2	23.200	0.000	0.000	0.000
Erie	Western	3	1991	0	1	2.500	0.916											
Erie	Western	3	1995										1	23	27.259	0.717	0.149	0.005
Erie	Western	3	1996	0	5	1.980	0.570	0.798	0.611	0.357	0.273	0.180						
Erie	Western	3	1997	1	9	1.411	0.238	0.633	0.512	0.211	0.171	0.150	1	68	22.292	0.363	0.044	0.002
Erie	Western	3	2000	0	1	2.000	0.693						1	4	24.200	0.231	0.115	0.005
Erie	Western	3	2002	0	8	1.563	0.280	0.821	0.670	0.290	0.237	0.186	1	22	27.813	0.942	0.201	0.007
Huron	Central	1	1968	1	18	7.917	2.012	2.328	0.381	0.549	0.090	0.069	1	18	16.091	2.302	0.543	0.034
Huron	Central	1	1971	1	13	8.462	2.090	2.259	0.344	0.627	0.095	0.074	1	25	15.920	0.863	0.173	0.011
Huron	Central	1	1972	1	12	7.250	1.937	2.301	0.304	0.664	0.088	0.092	1	22	15.300	1.209	0.258	0.017
Huron	Central	1	1974	1	12	7.958	2.072	0.582	0.072	0.168	0.021	0.021	1	19	19.105	0.951	0.218	0.011
Huron	Central	1	1980	0	1	8.509	2.141											
Huron	Central	2	1983	0	2	10.000	2.298	1.414	0.142	1.000	0.100	0.100	1	1	21.800			
Huron	Central	2	1984	1	3	10.000	2.296	1.323	0.137	0.764	0.079	0.076						
Huron	Central	2	1985	0	10	7.100	1.788	4.267	0.656	1.349	0.207	0.190	1	58	18.406	0.756	0.099	0.005
Huron	Central	2	1986	1	6	9.250	2.170	3.283	0.366	1.340	0.150	0.145	1	12	16.844	1.020	0.294	0.017
Huron	Central	2	1987	1	11	7.818	2.000	2.714	0.356	0.818	0.107	0.105	1	34	15.970	2.405	0.413	0.026
Huron	Central	2	1988	1	11	6.500	1.841	1.630	0.265	0.491	0.080	0.076	1	58	16.688	1.889	0.248	0.015
Huron	Central	2	1989	1	11	7.682	1.974	3.296	0.356	0.994	0.107	0.129	1	59	17.288	1.538	0.200	0.012
Huron	Central	2	1990	0	1	12.500	2.526											
Huron	Central	3	1993	1	9	7.278	1.940	2.412	0.311	0.804	0.104	0.110	1	60	19.576	0.954	0.123	0.006
Huron	Central	3	1994	0	9	5.278	1.509	2.682	0.639	0.894	0.213	0.169	1	20	16.889	1.780	0.398	0.024
Huron	Central	3	1997	1	4	11.125	2.378	3.172	0.293	1.586	0.147	0.143	1	13	17.646	0.458	0.127	0.007
Huron	Central	3	1999	1	11	8.218	2.083	1.795	0.232	0.541	0.070	0.066	1	38	18.861	1.364	0.221	0.012
Huron	Central	3	2000	0	9	7.756	1.800	5.040	0.821	1.680	0.274	0.217	1	36	17.278	1.687	0.281	0.016
Huron	Central	3	2001	0	1	11.500	2.442						1	1	19.800			
Huron	Central	3	2002	0	10	5.650	1.595	2.657	0.602	0.840	0.190	0.149	1	34	20.593	1.130	0.194	0.009
Huron	Georgian Bay	1	1970	1	16	10.844	2.373	1.661	0.152	0.415	0.038	0.038	1	159	18.678	0.588	0.047	0.002
Huron	Georgian Bay	1	1971	1	5	9.500	2.248	0.866	0.097	0.387	0.043	0.041	1	158	16.760	1.134	0.090	0.005
Huron	Georgian Bay	1	1974	1	8	8.938	2.167	2.026	0.231	0.716	0.082	0.080	1	51	18.480	0.664	0.093	0.005
Huron	Georgian Bay	2	1985	1	14	7.357	1.976	1.447	0.209	0.387	0.056	0.053	1	72	18.686	0.631	0.074	0.004
Huron	Georgian Bay	2	1986	1	8	7.563	2.002	1.522	0.230	0.538	0.081	0.071	1	72	16.027	2.035	0.240	0.015
Huron	Georgian Bay	2	1988	1	5	7.000	1.912	1.969	0.294	0.880	0.131	0.126	1	36	18.531	0.509	0.085	0.005
Huron	Georgian Bay	2	1989	1	14	6.750	1.891	1.327	0.203	0.355	0.054	0.053	1	74	18.882	1.025	0.119	0.006
Huron	Georgian Bay	2	1990	1	10	7.300	1.945	2.071	0.322	0.655	0.102	0.090	1	73	20.235	1.012	0.118	0.006
