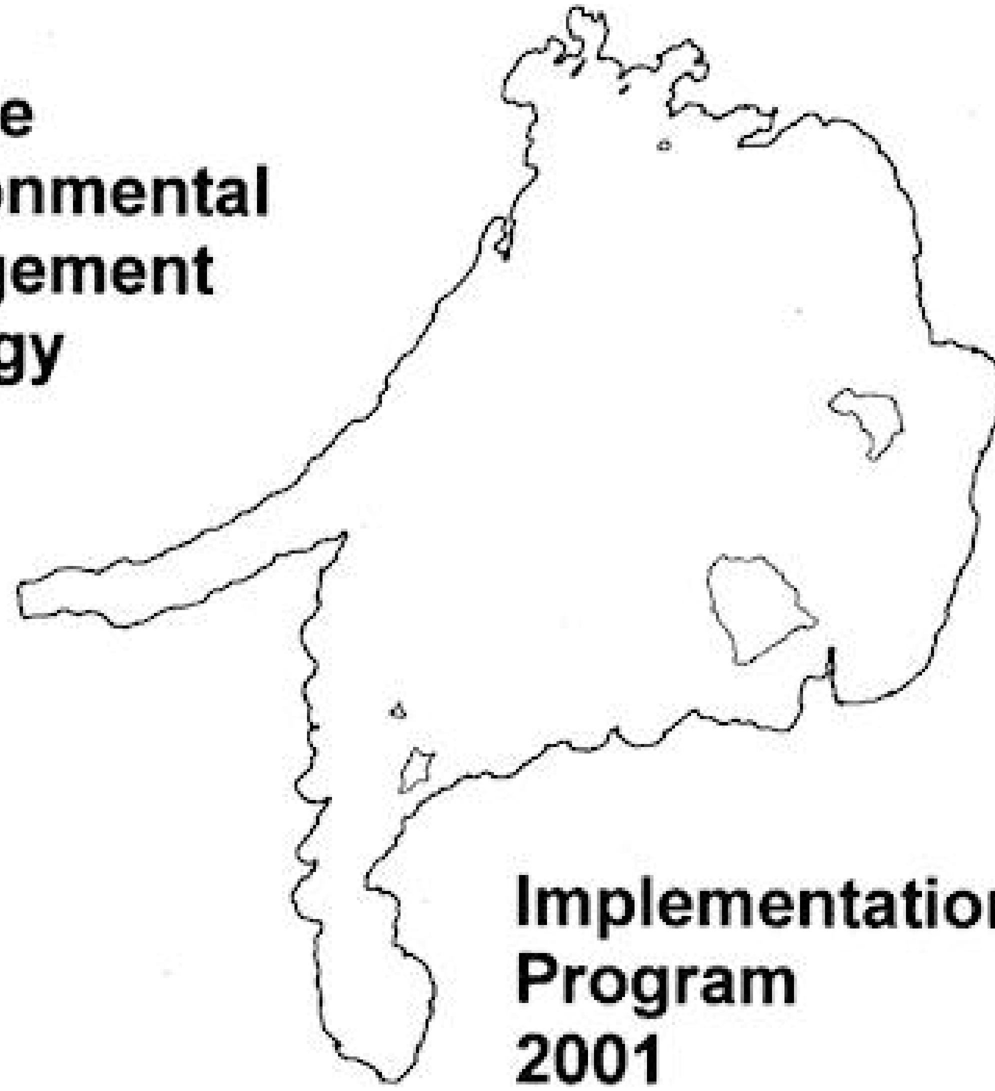
Lake Simcoe Environmental Management Strategy



Implementation Program 2001

Lake Simcoe Water Quality Update: LSEMS Phase II Progress Report, 1995-1999

Technical Report: Imp. B.19

Lake Simcoe Water Quality Update: LSEMS Phase II Progress Report, 1995-1999.

Ontario Ministry of the Environment,
Biomonitoring Section,
Environmental Monitoring and Reporting Branch,
125 Resources Road,
Toronto, ON M9P 3V6

Prepared by:

K.H. Nicholls,
S-15 Concession 1,
RR #1, Sunderland,
ON LOC 1H0

LSEMS Implementation
Technical Report No. Imp.B.19

May, 2001

LAKE SIMCOE ENVIRONMENTAL MANAGEMENT STRATEGY IMPLEMENTATION PROGRAM

FOREWORD

This report is one of a series of technical reports prepared in the course of the Lake Simcoe Environmental Management Strategy (LSEMS) Implementation Program. This program is under the direction of the LSEMS Steering and Technical Committees, comprised of representatives of:

- Lake Simcoe Region Conservation Authority;
- Ministry of Agriculture, Food and Rural Affairs;
- Ministry of the Environment;
- Ministry of Municipal Affairs and Housing;
- Ministry of Natural Resources;
- Regional Municipalities of York and Durham;
- County of Simcoe;
- Cities of Barrie, Orillia and Kawartha Lakes;
- Towns of Bradford West Gwillimbury, Innisfil and New Tecumseth; and
- Townships of Oro-Medonte and Ramara.

The Lake Simcoe Environmental Management Strategy (LSEMS) studies were initiated in 1981 in response to concern over the loss of a coldwater fishery in Lake Simcoe. The studies concluded that increased urban growth and poor agricultural practices within the drainage basin were filling the lake with excess nutrients. These nutrients promote increased weed growth in the lake with the end result being a decrease in the water's oxygen supply. The "Final Report and Recommendations of the Steering Committee" was released in 1985. The report recommended that a phosphorus control strategy be designed to reduce phosphorus inputs from rural and urban sources. In 1990 the Lake Simcoe Region Conservation Authority was given overall coordination responsibilities for Phase I Implementation, as outlined in the LSEMS Cabinet Submission and subsequent agreement (Recommendation E.1). At the completion of Phase I Implementation, a report was produced. "LSEMS Implementation Program - Summary of Phase I and Recommendations for Phase II, 1995" outlined the activities and progress during Phase I and presented recommendations for Phase II of the LSEMS Implementation Program. The LSEMS Implementation Program is currently preparing for Phase III of the program.

The goal of the LSEMS Implementation Program is to improve and protect the health of the Lake Simcoe watershed ecosystem and improve associated recreational opportunities by:

1. Restoring a self sustaining coldwater fishery,
2. Improving water quality,
3. Reducing phosphorus loads to Lake Simcoe, and,
4. Protecting natural heritage features and functions.

The LSEMS Implementation Program will continue to initiate remedial measures and control options designed to reduce phosphorus inputs entering Lake Simcoe, monitor the effectiveness of these remedial measures and controls and evaluate the overall response of the lake to this program. Through cost sharing programs, environmental awareness by the public and further studies, the goal of restoring a naturally reproducing coldwater fishery in Lake Simcoe by improving water quality can be reached.

Questions with respect to the contents of this report should be directed to:

Michael Walters
Manager, Environmental Services
Lake Simcoe Region Conservation Authority
120 Bayview Parkway, P.O. Box 282
Newmarket, ON. L3Y 4Xl
Telephone: 905 895-1281 ext. 234
Fax: 905 853-5881
E-mail: m.walters@lsrca.on.ca
Website: www.lsrca.on.ca

OR

Wolfgang Scheider
Manager, Biomonitoring Section -
Environmental Monitoring & Reporting Section
Ministry of the Environment
125 Resources Road
Etobicoke, ON. M9P 3V6
Telephone: 416 327-6535
Fax: 416 327-6519
E-mail: wolfgang.scheider@ene.gov.on.ca
Website: www.ene.gov.on.ca

Summary

This brief report on Lake Simcoe water quality represents the lake monitoring component of the Ministry of the Environment's contribution to the LSEMS Phase II progress report for 1995-1999. Four "indicator" variables, total phosphorus (TP), chlorophyll *a,* Secchi disk visibility (a measure of water clarity) and dissolved oxygen have been measured consistently at 12 sampling locations in Lake Simcoe for the May-October periods of the past 20-25 years. Results are also reported for samples collected year-round from four municipal water supply intakes in the lake and from the outflow at Atherley. Statistically significant trends in all four of these variables were found at some of the monitored Lake Simcoe stations; chlorophyll *a* showed the least evidence of long-term trends, while the most dramatic changes were in water clarity.

TP concentrations were generally lower during the 1990's than during the 1980's as revealed by the data from the main lake (May-October) sampling stations, the water intakes and the lake outflow; however, long-term trends were complicated by shorter periods of increases and decreases over 3-6 year intervals. Decreasing TP trends for the period ending in 1999 were found only at Cook's Bay stations C1, C6 and C9, and for Station N31 at the north end of the lake, and for Station K39 in Kempenfelt Bay for both the 1975-1994 and 1975-1999 periods. Overall rates of TP decline ranged from 0.15 to 1.0 $\mu g\ L^{-1}\ yr^{-1}$, some of which could be attributed to removal of particulate TP from the lakewater by zebra mussels since their establishment in the lake in 1994-95. More specific tests of the zebra mussel effect (detection of step trends between 4-year pre- and post zebra mussel time periods) revealed significantly lower TP concentrations for the post zebra mussel time period at all sampling stations except N32 at the north end of the lake, the Kempenfelt Bay stations and main lake Station K45. At the seven sampling stations showing statistically significant change, percentage reductions in TP associated with the zebra mussel establishment in the lake ranged from 21 to 41 %.

The apparent effects of the establishment of zebra mussels on Lake Simcoe water clarity were very dramatic. Water clarity during the 4-year post zebra mussel period 1996-1999 was as much as 67 and 65 % higher than during the pre-mussel period of 1991-1994 at stations E50 and E51 on the east side of the lake, and 69 % higher at Station N31 at the north end of the lake. Significant step trends in water clarity were detected for all sampling stations, even the deep-water Kempenfelt Bay and main lake sites, where water clarity increased by 22, 38 and 43 % at stations K45, K42 and K39, respectively.

The volume-weighted deep-water oxygen depletion rate (normalized to a 4°C rate) revealed a downward trend through the 1990's (ignoring the 1999 data, which may be in error). This was in contrast to a worsening (increasing depletion rates) trend through the 1980's. Apparent improvements may relate to declining trends in TP and to the recent impacts of zebra mussels. Several more years of monitoring data may be required to determine if the apparent improvements in dissolved oxygen can be sustained.

Table of Contents

Introduction

The Lake Simcoe Environmental Management Strategy (LSEMS) requires progress reports at the end of each 5-year term from each of the collaborating agencies (Ontario Ministries of Agriculture and Food and Rural Affairs, Natural Resources, and Environment, and the Lake Simcoe Region Conservation Authority). Highlights from each of these reports are incorporated into a single summary report by the LSRCA for general distribution. This brief report on water quality represents the Ministry of the Environment's (lake monitoring component) contribution to the LSEMS Phase II progress report for 1995-1999. It updates some aspects of long-term trends presented in previous, more comprehensive water quality reports (Nicholls 1995; Nicholls 1998).

Four "indicator" variables (total phosphorus (TP), chlorophyll *a,* Secchi disk visibility and dissolved oxygen) have been measured consistently at 12 sampling locations in Lake Simcoe for several years (Fig. 1). Although many nutrients are required by aquatic plants and algae for their growth in lake waters, phosphorus is considered to be in shortest supply relative to the needs of these organisms in Lake Simcoe. Phosphorus is also the nutrient most amenable to control at source and therefore has been targeted for reduced inputs to Lake Simcoe (Nicholls 1997; Walker 1997) in order to control algal growth in the lake. Chlorophyll *a* is the green photosynthetic pigment found in most algae and has been used here as an index of "abundance" of algae suspended in the water column. Water clarity has been measured with a Secchi disk (a 22 cm diam. black and white disk lowered into the lake on a calibrated rope) and is simply the recorded depth at which the disk is no longer visible to the observer at the lake surface. Shallow readings of the Secchi disk indicate high densities of suspended particles (usually algae). So, lakes with high TP concentrations usually have high concentrations of chlorophyll *a* and low Secchi disk readings. Excess loading of phosphorus to lakes allows excessive amounts of algae to grow in the water column, contributing to poor water clarity and a loss of dissolved oxygen in the bottom waters after the algae sink and decompose at or near the lake bottom.

This report places emphasis on these four water quality variables and is semi-technical in content, having been written specifically for members of the public who are familiar with Lake Simcoe environmental issues and problems.

Methods

Field and laboratory methods were essentially the same as those outlined in Nicholls (1998), except that during 1999, field work was done by staff from the Dorset Environmental Science Centre (Ministry of the Environment), whereas for the previous eight years, all sampling had been done by MOE contractors, Mark and Vanessa Ledlie of Bionomics. A total of twelve main lake stations have been regularly sampled (Fig. 1). The 1999 dissolved oxygen data may have been biased by a faulty meter at least for the early part of the season (Bev Clark, Dorset ESC, personal communication); these data should be interpreted with caution. Although it is outside the temporal terms of reference for this report, dissolved oxygen data for 2000 have also been summarized and included here in calculations of dissolved oxygen depletion rates to help bridge the gap created by potentially erroneous 1999 data.

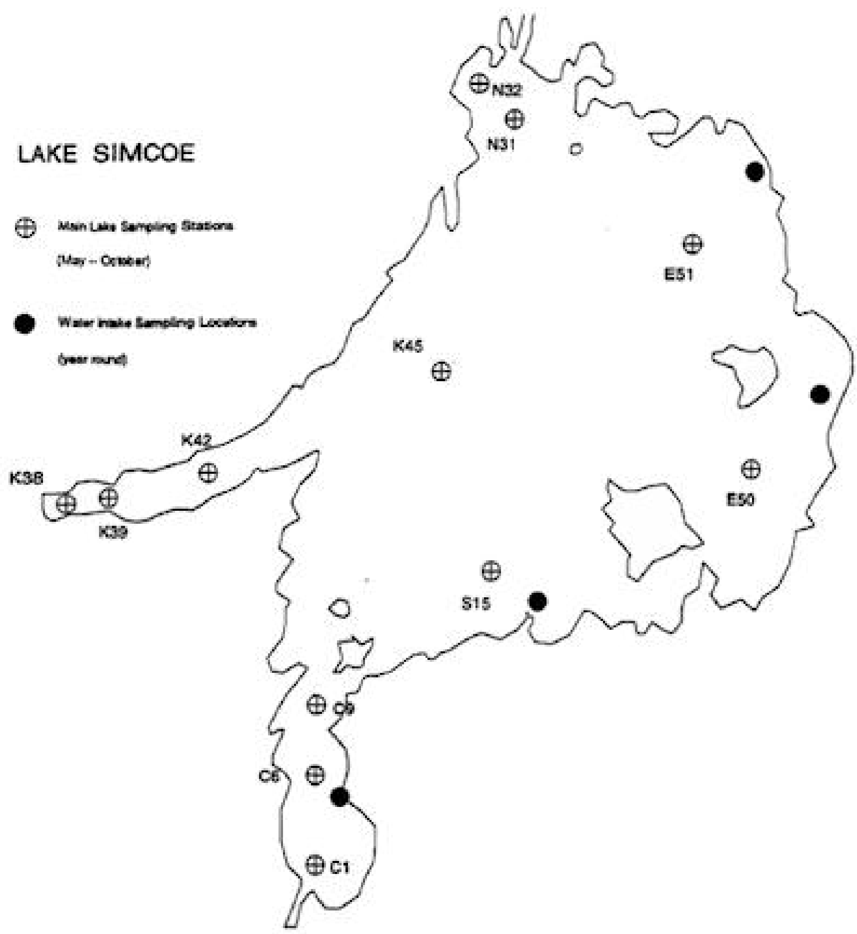


Figure 1. Locations of the 12 regular main lake and four municipal water supply intake sampling locations in Lake Simcoe.

Outlier detection was based on a subjective evaluation of extreme values in a short term trend context (i.e. was the extreme value under question accompanied by higher than usual values immediately before and/or after the problem date, and were data for other variables corroborative of the high values). Using this approach, a more realistic identification of problem data was made than by a strict adherence to some mathematical criterion for detection of outliers. For example, high TP values of 0.178 and 0.119 mg/L at Stations C6 and C9 on June 11, 1994 and July 21, 1980, respectively, were replaced by linear interpolation between adjacent data because (1) they were an order of magnitude higher than adjacent data (suggesting possibly a decimal placement error in the laboratory during initial recording of analytical results), (2) there was no evidence of high values immediately before or after these dates, and hence no evidence of a short-term trend to which the high values in question might have constituted a legitimate peak, and (3), there was no evidence of corroborating data among other water quality variables (total Kjeldahl nitrogen or chlorophyll were not significantly higher; Secchi disk visibility was not significantly lower). So, while these two high values of 0.178 and 0.119 mg/L were replaced, this approach to outlier detection led to the retention of some other equally high TP values.

For example, a high TP value of 0.166 mg/L at Station C1 on 16 September, 1996 was retained in the data set because it was accompanied by a rise in chlorophyll to 44 µg/L (from 1.8 µg/L) and a decrease in Secchi disk visibility to 0.75 m (from a value >3 m, the lake bottom at this location). Similarly, a recorded value of 0.140 mg/L for Station K45 on 19 August, 1996 was retained in the data set because Secchi disk visibility had declined drastically to 2.0 m (from 8.75 m measured two weeks previously). In all, 16 extreme TP values (of the approximately 2600 TP values in the database) and only one chlorophyll *a* value (Appendix Table 1) were replaced by linear interpolation of adjacent data before plotting and analyses of trends in the May-October lake station data base. Similarly, 23 TP outliers in the water intake data sets were replaced (Appendix Table 2).

Analysis of trends relied on robust non-parametric statistical techniques that are especially useful for water quality data characterized by seasonality and serial dependency (Cluis *et al.* 1989). Plotting and testing for trends in total phosphorus was after replacement of outliers as outlined above. Monotonic time trend detection was done twice: first for the pre-zebra mussel period of 1980-1994 or 1975-1994, depending on the earliest availability of data, and again for the entire period of available data ending in 1999. For step-trend detection associated with the establishment of zebra mussels in Lake Simcoe, 1995 (a transition year) was eliminated and a four-year pre-zebra mussel period (1991-1994) was tested against a four-year (1996-1999) post zebra mussel period of data.

Results and Discussion

Total phosphorus (TP)

TP trends for the Lake Simcoe sampling stations (Figs. 2, 3) reveal some consistent patterns including higher values during the late 1970's (at the three sampling stations where 1970's data are available) and early 1980's and again during the early 1990's. The intervening period from about 1986 to 1990 was characterized by the lowest TP concentrations, except for the late 1990's when equally low or lower concentrations of TP were measured at many stations. Although not as clear, this pattern was also found in the year-round water intake data, especially in the Sutton and Keswick intake samples (Fig. 4). The trend to increasing TP concentrations during the early 1990's was also apparent in sample collected in the outflow of the lake at Atherley (Fig. 5). On the whole, TP concentrations were lower during the 1990's than during the 1980's as revealed by the data from the main lake, the water intake and the lake outflow sampling locations.