Huron	Georgian Bay	3	1993	1	5	7.600	2.007	1.782	0.227	0.797	0.102	0.105	1	23	20.148	0.270	0.056	0.003
Huron	Georgian Bay	3	1994	1	17	8.706	2.140	2.000	0.227	0.485	0.055	0.056	1	86	16.986	1.749	0.189	0.011
Huron	Georgian Bay	3	1999	1	14	8.900	2.159	2.091	0.245	0.559	0.066	0.063	1	92	20.150	1.278	0.133	0.007
Huron	Georgian Bay	3	2000	1	10	9.200	2.202	1.798	0.193	0.569	0.061	0.062	1	80	18.764	0.999	0.112	0.006
Huron	Georgian Bay	3	2002	1	11	11.273	2.397	2.453	0.245	0.740	0.074	0.066	1	73	20.930	1.605	0.188	0.009
Huron	North Channel	1	1968	1	6	6.500	1.817	2.074	0.387	0.847	0.158	0.130	1	6	16.417	1.870	0.763	0.046
Huron	North Channel	1	1970										1	3	17.407	0.012	0.007	0.000

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Appendix *(continued)*

Lake	Basin	Period	Year	Usage Flag secchi	N secchi	Mean secchi	Mean log secchi	Stdev secchi	Stdev log secchi	SE secchi	SE log secchi	RSE Secchi	Usage Flag temperature	N surface water temperature	Mean surface water temperature	Stdev surface water temperature	SE Surface water temperature	RSE Water temperature
Huron	North Channel	1	1971	0	3	6.167	1.792	1.756	0.288	1.014	0.166	0.164	1	7	15.944	0.913	0.345	0.022
Huron	North Channel	1	1972	1	3	6.000	1.782	1.000	0.168	0.577	0.097	0.096	1	5	15.200	1.279	0.572	0.038
Huron	North Channel	1	1974										1	2	18.600	0.000	0.000	0.000
Huron	North Channel	2	1985	0	3	7.833	2.001	2.930	0.434	1.691	0.250	0.216	1	21	18.636	0.624	0.136	0.007
Huron	North Channel	2	1986	1	3	6.333	1.843	0.577	0.089	0.333	0.051	0.053	1	9	16.474	0.678	0.226	0.014
Huron	North Channel	2	1987	0	2	5.500	1.701	0.707	0.129	0.500	0.091	0.091	1	12	15.529	2.531	0.730	0.047
Huron	North Channel	2	1988	1	4	6.075	1.788	1.193	0.209	0.596	0.105	0.098	1	20	16.955	1.662	0.372	0.022
Huron	North Channel	2	1989	0	2	10.000	2.255	4.243	0.438	3.000	0.310	0.300	1	22	17.839	0.725	0.155	0.009
Huron	North Channel	3	1993	0	4	8.125	2.047	2.594	0.377	1.297	0.189	0.160	1	21	19.725	0.739	0.161	0.008
Huron	North Channel	3	1994	0	4	7.125	1.891	3.351	0.423	1.675	0.212	0.235	1	9	16.211	2.299	0.766	0.047
Huron	North Channel	3	1999	1	16	7.931	2.060	1.176	0.149	0.294	0.037	0.037	1	29	19.413	1.140	0.212	0.011
Huron	North Channel	3	2000	0	9	5.611	1.598	3.090	0.528	1.030	0.176	0.184	1	28	18.655	1.105	0.209	0.011
Huron	North Channel	3	2002	0	4	7.125	1.918	2.658	0.338	1.329	0.169	0.186	1	14	20.477	0.954	0.255	0.012
Huron	Northern	1	1968	1	6	6.417	1.827	1.908	0.265	0.779	0.108	0.121	1	6	16.432	0.858	0.350	0.021
Huron	Northern	1	1970	0	2	10.000	2.303	0.000	0.000	0.000	0.000	0.000						
Huron	Northern	1	1971	1	7	6.214	1.789	1.845	0.294	0.697	0.111	0.112	1	12	16.358	0.850	0.245	0.015
Huron	Northern	1	1972	0	5	5.400	1.489	2.608	0.845	1.166	0.378	0.216	1	2	16.000	2.121	1.500	0.094
Huron	Northern	1	1974	1	4	8.250	2.096	1.500	0.203	0.750	0.101	0.091	1	3	17.867	0.981	0.567	0.032
Huron	Northern	2	1984	0	2	9.500	2.246	1.414	0.149	1.000	0.106	0.105						
Huron	Northern	2	1985	0	6	5.917	1.604	3.169	0.715	1.294	0.292	0.219	1	30	20.272	1.382	0.252	0.012