Owing to the existence of the cyclic patterns in long-term TP levels described above, overall long-term trends at many locations were not detected (a net result of short-term increasing trends cancelling out short-term decreasing trends). Consequently, for the entire period of TP measurements ending in 1999, the only statistically significant trends were found for stations C1, C6, C9, N31 and K39, where TP declined at overall rates of 0.65, 1.0, 0.25, 0.15 and 0.4 $\mu g\ L^{-1}\ yr^{-1}$, respectively (Table 1). Similar long-term trends in TP were found at three of the four water intake sites; only the Keswick data failed to reveal a significant TP decline (Table 2).

At Station N31 and all three Cook's Bay stations, the long-term trends became insignificant when restricted to the pre-zebra mussel period ending in 1994. This suggests that the long-term trend may have been influenced by the establishment of zebra mussels in the lake (as has been observed for other lakes, e.g. Nicholls *et al.* 1999). When these data were examined more specifically for a possible zebra mussel effect (detection of step trends between 4-year pre- and post zebra mussel time periods), significantly lower TP concentrations were found for the post zebra mussel period at all sampling stations except

N32, the Kempenfelt Bay stations and main lake Station K45 (Table 3). Percentage reductions in TP associated with the zebra mussel establishment in the lake ranged from 21 to 41 % at the seven sampling stations showing significant change. The mechanism of TP reduction resulting from zebra mussel invasion of Lake Simcoe is presumably the same as that known for Lake Erie (Holland *et al.* 1995; Nicholls *et al.* 1999) and Saginaw Bay of Lake Huron (Johengen *et al.* 1995), whereby the filter-feeding activity of the mussels removes particulate TP from the water column above the mussel colonies on the lake bottom.

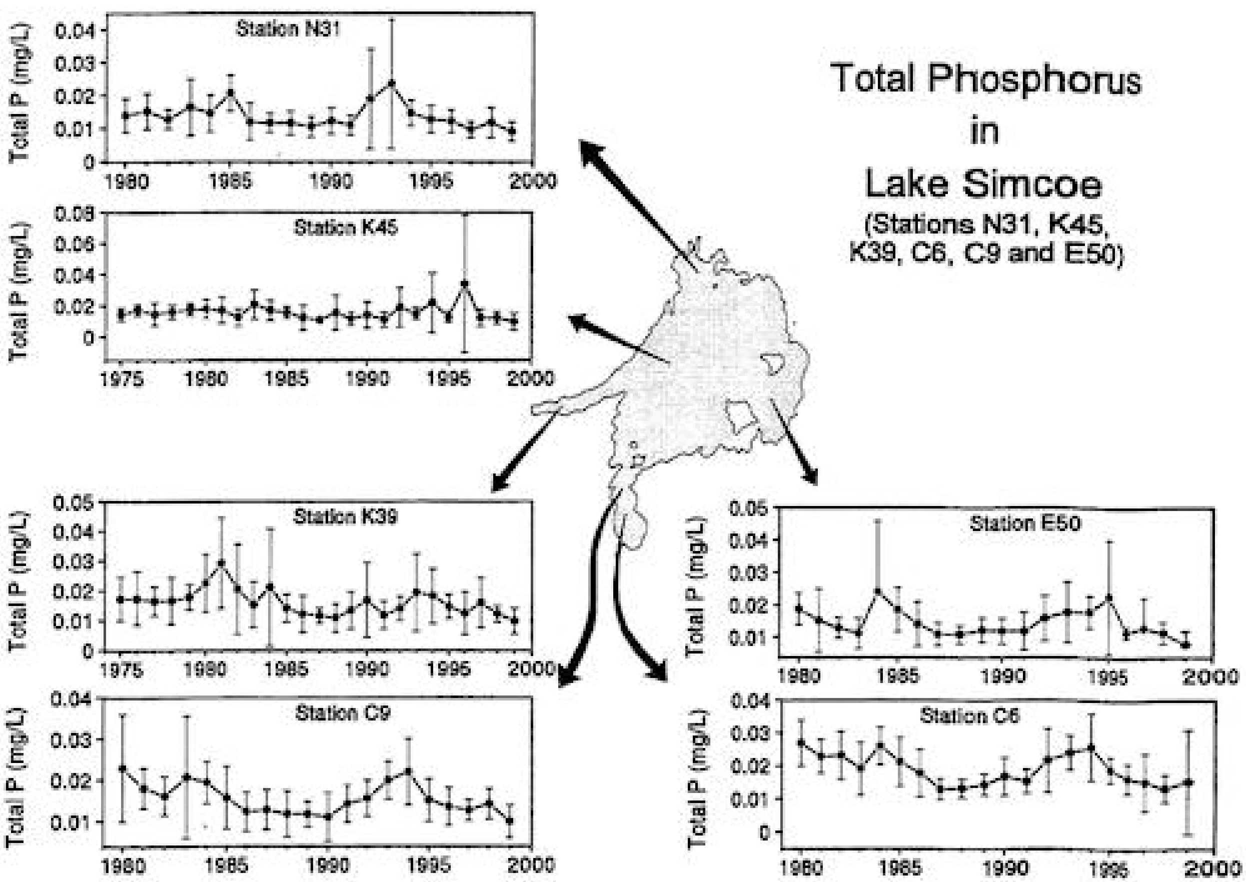


Figure 2. May-October mean TP concentrations (±1 st. dev.) at Lake Simcoe sampling stations N31, K39, K45, C6, C9, and E50 after outlier replacement (see Appendix Table 1). Note the differences in axes scales.

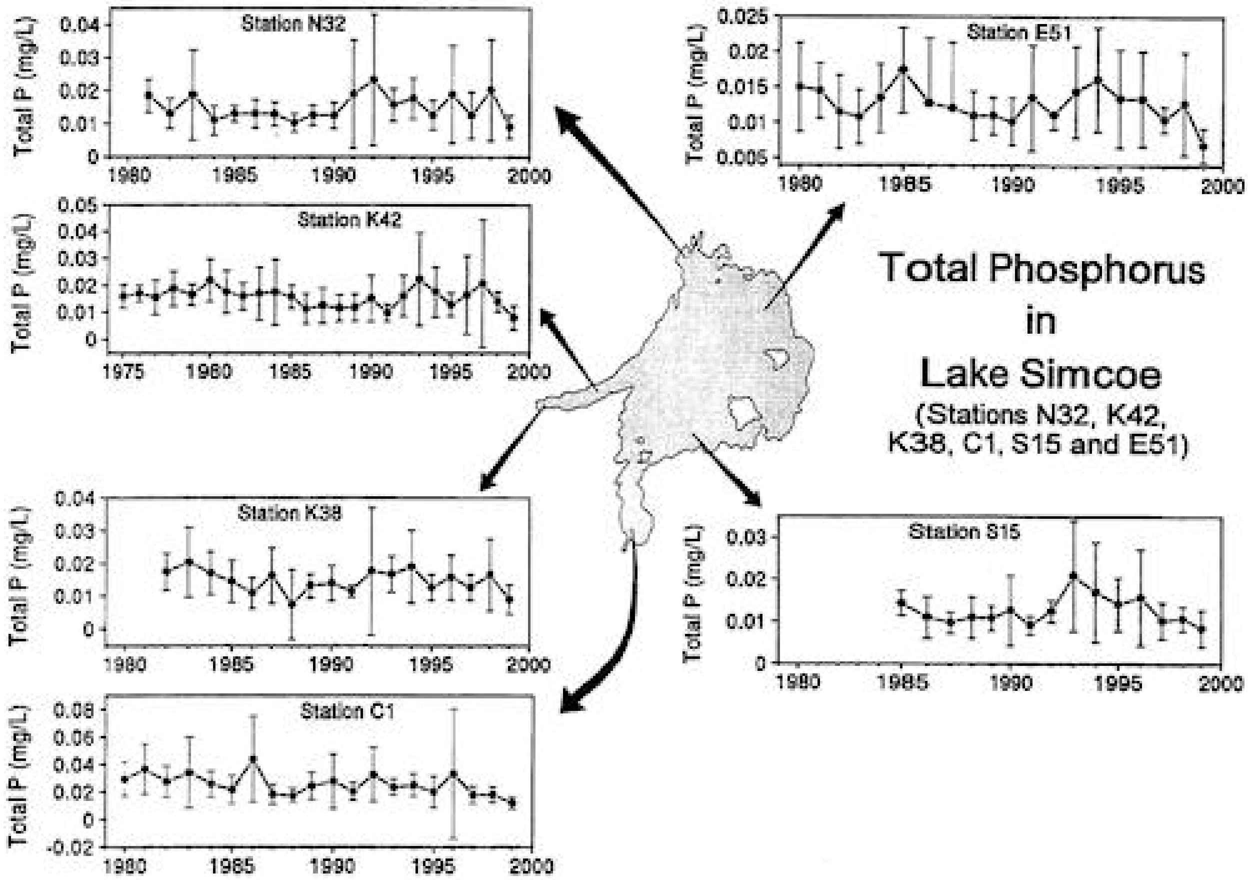


Figure 3. May-October mean TP concentrations (±1 st. dev.) at Lake Simcoe sampling stations N32, K38, K42, C1, S15, and E51 after outlier replacement (see Appendix Table 1). Note the differences in axes scales.