Huron	Northern	2	1986	1	6	9.833	2.253	2.696	0.281	1.101	0.115	0.112	1	26	19.396	1.403	0.275	0.014
Huron	Northern	2	1987	0	8	7.163	1.867	3.160	0.516	1.117	0.182	0.156	1	24	18.201	1.192	0.243	0.013
Huron	Northern	2	1988	0	7	5.300	1.578	2.440	0.460	0.922	0.174	0.174	1	36	19.422	1.190	0.198	0.010
Huron	Northern	2	1989	1	6	7.417	1.968	2.131	0.297	0.870	0.121	0.117	1	34	19.927	1.399	0.240	0.012
Huron	Northern	2	1990	0	1	12.500	2.526											
Huron	Northern	3	1993	0	4	7.500	1.879	3.674	0.667	1.837	0.333	0.245	1	33	22.465	1.789	0.311	0.014
Huron	Northern	3	1994	0	5	3.400	1.156	1.294	0.425	0.579	0.190	0.170	1	11	19.293	1.188	0.358	0.019
Huron	Northern	3	1997	0	2	7.750	2.047	0.354	0.046	0.250	0.032	0.032	1	3	18.300	0.721	0.416	0.023
Huron	Northern	3	1999	1	5	7.900	2.029	2.460	0.308	1.100	0.138	0.139	1	22	21.085	0.810	0.173	0.008
Huron	Northern	3	2000	1	5	8.500	2.129	1.414	0.165	0.632	0.074	0.074	1	21	20.522	1.149	0.251	0.012
Huron	Northern	3	2002	0	1	6.000	1.792						1	22	20.752	3.087	0.658	0.032
Huron	SagBay—Inner	1	1971	0	3	1.167	−0.157	1.155	0.929	0.667	0.536	0.571	1	1	20.300			
Huron	SagBay—Inner	1	1972	0	2	3.000	1.099	0.000	0.000	0.000	0.000	0.000	1	1	17.500			
Huron	SagBay—Inner	1	1974	0	1	7.000	1.946						1	2	19.100	0.000	0.000	0.000
Huron	SagBay—Inner	1	1975	1	4	1.450	0.362	0.238	0.154	0.119	0.077	0.082						
Huron	SagBay—Inner	1	1976	0	1	1.200	0.182											
Huron	SagBay—Inner	1	1977	0	2	1.000	0.000	0.000	0.000	0.000	0.000	0.000						
Huron	SagBay—Inner	1	1978	1	3	1.400	0.330	0.200	0.144	0.115	0.083	0.082						
Huron	SagBay—Inner	2	1985	0	1	1.500	0.405						1	7	20.371	1.713	0.648	0.032
Huron	SagBay—Inner	2	1986	0	1	1.500	0.405						1	6	18.167	2.885	1.178	0.065
Huron	SagBay—Inner	2	1987	0	3	6.767	1.738	3.995	0.792	2.307	0.457	0.341	1	6	18.468	0.621	0.254	0.014
Huron	SagBay—Inner	2	1988	0	2	0.800	−0.223	0.000	0.000	0.000	0.000	0.000	1	6	19.108	0.551	0.225	0.012
Huron	SagBay—Inner	2	1989	0	2	6.500	1.869	0.707	0.109	0.500	0.077	0.077	1	6	20.093	1.603	0.655	0.033
Huron	SagBay—Inner	2	1991	1	18	1.089	0.068	0.194	0.201	0.046	0.047	0.042						
Huron	SagBay—Inner	2	1992	1	18	1.561	0.343	0.750	0.470	0.177	0.111	0.113						
Huron	SagBay—Inner	3	1993	0	9	3.067	1.006	1.924	0.458	0.641	0.153	0.209	1	6	23.117	0.804	0.328	0.014
Huron	SagBay—Inner	3	1994	1	9	1.661	0.413	0.747	0.466	0.249	0.155	0.150	0	2	18.450	4.596	3.250	0.176
Huron	SagBay—Inner	3	1995	0	8	1.444	0.283	0.649	0.435	0.230	0.154	0.159						
Huron	SagBay—Inner	3	1996	1	8	2.050	0.690	0.529	0.252	0.187	0.089	0.091						
Huron	SagBay—Inner	3	1999	0	2	8.250	1.778	8.132	1.218	5.750	0.861	0.697	1	4	20.443	1.660	0.830	0.041
Huron	SagBay—Inner	3	2000	0	1	2.000	0.693						1	4	20.770	2.263	1.132	0.054
Huron	SagBay—Inner	3	2002										1	4	21.815	1.366	0.683	0.031
Huron	SagBay—Outer	1	1968	0	2	1.000	−0.144	0.707	0.777	0.500	0.549	0.500	0	2	22.065	0.686	0.485	0.022
Huron	SagBay—Outer	1	1971	0	1	6.000	1.792						0	3	19.067	0.709	0.410	0.021

Huron	SagBay—Outer	1	1972	0	2	2.750	0.896	1.768	0.694	1.250	0.490	0.455	0	3	17.300	0.300	0.173	0.010
Huron	SagBay—Outer	1	1974	0	1	9.000	2.197						0	6	19.233	0.831	0.339	0.018
Huron	SagBay—Outer	2	1985	0	2	8.500	2.124	2.121	0.252	1.500	0.178	0.176	0	9	19.334	0.413	0.138	0.007
Huron	SagBay—Outer	2	1986										0	6	15.633	0.517	0.211	0.013
Huron	SagBay—Outer	2	1987	0	1	9.800	2.282						0	9	18.987	0.236	0.079	0.004
Huron	SagBay—Outer	2	1988	0	2	8.250	2.110	0.354	0.043	0.250	0.030	0.030	0	9	20.100	0.377	0.126	0.006
Huron	SagBay—Outer	2	1989	0	2	10.000	2.303	0.000	0.000	0.000	0.000	0.000	0	8	19.269	0.287	0.101	0.005
Huron	SagBay—Outer	2	1991	0	8	6.113	1.557	4.272	0.789	1.510	0.279	0.247						
Huron	SagBay—Outer	2	1992	0	7	7.114	1.897	2.687	0.396	1.015	0.150	0.143						
Huron	SagBay—Outer	3	1993	0	6	8.067	1.992	3.753	0.487	1.532	0.199	0.190	0	9	21.388	0.250	0.083	0.004
Huron	SagBay—Outer	3	1994	0	7	6.257	1.696	3.391	0.581	1.282	0.219	0.205	0	3	18.633	0.551	0.318	0.017
Huron	SagBay—Outer	3	1995	0	4	5.063	1.475	3.085	0.634	1.542	0.317	0.305						
Huron	SagBay—Outer	3	1996	0	4	4.275	1.358	1.921	0.531	0.960	0.265	0.225						
Huron	SagBay—Outer	3	1999	0	2	8.250	2.106	1.061	0.129	0.750	0.091	0.091	0	6	20.053	0.570	0.233	0.012
Huron	SagBay—Outer	3	2000										0	6	19.140	0.681	0.278	0.015
Huron	SagBay—Outer	3	2002	0	1	10.000	2.303						0	6	20.745	0.653	0.267	0.013
Huron	Southern	1	1968	1	25	7.720	2.014	1.809	0.258	0.362	0.052	0.047	1	26	18.548	1.875	0.368	0.020
Huron	Southern	1	1970	0	1	12.000	2.485											
Huron	Southern	1	1971	1	21	6.595	1.736	3.212	0.620	0.701	0.135	0.106	1	33	18.194	1.277	0.222	0.012
Huron	Southern	1	1972	1	25	7.820	1.982	2.684	0.428	0.537	0.086	0.069	1	45	15.727	1.738	0.259	0.016
Huron	Southern	1	1974	1	20	7.900	1.924	3.712	0.644	0.830	0.144	0.105	1	83	18.486	1.534	0.168	0.009
Huron	Southern	2	1983	0	1	11.000	2.398						1	4	22.000	0.622	0.311	0.014
Huron	Southern	2	1984	0	4	14.250	2.595	5.560	0.413	2.780	0.206	0.195						
Huron	Southern	2	1985	1	13	8.769	2.097	3.492	0.409	0.968	0.113	0.110	1	80	19.594	1.042	0.116	0.006
Huron	Southern	2	1986	1	11	7.364	1.907	3.340	0.441	1.007	0.133	0.137	1	48	19.362	1.106	0.160	0.008
Huron	Southern	2	1987	1	11	9.773	2.246	2.161	0.302	0.651	0.091	0.067	1	80	18.618	1.320	0.148	0.008
Huron	Southern	2	1988	1	12	8.400	2.074	2.948	0.341	0.851	0.098	0.101	1	78	18.972	1.706	0.193	0.010
Huron	Southern	2	1989	1	14	8.250	2.081	2.045	0.255	0.547	0.068	0.066	1	77	19.587	1.126	0.128	0.007
Huron	Southern	2	1990	0	2	11.250	2.414	1.768	0.158	1.250	0.112	0.111						
Huron	Southern	2	1991	0	1	12.800	2.549											
Huron	Southern	3	1993	1	11	9.727	2.265	1.438	0.148	0.434	0.045	0.045	1	79	21.134	1.993	0.224	0.011
Huron	Southern	3	1994	1	10	9.230	2.145	3.538	0.435	1.119	0.138	0.121	1	28	18.307	1.832	0.346	0.019
Huron	Southern	3	1997	0	1	15.000	2.708						1	16	19.105	0.951	0.238	0.012
Huron	Southern	3	1998	0	2	15.500	2.741	0.000	0.000	0.000	0.000	0.000						
Huron	Southern	3	1999	1	13	8.423	2.050	3.622	0.413	1.005	0.114	0.119	1	53	20.302	0.983	0.135	0.007
Huron	Southern	3	2000	1	11	8.409	2.079	2.508	0.353	0.756	0.106	0.090	1	52	19.143	2.267	0.314	0.016