The lesser impact at deep-water locations in Kempenfelt Bay and at Station K45 is understandable given the known distribution of zebra mussels in shallow-water regions of lakes; impacts are likely to be greatest in shallower waters where the ratio of overlying water volume to mussel substrate area is lowest.

<u>Chlorophyll *a* and Water Clarity</u>

With several May-October averages in 6-10 µg/L range (especially during the 1980's), chlorophyll concentrations were highest at Station C1 in southern Cook's Bay, undoubtedly reflecting the proximity to a major source of nutrients from the Holland River. Chlorophyll levels declined northward through Station C6 to Station C9 where may-October means were about one-half of those measured at Station C1 (Fig. 6a). Chlorophyll *a* levels were generally in the 2-4 µg/L range for the remainder of the Lake Simcoe stations (Fig. 6a, 6b). These chlorophyll levels (an indication of the amount of suspended algae in the water column) were reflected in the water clarity measurements, especially at the Cook's Bay stations [for more detail on the interrelationships among TP, chlorophyll and water clarity for the lower Holland River and Cook's Bay, see Nicholls (1998)]. Secchi disk visibilities were lowest at C1 (often averaging < 2 m during the 1980's), intermediate at C6 (averaging about 3 m), and higher at C9 (averaging nearly 4 m during the 1980's; Fig. 7a).

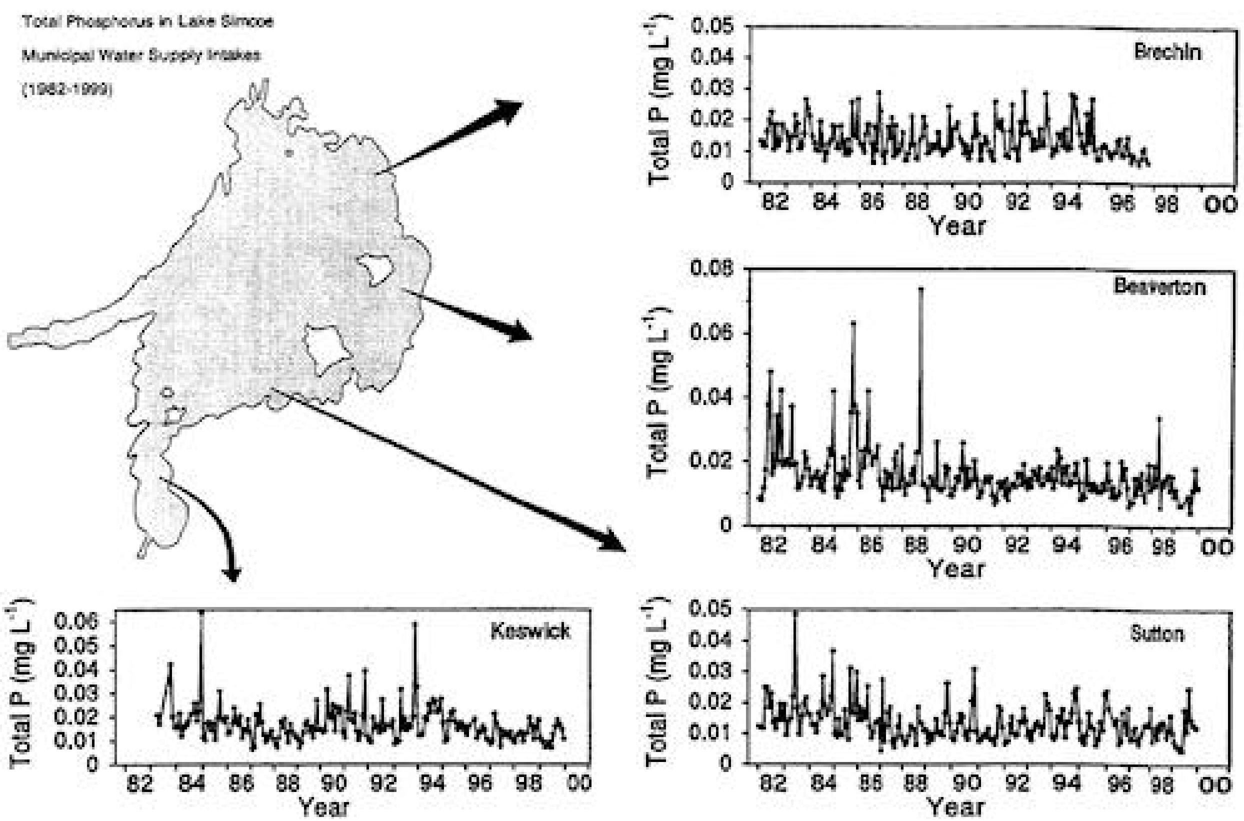


Figure 4. Monthly mean concentrations of total phosphorus in samples from four municipal water supply intakes in Lake Simcoe (Note the difference in Y-axis scales).

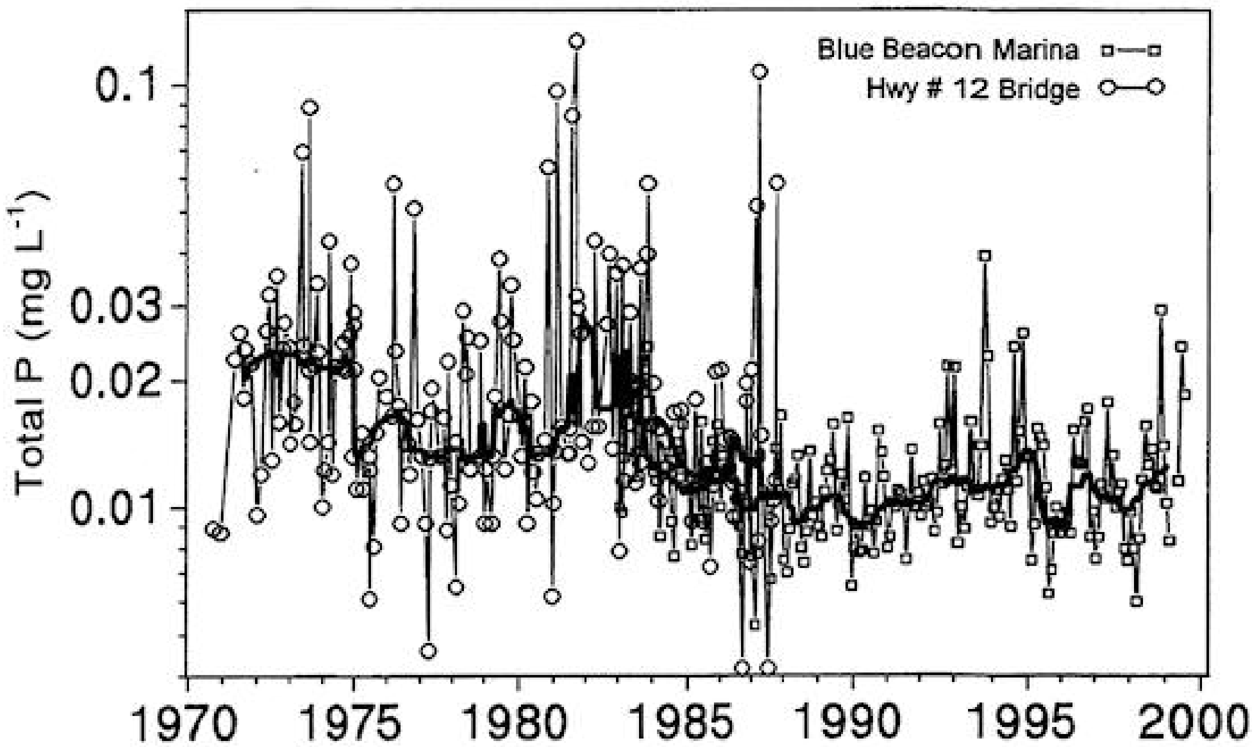


Figure 5. Total phosphorus concentrations in the Lake Simcoe outflow at Atherley: the Hwy #12 Bridge samples were collected approximately monthly during 1971-1987, while the Blue Beacon Marina samples were collected about twice weekly during 1984-1999 (plotted points are monthly means). The thick line represents the 12-month moving median for each sampling location.

There were improvements in water clarity after 1994 at all sampling locations, but most dramatically at Stations E50, E51 (Fig. 7a) and N31 (Fig. 7b).

Long-term decreases in chlorophyll *a* concentrations and increases in water clarity were evident at several lake Simcoe sampling stations. For the data collection period ending in 1994 (pre- zebra mussel establishment), nine sampling stations (C6, C9, E50, E51, N32, K38, K39, K42 and K45) showed statistically significant rates of chlorophyll decline ranging from -0.156 µg/L/yr to -0.053 µg/L/yr (Table 1). For most of these the decline was more significant when the trend was calculated for the period ending in 1999; but, this seems to have resulted simply from incorporation of more years (increasing the degrees of freedom for the statistical tests) rather than from an apparent zebra mussel influence. Support for this lies in the slopes (rates of chlorophyll *a* decrease) which were not as great for the period ending 1999 at eight of the nine stations in question. More direct evidence for a minimal influence of zebra mussels on chlorophyll *a* comes from the "before and after" comparisons. Only stations C1 and N31 showed a significant step trend for the pre- and post zebra mussel 4-year comparisons (Table 3).