Huron	Southern	3	2001	0	2	11.750	2.424	4.596	0.402	3.250	0.284	0.277	1	2	22.700	0.566	0.400	0.018
Huron	Southern	3	2002	1	17	10.512	2.043	5.187	1.057	1.258	0.256	0.120	1	52	21.223	1.171	0.162	0.008
Ontario	Bay of Quinte	1	1972										1	32	20.906	1.376	0.243	0.012
Ontario	Bay of Quinte	1	1973										1	28	23.718	0.960	0.181	0.008
Ontario	Bay of Quinte	1	1974										1	28	22.104	1.221	0.231	0.010
Ontario	Bay of Quinte	1	1975										1	32	21.988	1.395	0.247	0.011
Ontario	Bay of Quinte	1	1976										1	39	20.541	1.415	0.227	0.011
Ontario	Bay of Quinte	1	1977										1	40	20.775	1.615	0.255	0.012
Ontario	Bay of Quinte	1	1978										1	37	21.795	2.577	0.424	0.019
Ontario	Bay of Quinte	1	1979										1	24	20.600	1.802	0.368	0.018
Ontario	Bay of Quinte	1	1980										1	24	23.450	1.102	0.225	0.010
Ontario	Bay of Quinte	1	1981										1	20	22.380	1.174	0.262	0.012
Ontario	Bay of Quinte	2	1982										1	16	21.588	1.597	0.399	0.018
Ontario	Bay of Quinte	2	1983	0	9	1.622	0.381	0.853	0.458	0.284	0.153	0.175						
Ontario	Bay of Quinte	2	1984	1	6	1.067	0.045	0.242	0.209	0.099	0.085	0.093						
Ontario	Bay of Quinte	2	1985	0	6	1.450	0.260	0.782	0.504	0.319	0.206	0.220						
Ontario	Bay of Quinte	2	1986	0	6	1.583	0.395	0.631	0.389	0.257	0.159	0.163						
Ontario	Bay of Quinte	2	1987	0	6	1.625	0.281	1.191	0.676	0.486	0.276	0.299						
Ontario	Bay of Quinte	2	1988	0	6	1.658	0.368	1.005	0.559	0.410	0.228	0.247	1	6	23.217	2.098	0.857	0.037
Ontario	Bay of Quinte	2	1989	0	8	1.575	0.320	1.002	0.517	0.354	0.183	0.225	1	6	21.400	1.035	0.423	0.020
Ontario	Bay of Quinte	2	1990	1	13	1.408	0.218	0.716	0.527	0.199	0.146	0.141	1	13	23.200	1.056	0.293	0.013
Ontario	Bay of Quinte	2	1991	0	10	1.505	0.236	1.096	0.569	0.347	0.180	0.230	1	10	22.840	0.631	0.200	0.009
Ontario	Bay of Quinte	2	1992	1	12	1.346	0.180	0.692	0.505	0.200	0.146	0.148	0	12	21.942	1.405	0.406	0.018

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Appendix (*continued*)

Lake	Basin	Period	Year	Usage Flag secchi	N secchi	Mean secchi	Mean log secchi	Stdev secchi	Stdev log secchi	SE secchi	SE log secchi	RSE Secchi	Usage Flag temperature	N surface water temperature	Mean surface water temperature	Stdev surface water temperature	SE Surface water temperature	RSE Water temperature
Ontario	Bay of Quinte	3	1993	0	10	1.875	0.506	1.022	0.511	0.323	0.162	0.172	1	9	23.100	0.740	0.247	0.011
Ontario	Bay of Quinte	3	1994	0	8	1.575	0.131	1.593	0.779	0.563	0.276	0.358	1	6	22.533	0.698	0.285	0.013
Ontario	Bay of Quinte	3	1995	0	8	1.563	0.307	0.943	0.550	0.333	0.194	0.213	1	7	24.543	0.746	0.282	0.011
Ontario	Bay of Quinte	3	1996	0	10	2.335	0.709	1.312	0.551	0.415	0.174	0.178	1	9	22.578	1.207	0.402	0.018
Ontario	Bay of Quinte	3	1997	1	10	3.005	1.049	0.987	0.344	0.312	0.109	0.104	1	10	21.550	0.954	0.302	0.014
Ontario	Bay of Quinte	3	1998	0	10	2.500	0.789	1.359	0.529	0.430	0.167	0.172	1	10	23.700	0.783	0.248	0.010
Ontario	Bay of Quinte	3	1999	0	10	2.750	0.817	1.740	0.681	0.550	0.215	0.200	1	8	22.175	0.709	0.251	0.011