The apparent effects of the establishment of zebra mussels on Lake Simcoe water clarity was very dramatic. Water clarity during the 4-year post zebra mussel period 1996-1999 was as much as 65, 67 and 69 % higher at stations E51, E50 and N31 than during the pre-mussel period of 1991-1994 (Table 3). Significant step trends were detected for all sampling stations, even the deep-water sites where water clarity increased by 22, 38 and 43 % at stations K45, K42 and K39 (Table 3). There are several possible reasons why the observed improvements in water clarity associated with the zebra mussel establishment were so much greater than for chlorophyll *a*: 1) the removal of particles suspended in the water column has a disproportionately greater effect on light transmission, owing in part to the exponential nature of light extinction with depth in lake water; 2) all suspended particles influence water clarity and are potentially removed by zebra mussel filtration, whereas not all suspended particles contain chlorophyll. In shallow-water areas, susceptible to wind-induced turbulence, the lake sediments can be the origin of a high proportion of suspended particles; 3) the chlorophyll data were highly variable, thus requiring *a* greater decline post zebra mussel establishment to demonstrate statistical significance; 4) the chlorophyll a test is relatively imprecise at the low levels (< 2 µg/L) measured in many of the samples.

Dissolved Oxygen

Lake Simcoe's most serious water quality problem is its loss of dissolved oxygen in deep-water zones of the lake every summer. Typically, early summer dissolved oxygen (DO) concentrations have been in the 10-12 mg/L range, but rapidly declined to about 2 mg/L in the deepest waters by late September or early October (Fig. 8). Two recent exceptions were observed in 1997 and 1999, when early fall concentrations were in the 4-5 mg/L range in the deepest parts of the lake.

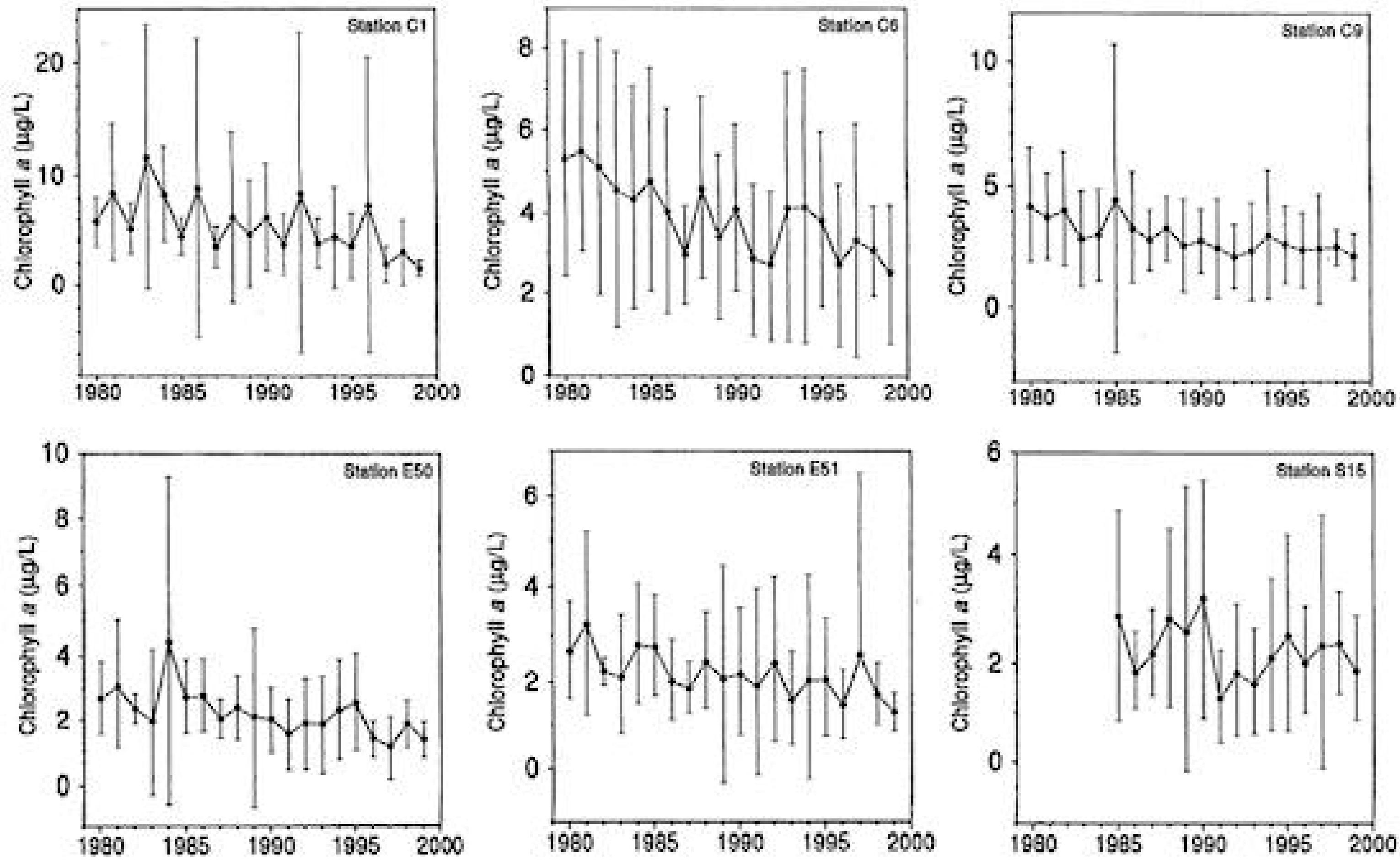


Figure 6a. May-October mean chlorophyll *a* concentrations (±1 st. dev.) for Lake Simcoe sampling stations C1, C6, C9, E50, E51, S15. Note the differences in the Y-axis scales.

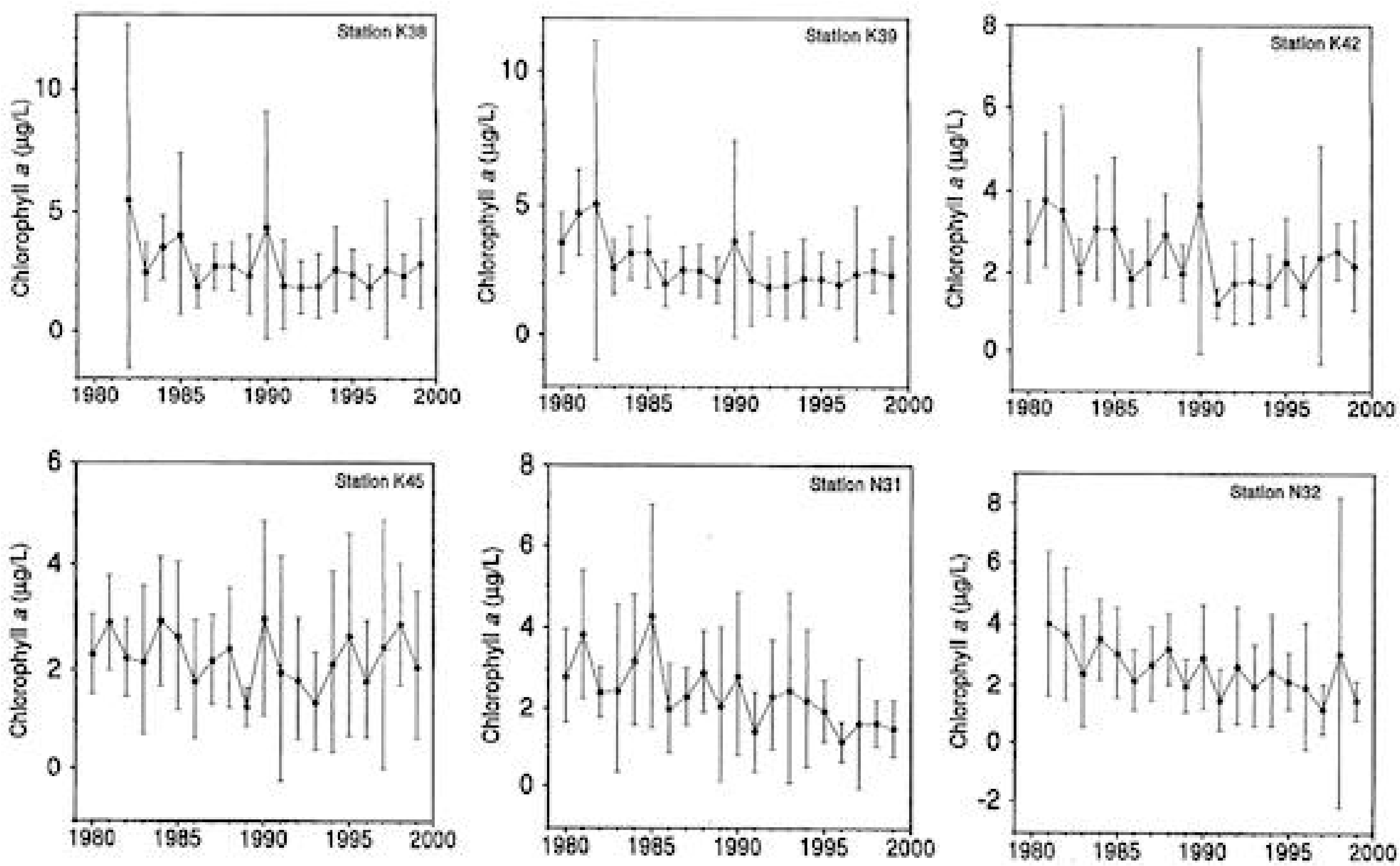


Figure 6b. May-October mean chlorophyll *a* concentrations (±1 st. dev.) for Lake Simcoe sampling stations K38, K39, K42, K45, N31 and N32. Note the differences in the Y-axis scales.

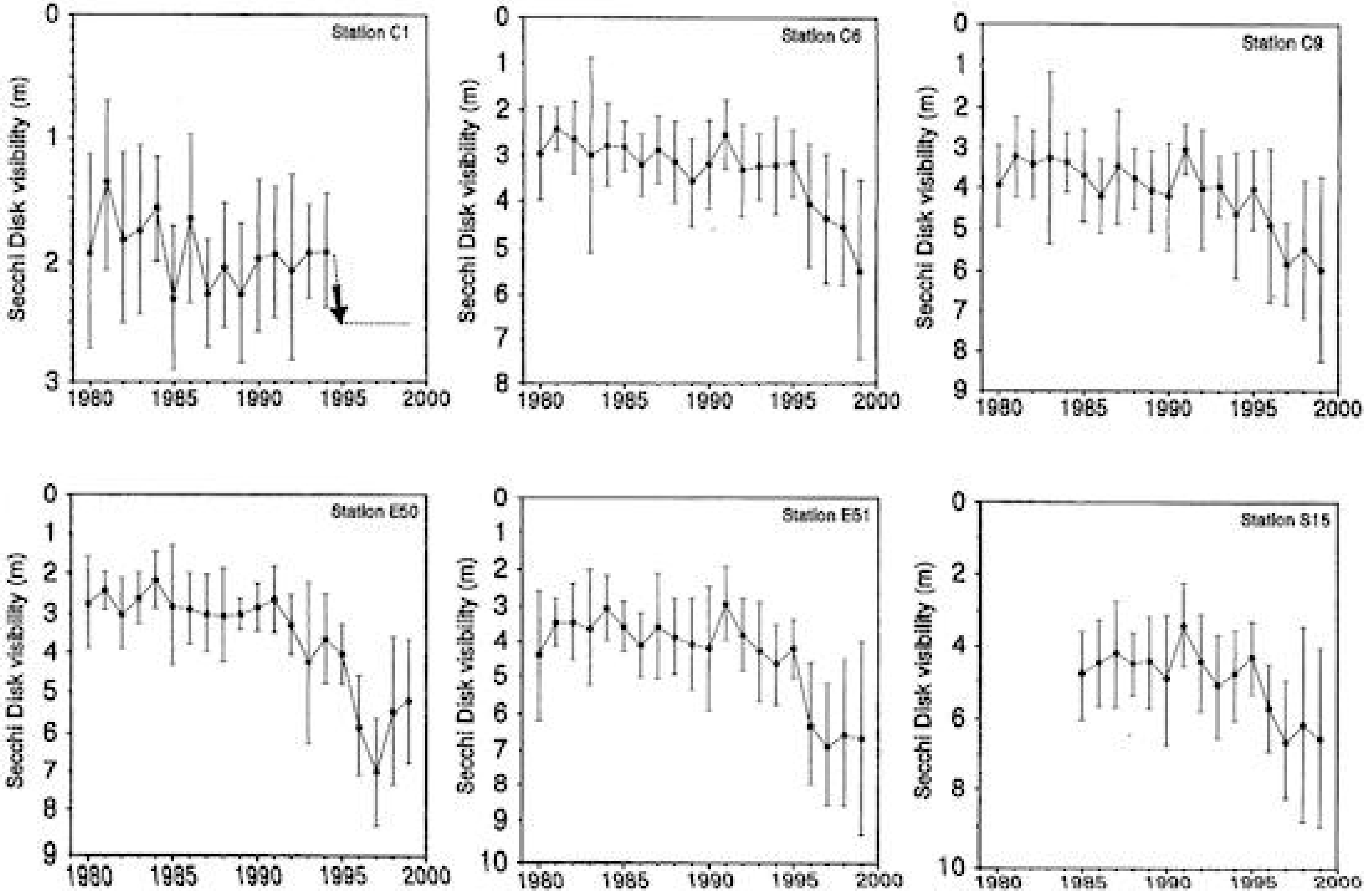


Figure 7a. May-October mean Secchi disk visibilities (±1 st. dev.) for Lake Simcoe sampling stations C1, C6, C9, E50, E51, S15. The arrow after 1995 for station C1 indicates that mean Secchi disk visibility could not be calculated because of a high number of readings greater that the bottom depth at *this station. Note the differences in the Y-axis scales.*

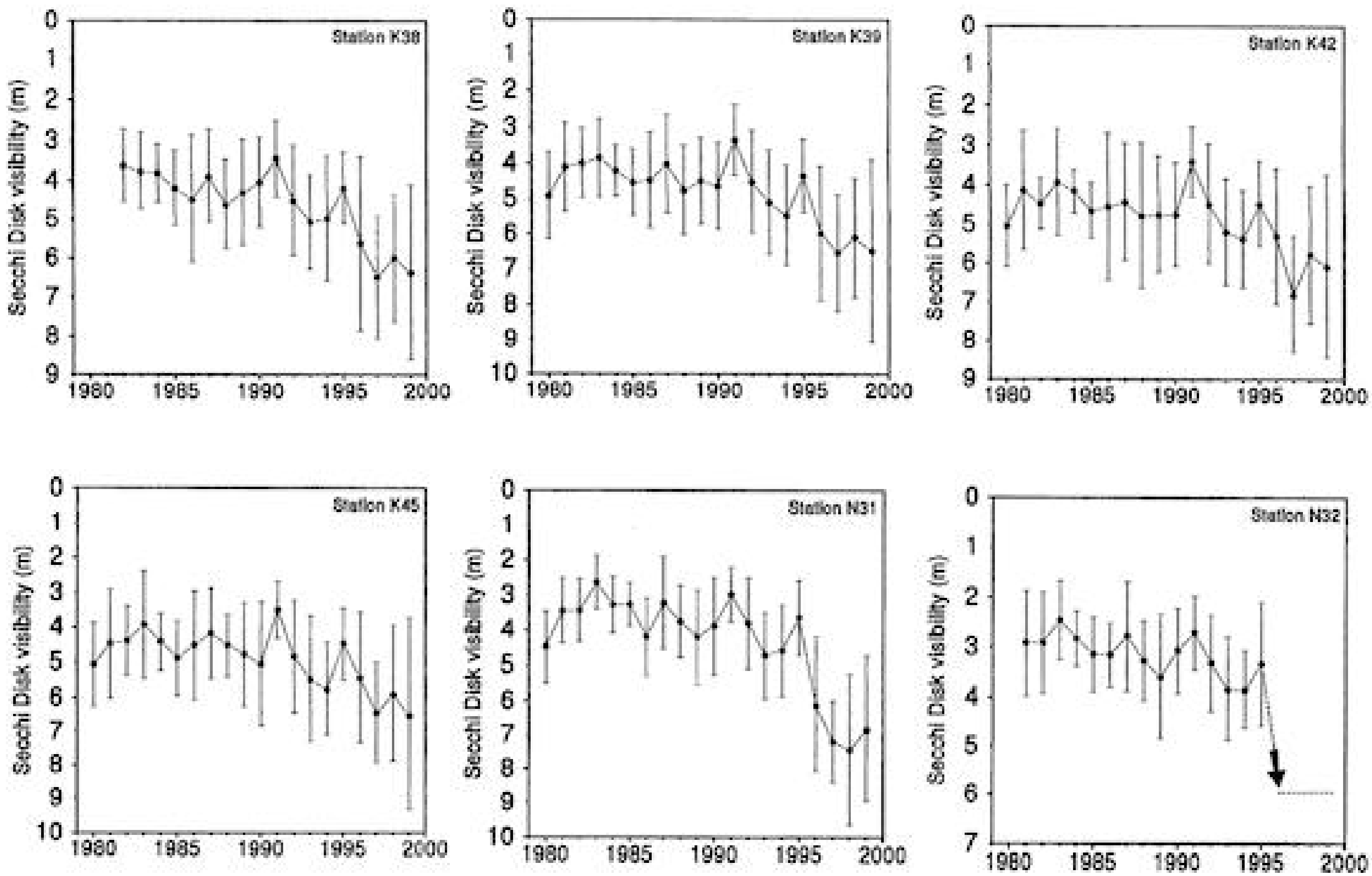


Figure 7b. May-October mean Secchi disk visibilities (±1 st. dev.) for Lake Simcoe sampling stations K38, K39, K42, K45, N31 and N32. *The* arrow after 1995 for station N32 indicates that mean *Secchi disk visibility could* not be calculated because of a high number of readings greater that the bottom depth at this station. Note differences in the Y-axis scales.