Ontario	Bay of Quinte	3	2000	1	15	2.667	0.888	1.213	0.439	0.313	0.113	0.117	1	15	22.967	1.537	0.397	0.017
Ontario	Bay of Quinte	3	2001	0	11	3.282	0.987	2.021	0.692	0.609	0.209	0.186	1	11	23.473	1.086	0.328	0.014
Ontario	Eastern	1	1968	1	10	3.500	1.243	0.527	0.146	0.167	0.046	0.048	1	31	20.542	0.350	0.063	0.003
Ontario	Eastern	1	1969	1	21	2.738	0.986	0.574	0.213	0.125	0.047	0.046	1	88	22.461	1.839	0.196	0.009
Ontario	Eastern	1	1970	1	10	2.080	0.718	0.361	0.180	0.114	0.057	0.055	1	69	21.487	1.922	0.231	0.011
Ontario	Eastern	1	1971	0	4	1.375	0.275	0.479	0.338	0.239	0.169	0.174	1	27	18.513	4.229	0.814	0.044
Ontario	Eastern	1	1972										1	160	19.890	1.663	0.131	0.007
Ontario	Eastern	1	1974	1	47	2.177	0.722	0.735	0.339	0.107	0.050	0.049	1	206	22.150	1.078	0.075	0.003
Ontario	Eastern	1	1975	1	26	2.138	0.742	0.412	0.196	0.081	0.038	0.038	1	75	21.860	0.614	0.071	0.003
Ontario	Eastern	1	1976	1	18	2.722	0.993	0.352	0.139	0.083	0.033	0.031	1	130	20.087	1.133	0.099	0.005
Ontario	Eastern	1	1977	1	28	3.571	1.260	0.607	0.166	0.115	0.031	0.032	1	98	19.970	1.122	0.113	0.006
Ontario	Eastern	1	1978	1	25	2.984	1.073	0.616	0.209	0.123	0.042	0.041	1	105	20.985	0.797	0.078	0.004
Ontario	Eastern	1	1979	1	41	2.837	1.026	0.498	0.192	0.078	0.030	0.027	1	200	20.951	1.569	0.111	0.005
Ontario	Eastern	1	1981	1	63	2.808	1.011	0.585	0.213	0.074	0.027	0.026	1	109	21.530	0.571	0.055	0.003
Ontario	Eastern	2	1982	1	18	1.889	0.622	0.323	0.172	0.076	0.041	0.040	1	102	20.510	1.214	0.120	0.006
Ontario	Eastern	2	1983	0	1	2.500	0.916						1	4	23.350	0.332	0.166	0.007
Ontario	Eastern	2	1985	1	24	2.704	0.948	0.865	0.309	0.177	0.063	0.065	1	105	20.840	1.046	0.102	0.005
Ontario	Eastern	2	1986	1	25	3.159	1.135	0.587	0.177	0.117	0.035	0.037	1	111	21.196	0.997	0.095	0.004
Ontario	Eastern	2	1987	1	25	2.212	0.783	0.314	0.151	0.063	0.030	0.028	1	97	22.209	1.154	0.117	0.005
Ontario	Eastern	2	1988	1	25	3.088	1.117	0.465	0.149	0.093	0.030	0.030	1	97	24.174	0.931	0.095	0.004
Ontario	Eastern	2	1989	1	22	3.850	1.322	0.796	0.248	0.170	0.053	0.044	1	117	22.183	1.140	0.105	0.005
Ontario	Eastern	2	1990	1	19	3.889	1.298	1.597	0.335	0.366	0.077	0.094	1	97	22.349	0.528	0.054	0.002
Ontario	Eastern	2	1991	1	22	4.030	1.352	1.226	0.295	0.261	0.063	0.065	1	62	22.256	0.610	0.077	0.003
Ontario	Eastern	2	1992	0	6	2.517	0.832	1.030	0.501	0.421	0.205	0.167	0	63	18.398	1.518	0.191	0.010
Ontario	Eastern	3	1993	1	17	4.129	1.400	0.834	0.197	0.202	0.048	0.049	1	55	21.732	0.754	0.102	0.005
Ontario	Eastern	3	1996										1	5	22.253	0.056	0.025	0.001
Ontario	Eastern	3	1997	0	2	1.676	0.517	0.000	0.000	0.000	0.000	0.000	1	4	20.597	1.183	0.591	0.029
Ontario	Eastern	3	1998	1	13	5.623	1.707	1.120	0.211	0.311	0.059	0.055	1	69	21.663	1.324	0.159	0.007
Ontario	Eastern	3	1999	0	2	6.000	1.788	0.707	0.118	0.500	0.084	0.083	1	5	21.604	0.181	0.081	0.004
Ontario	Eastern	3	2000	0	1	4.500	1.504						1	8	20.915	0.610	0.216	0.010
Ontario	Eastern	3	2001	1	13	6.769	1.908	0.703	0.102	0.195	0.028	0.029	1	46	21.786	1.336	0.197	0.009
Ontario	Eastern	3	2002	0	1	7.000	1.946						1	9	22.044	0.802	0.267	0.012
Ontario	Outlet Basin	1	1968										1	4	20.400	0.469	0.235	0.011
Ontario	Outlet Basin	1	1969	1	4	2.750	0.997	0.500	0.203	0.250	0.101	0.091	1	23	21.737	2.331	0.486	0.022
Ontario	Outlet Basin	1	1970	1	5	2.160	0.758	0.371	0.171	0.166	0.077	0.077	1	16	22.239	1.003	0.251	0.011
Ontario	Outlet Basin	1	1971	0	1	2.000	0.693						1	6	20.583	0.781	0.319	0.015
Ontario	Outlet Basin	1	1972										1	20	20.660	1.071	0.239	0.012
Ontario	Outlet Basin	1	1974	1	13	2.000	0.666	0.456	0.253	0.127	0.070	0.063	1	48	21.681	0.681	0.098	0.005
Ontario	Outlet Basin	1	1975	0	4	1.325	0.245	0.450	0.299	0.225	0.149	0.170	1	31	21.934	0.647	0.116	0.005
Ontario	Outlet Basin	1	1976	1	11	2.409	0.842	0.584	0.313	0.176	0.094	0.073	1	39	20.388	0.470	0.075	0.004
Ontario	Outlet Basin	1	1977	0	1	5.000	1.609						1	34	21.206	0.679	0.117	0.005
Ontario	Outlet Basin	1	1978										1	42	21.037	1.002	0.155	0.007
Ontario	Outlet Basin	1	1979	1	10	3.120	1.086	1.057	0.338	0.334	0.107	0.107	1	72	22.154	1.657	0.195	0.009
Ontario	Outlet Basin	1	1981	1	4	2.500	0.889	0.707	0.264	0.354	0.132	0.141	1	41	21.886	0.698	0.109	0.005
Ontario	Outlet Basin	2	1982	1	14	1.843	0.553	0.668	0.353	0.178	0.094	0.097	1	47	21.211	1.085	0.158	0.007
Ontario	Outlet Basin	2	1983	0	2	3.750	1.320	0.354	0.094	0.250	0.067	0.067	1	8	22.438	0.614	0.217	0.010
Ontario	Outlet Basin	2	1984	0	2	2.000	0.693	0.000	0.000	0.000	0.000	0.000	1	8	21.788	0.951	0.336	0.015

Ontario	Outlet Basin	2	1985	0	6	3.000	1.029	1.342	0.389	0.548	0.159	0.183	1	49	21.519	0.649	0.093	0.004
Ontario	Outlet Basin	2	1986	0	5	2.500	0.876	0.866	0.301	0.387	0.135	0.155	1	51	21.702	0.729	0.102	0.005
Ontario	Outlet Basin	2	1987	1	8	2.825	1.021	0.542	0.202	0.192	0.071	0.068	1	54	21.886	0.976	0.133	0.006
Ontario	Outlet Basin	2	1988	1	8	3.750	1.271	1.221	0.354	0.432	0.125	0.115	1	56	24.111	1.060	0.142	0.006
Ontario	Outlet Basin	2	1989	1	14	3.386	1.179	0.897	0.313	0.240	0.084	0.071	1	56	22.512	0.645	0.086	0.004
Ontario	Outlet Basin	2	1990	1	10	2.840	1.020	0.622	0.237	0.197	0.075	0.069	1	54	22.148	0.516	0.070	0.003
Ontario	Outlet Basin	2	1991	1	6	3.817	1.306	1.199	0.267	0.490	0.109	0.128	1	36	22.555	0.699	0.116	0.005
Ontario	Outlet Basin	2	1992	1	9	3.167	1.146	0.409	0.123	0.136	0.041	0.043	0	36	19.131	0.683	0.114	0.006
Ontario	Outlet Basin	3	1993	1	8	4.688	1.513	1.163	0.286	0.411	0.101	0.088	1	29	22.038	0.614	0.114	0.005
Ontario	Outlet Basin	3	1994	1	4	5.500	1.701	0.577	0.105	0.289	0.053	0.052	1	6	20.400	1.244	0.508	0.025
Ontario	Outlet Basin	3	1995	0	5	2.550	0.886	0.942	0.345	0.421	0.154	0.165						
Ontario	Outlet Basin	3	1998	1	8	4.150	1.398	0.965	0.244	0.341	0.086	0.082	1	25	21.960	0.736	0.147	0.007
Ontario	Outlet Basin	3	1999										1	2	22.216	0.187	0.132	0.006
Ontario	Western	1	1968	1	22	3.068	1.050	1.137	0.396	0.242	0.084	0.079	1	65	17.453	3.540	0.439	0.025
Ontario	Western	1	1969	1	27	2.493	0.890	0.552	0.219	0.106	0.042	0.043	1	249	21.133	3.400	0.215	0.010
Ontario	Western	1	1970	1	20	2.040	0.651	0.723	0.370	0.162	0.083	0.079	1	121	20.657	2.731	0.248	0.012