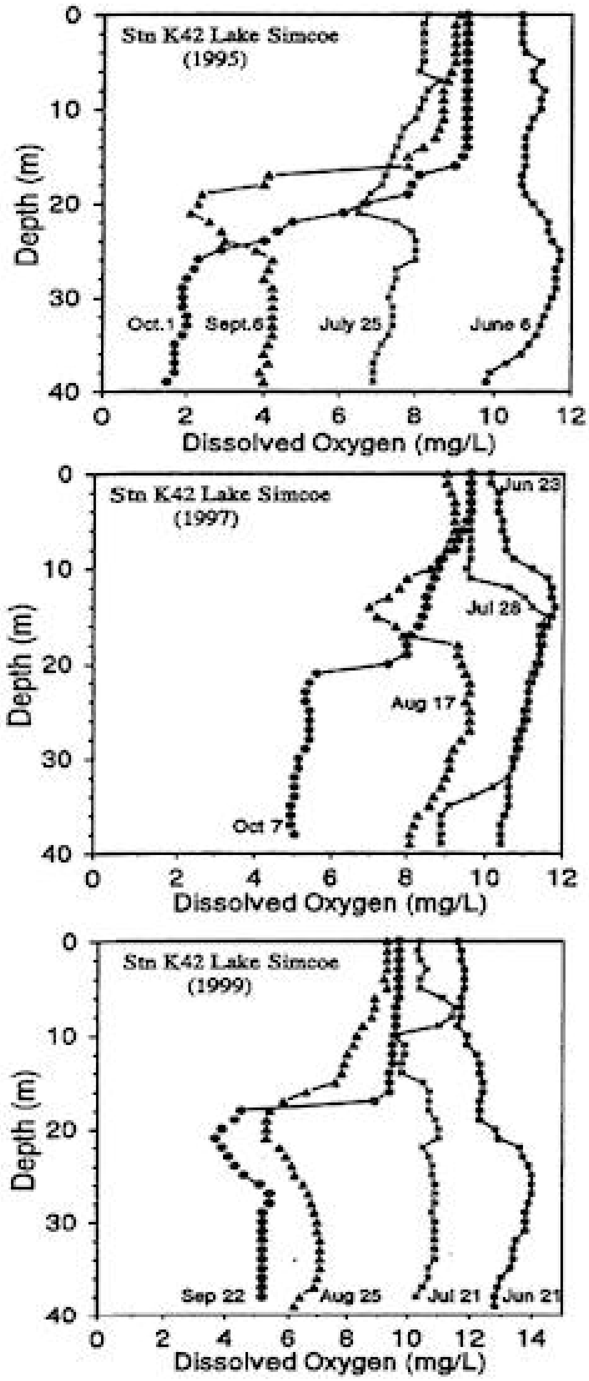


Figure 8. Progressive loss of dissolved oxygen in Lake Simcoe (Station K42) during the summer-fall periods of 1995-1999. Concentrations measured during 1999 may be in error, at least during the early summer, owing to a malfunctioning dissolved oxygen meter (see Methods). Note the difference in the X-axis scale for 1999.

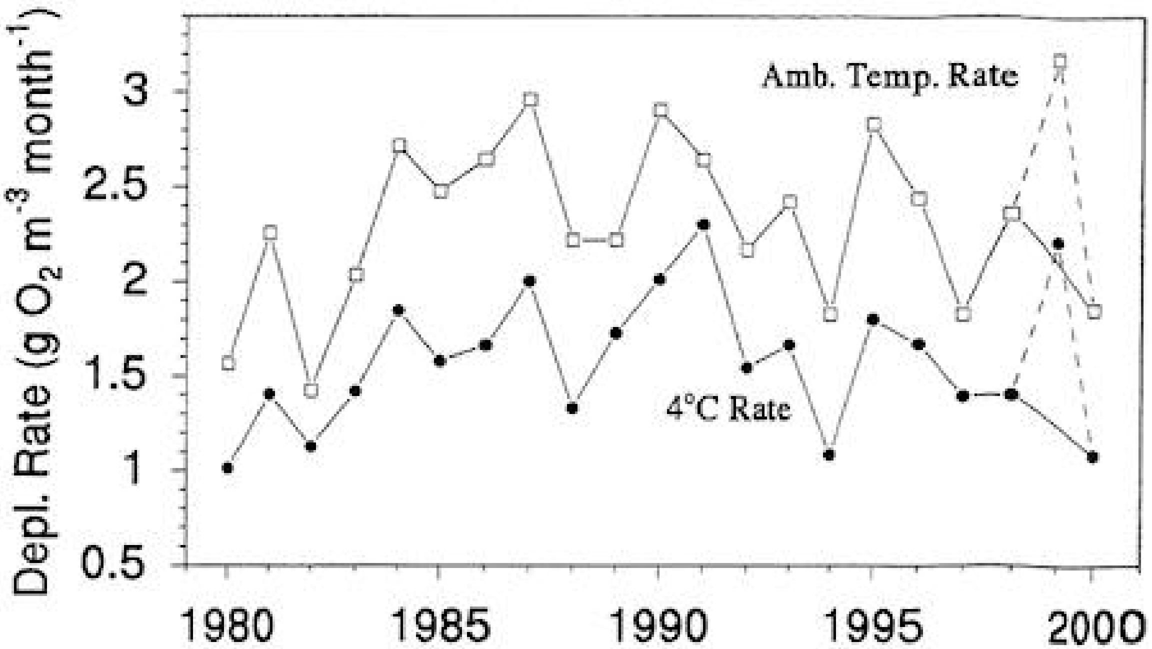


Figure 9. Volume-weighted dissolved oxygen depletion rate in the 18 m - bottom zone of Lake Simcoe for the mid-June to mid-September periods of 1980-2000. Amb. Temp. Rate = depletion rate at ambient temperatures; 4°C Rate = rate after normalization to a rate at four degrees C (to account for the effects of significant differences in inter-annual deep-water temperatures). Suspected malfunctioning of the instrument used in 1999 may have contributed to anomalously high values. Any assessment of trend should probably ignore the 1999 values (see also Fig. 8).

However, the 1999 data may be erroneous (see Methods section). The LSEMS interim end-of-summer DO objective is 5 mg/L for lake trout habitat [provisionally defined as the mid-September volume-weighted DO concentration in the 18 m to lake bottom zone of the lake (Nicholls 1997)]. However, it is unlikely that this objective can be achieved consistently as long as depletion rates remain as high as they have been. There are encouraging signs of improvement, however. The volume-weighted deep-water oxygen depletion rate (normalized to a 4°C rate) has been trending downward through the 1990's (Fig. 9) (again, ignoring the 1999 data which may be in error). This is in contrast to the worsening trend through the 1980's (Fig. 9).

It is possible that the observed lowered DO depletion rates of the late 1990's is in response to declining TP concentrations in the lake; it could also be attributed to lower sedimentation rates of particulate organic matter in the deep-water regions of the lake as a result of zebra mussel filtration. Because it is not known how long the zebra mussel population in Lake Simcoe can be sustained at present levels, continued monitoring of TP, chlorophyll *a*, water clarity, dissolved oxygen and other water quality variables is critical. Zebra mussel densities could be drastically reduced at some future time (e.g. parasite or other microbial-induced disease). Any benefits in terms of lower DO depletion rates that the lake may now be experiencing as a result of zebra mussel feeding, could be quickly undone. Relaxation of TP loading controls in light of apparently improving water quality at this time would therefore not be prudent. Present-day TP loading to the lake is about three times higher than the natural TP load supplied to the lake prior to the development of the Lake Simcoe basin by European settlers. Those early loads were associated with excellent water quality (low TP concentrations, high end-of-summer deep-water DO levels). In general, the most recent analyses of long-term data indicated some recent improvements in Lake Simcoe water quality. Certainly, there were no strong indications of consistently worsening water quality during the 2-decades prior to zebra mussel establishment. This is consistent with recent calculations showing no evidence of recent increases in TP loading to the lake (Scott *et al.* 2001; Nicholls 2001).

Acknowledgments

Joyce Clark, Janet Humber, Ted Sheldon, Mark and Vanessa Ledlie and MNR's LSFAU did most of the sampling and measured temperature, dissolved oxygen and Secchi disk visibility. Lynda Nakamoto helped with data organization during the early 1990's. Staff of the Laboratory Services Branch, Ministry of the Environment performed the chemical analyses. Steve Maude and Wolfgang Scheider provided helpful comments on the draft of this report.

References

Cluis, D., Langlois, C., Van Coillie, R., and Laberge, C. 1989. Development of a software package for trend detection in temporal series: application to water and industrial effluent quality data for the St. Lawrence River. *Environ. Monit. and Assessment* 12: 429-441.

Holland, R.E., Johengen, T.H., and Beeton, A.M. 1995. Trends in nutrient concentrations in Hatchery Bay, western Lake Erie, before and after *Dreissena polymorpha. Can. J. Fish. Aquat. Sci.* 52:1201-1209.

Johengen, T.H., Nalepa, T.F., Fahnenstiel, G.L., and Goudy, G. 1995. Nutrient changes in Saginaw Bay, Lake Huron, after the establishment of the zebra mussel *(Dreissena polymorpha). J. Great Lakes Res.* 21:449-464.

Nicholls, K.H. 1995. Some recent water quality trends in Lake Simcoe, Ontario: implications for basin planning and limnological research. *Can. Water Res. J.* 20: 213-226.

Nicholls, K.H. 1997. A limnological basis for a Lake Simcoe phosphorus loading objective. *J. Lake and Reserv. Manage.* 13: 189-198.

Nicholls, K.H. 1998. *Lake Simcoe Water Quality Update, with Emphasis on Phosphorus Trends.* LSEMS Implementation Technical Report No. Imp.B.18. Lake Simcoe Region Conservation Authority, Newmarket, Ontario. 21 p.

Nicholls, K.H. 2001. *Phosphorus loading to Lake Simcoe, 1990-1998: Highlights and preliminary interpretation in historical and ecosystem contexts.* LSEMS Implementation Technical Report No. Imp.A4. Lake Simcoe Region Conservation Authority, Newmarket, Ontario.

Nicholls, K.H.., S.J. Standke, and G.J. Hopkins. 1999. Effects of dreissenid mussels on nitrogen and phosphorus in north shore waters of Lake Erie. *In* M. Munawar, T. Edsall and I. Munawar (Eds), *State of Lake Erie (SOLE) - Past, Present and Future,* pp. 323-336. Ecovision World Monograph Series. Backhuys Publ., Leiden, The Netherlands.