Ontario	Western	1	1971	1	25	1.608	0.423	0.532	0.329	0.106	0.066	0.066	1	140	17.800	4.379	0.370	0.021
Ontario	Western	1	1972										1	593	16.805	3.195	0.131	0.008
Ontario	Western	1	1974	1	87	1.889	0.558	0.741	0.401	0.079	0.043	0.042	1	397	20.892	2.189	0.110	0.005
Ontario	Western	1	1975	1	30	1.853	0.570	0.588	0.313	0.107	0.057	0.058	1	141	20.503	1.391	0.117	0.006
Ontario	Western	1	1976	1	33	2.667	0.940	0.816	0.287	0.142	0.050	0.053	1	208	19.344	2.079	0.144	0.007
Ontario	Western	1	1977	1	28	2.671	0.931	0.850	0.338	0.161	0.064	0.060	1	194	18.351	1.800	0.129	0.007
Ontario	Western	1	1978	1	31	2.406	0.775	1.083	0.474	0.195	0.085	0.081	1	202	19.088	1.506	0.106	0.006
Ontario	Western	1	1979	1	30	2.543	0.872	0.822	0.378	0.150	0.069	0.059	1	300	17.890	1.914	0.111	0.006
Ontario	Western	1	1980										1	20	21.085	0.737	0.165	0.008
Ontario	Western	1	1981	1	45	2.387	0.792	0.934	0.409	0.139	0.061	0.058	1	349	20.947	1.431	0.077	0.004
Ontario	Western	2	1982	1	36	1.806	0.500	0.777	0.436	0.130	0.073	0.072	1	321	17.948	4.340	0.242	0.013
Ontario	Western	2	1983	0	2	2.550	0.936	0.071	0.028	0.050	0.020	0.020	1	190	21.347	2.147	0.156	0.007
Ontario	Western	2	1984	0	6	2.450	0.803	1.147	0.485	0.468	0.198	0.191	1	272	21.601	2.492	0.151	0.007
Ontario	Western	2	1985	1	32	3.066	1.035	1.322	0.421	0.234	0.074	0.076	1	205	20.855	1.265	0.088	0.004
Ontario	Western	2	1986	1	34	2.462	0.876	0.535	0.229	0.092	0.039	0.037	1	203	19.283	2.004	0.141	0.007
Ontario	Western	2	1987	1	35	2.046	0.647	0.848	0.362	0.143	0.061	0.070	1	216	21.461	2.905	0.198	0.009
Ontario	Western	2	1988	1	37	2.989	1.060	0.820	0.264	0.135	0.043	0.045	0	246	17.302	4.630	0.295	0.017
Ontario	Western	2	1989	1	34	3.068	1.071	0.955	0.326	0.164	0.056	0.053	1	234	20.269	2.726	0.178	0.009
Ontario	Western	2	1990	1	34	3.129	1.077	1.251	0.350	0.215	0.060	0.069	1	319	21.196	1.445	0.081	0.004
Ontario	Western	2	1991	1	29	4.307	1.409	1.333	0.338	0.247	0.063	0.057	1	110	20.633	1.930	0.184	0.009
Ontario	Western	2	1992	1	19	3.174	1.119	1.044	0.254	0.240	0.058	0.076	0	107	17.825	1.370	0.132	0.007
Ontario	Western	3	1993	1	26	5.250	1.610	1.557	0.331	0.305	0.065	0.058	1	109	20.407	1.569	0.150	0.007
Ontario	Western	3	1994	1	4	4.438	1.484	0.591	0.129	0.295	0.064	0.067	1	7	17.743	1.601	0.605	0.034
Ontario	Western	3	1995	1	4	2.688	0.964	0.688	0.257	0.344	0.129	0.128						
Ontario	Western	3	1996	0	2	7.500	2.013	0.707	0.094	0.500	0.067	0.067	1	9	20.936	2.491	0.830	0.040
Ontario	Western	3	1997	0	2	2.057	0.721	0.108	0.052	0.076	0.037	0.037	1	8	19.268	0.421	0.149	0.008
Ontario	Western	3	1998	1	27	4.937	1.580	0.919	0.186	0.177	0.036	0.036	1	114	22.819	1.337	0.125	0.005
Ontario	Western	3	1999	1	5	4.900	1.583	0.652	0.125	0.292	0.056	0.059	1	16	19.029	3.967	0.992	0.052
Ontario	Western	3	2000	0	1	5.500	1.705						1	1	21.127			
Ontario	Western	3	2001	1	8	6.500	1.853	1.225	0.214	0.433	0.076	0.067	1	52	21.574	0.834	0.116	0.005
Ontario	Western	3	2002	0	1	6.000	1.792						1	6	22.460	0.422	0.172	0.008

Usage flags designate whether the data point was used (1) or not used (0).

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