Scott, L.D., Winter, J.G., Futter, M.N., and Girard, R.E. 2001. *Annual Water Balances and Phosphorus Loading for Lake Simcoe, 1990-1998.* LSEMS Implementation Report No. IMP.A3. Lake Simcoe Region Conservation Authority, Newmarket, Ontario.

Walker, R.R. 1997. Strategies to rehabilitate Lake Simcoe - modelling phosphorus loads, remedial measures and control options. *J. Lake and Reserv. Manage.* 13: 214-225.

Table 1. Detection of time trends using non-parametric tests from Cluis *et al.* (1989) in total phosphorus (TP) and chlorophyll *a* (Chl *a)* concentrations and in Secchi disk visibilities (S.D.) at the 12 main Lake Simcoe sampling locations. The time period up to and including 1994 is considered to predate the major influences of the zebra mussel invasion of the lake. Trend analysis (Cluis et al.1989) was based on grouping data into 12-month intervals (1 interval per year). No S.D. trend statistics were calculated for Stations C1 and N32 because of a frequent lack of valid S.D. measurements (S.D. visibilities on the lake bottom) in the post zebra mussel years (1996-99) at these locations.

Location	Time Period	TP			Chl *a*			S.D.[1]		
		Trend[2]	Slope (µg/L/yr)	RMSE[3] (µg/L)	Trend[2]	Slope (µg/L/yr)	RMSE[3] (µg/L)	Trend[2]	Slope (m/yr)	RMSE[3] (m)
C1	1980-99	**	-0.65	7	**	-0.261	2.04	-	-	-
C1	1980-94	ns	NA	NA	ns	NA	NA	ns	NA	NA
C6	1980-99	*	-1	5	***	-0.121	0.55	***	0.10	0.47
C6	1980-94	ns	NA	NA	**	-0.135	0.60	**	0.034	0.26
C9	1980-99	*	-0.25	3	***	-0.087	0.43	***	0.113	0.52
C9	1980-94	ns	NA	NA	**	-0.116	0.46	*	0.050	0.37
S15	1985-99	ns	NA	NA	ns	NA	NA	*	0.143	0.63
S15	1985-94	ns	NA	NA	ns	NA	NA	ns	NA	NA
E50	1980-99	ns	NA	NA	***	-0.08	0.54	***	0.186	0.77
E50	1980-94	ns	NA	NA	**	-0.082	0.56	**	0.076	0.35

E51	1980-99	ns	NA	NA	**	-0.054	0.36	***	0.161	0.84
E51	1980-94	ns	NA	NA	*	-0.061	0.32	*	0.035	0.44
N31	1980-99	*	-0.15	3	**	-0.093	0.55	**	0.182	0.99
N31	1980-94	ns	NA	NA	ns	NA	NA	ns	NA	NA
N32	1981-99	ns	NA	NA	**	-0.093	0.56		-	
N32	1981-94	ns	NA	NA	**	-0.113	0.51	**	0.067	0.29
K38	1982-99	ns	NA	NA	ns	NA	NA	***	0.142	0.53
K38	1982-94	ns	NA	NA	*	-0.156	0.9	**	0.081	0.47
K39	1975-99	*	-0.4	5	***	-0.102	0.59	*	0.053	0.7
K39	1975-94	**	-0.45	5	***	-0.134	0.6	ns	NA	NA
K42	1975-99	ns	NA	NA	**	-0.052	0.75	ns	NA	NA
K42	1975-94	ns	NA	NA	**	-0.073	0.81	ns	NA	NA
K45	1975-99	ns	NA	NA	*	-0.026	0.49	ns	NA	NA
K45	1975-94	ns	NA	NA	**	-0.053	0.45	ns	NA	NA

[1] The Secchi disk was visible on the lake bottom at Stations C1 and N32 on many sampling dates after 1995, so tests for trends could not be done for dates after 1994.

[2] Significance of the trend indicated by *** ($P \leq 0.001$), ** ($P \leq 0.01$),* ($P \leq 0.05$), or ns ($P > 0.05$). When the trend is not significant (ns), then slope and RMSE entries are not applicable (NA).

[3] RMSE (root mean square error) is a measure of the precision of the monotonic trend model for the time interval indicated.

Table 2. Detection of time trends in total phosphorus (TP) from four Lake Simcoe municipal water supply intakes using non-parametric statistical tests (Cluis *et al*.1989). The time period up to and including 1994 predates the major influences of the zebra mussel invasion of the lake. Trend analysis was based on grouping data into 12 one-month intervals per year.

Intake Location	Time Period	Monotonic Trend Detection			Step Trend Detection (4-yr TP means; µg P/L)		
		Trend'	Slope (µg P/L•yr^{-1})	RMSE[2] (µg P/L)	1991-1994	1996-1999	RMSE[2]
Beaverton	1982-99	**	-0.56	8	13.9	12.8 ns	NA
Beaverton	1982-94	*	-0.69	9			
Brechin	1982-97	*	-0.2	6	14.8	11.1 **	6
Brechin	1982-94	ns	NA	NA			
Sutton	1982-99	**	-0.29	6	12.3	11.8 ns	NA
Sutton	1982-94	*	-0.46	6			
Keswick	1983-99	ns	NA	NA	19.4	12.9 **	7
Keswick	1983-94	ns	NA	NA			

[1] Significance of the trend indicated by *** ($P \leq 0.001$), ** ($P \leq 0.01$),* ($P \leq 0.05$), or ns ($P > 0.05$). When the trend is not significant (ns), then slope and RMSE entries are not applicable (NA).

[2] RMSE (root mean square error) is a measure of the precision of the trend model for the time interval indicated.

Table 3. Detection of step trends in total phosphorus (TP), chlorophyll *a* (Chl *a*) and Secchi disk visibility (SD) at sampling stations in Lake Simcoe for 4-year pre- and post zebra mussel time periods (1991-1994 vs 1996-1999). Because it was a transition year during the establishment of zebra mussels, 1995 was omitted from the analyses. Step trend analysis (Cluis *et al.* 1989) was based on grouping the data for each variable into three intervals for each May-October period of measurement (i.e. the means for the pre and post zebra mussel comparisons were comprised of 12 data values each. Asterisks indicate level of significant change (see footnote[2]).

Location	Four-Year Means Pre- and Post Zebra Mussel Establishment						RMSE[3]		
	TP (mg/L)		Chl *a* (µg/L)		SD (m)		TP	Chl *a*	SD
	1991-1994	1996-1999	1991-1994	1996-1999	1991-1994	1996-1999	(mg/L)	(µg/L)	(m)
C1	0.025	0.020 **	5.11	3.39 **	1.96	(-)[1]	0.009	3.49	NA
C6	0.022	0.015 *	3.47	2.91 ns	3.07	4.55 **	0.005	NA	0.78
C9	0.018	0.013 **	2.48	2.38 ns	3.91	5.48 *	0.003	NA	0.92
S15	0.015	0.011 *	1.70	2.13 ns	4.43	6.15 **	0.006	NA	1.27
E50	0.016	0.011 **	1.91	1.44 ns	3.46	5.78 *	0.004	NA	1.16
E51	0.014	0.011 **	1.98	1.78 ns	3.92	6.48 **	0.003	NA	1.25
N31	0.017	0.010 *	2.10	1.48 *	4.01	6.79 **	0.005	0.75	1.26
N32	0.019	0.015 ns	2.12	1.89 ns	3.43	(-)[1]	NA	NA	-
K38	0.016	0.013 ns	2.09	2.44 ns	4.51	6.02 *	NA	NA	1.03
K39	0.016	0.013 ns	2.05	2.31 ns	4.61	6.17 *	NA	NA	1.02
K42	0.016	0.015 ns	1.6	2.17 ns	4.61	5.89 *	NA	0.58	1.02
K45	0.016	0.017 ns	1.8	2.28 ns	4.9	6.00 *	NA	NA	I.48

1 The Secchi disk was visible on the lake bottom (non-valid reading) at Stations C1 and N32 on many sampling dates after 1995, so tests for step trends could not be done.

2 Significance of the step trend indicated by *** (*P* ≤ 0.001), ** (*P*≤ 0.01),* (*P* ≤ 0.05), or ns (*P* >0.05). When the trend is not significant (ns), then the RMSE entry is not applicable (NA).

3 RMSE (root mean square error) is a measure of the precision of the stepwise trend model for the time interval indicated.

Appendix Table 1. Replacement of total phosphorus (TP) and chlorophyll *a* (Chl *a)* outliers by linear interpolation (see Methods for details).

Station	Date	Original TP Value(mg/L)	Replacement TP Value (mg/L)
C6	21 July, 1980	0.119	0.025
C6	11 June, 1994	0.178	0.018
C6	11 October, 1994	0.310	0.031
C9	21 July, 1980	0.119	0.015
C9	22 August, 1994	0.198	0.020
E51	4 July, 1989	0.169	0.013
E51	6 May, 1992	0.156	0.012
S15	28 May, 1991	0.145	0.011
S15	5 May, 1995	0.128	0.016
K39	22 June, 1976	0.160	0.012
K45	16 August, 1988	0	0.021
K45	29 August, 1988	0	0.014
K45	6 May, 1992	0	0.015
K45	5 August, 1992	0.135	0.013
K45	30 May, 1993	0.176	0.012
N31	26 September, 1993	0	0.020

Station	Date	Original Chl *a* Value (µg/L)	Replacement Chl *a* Value (µg/L)
C9	2 October, 1984	0	4.3

Appendix Table 2. Replacement of total phosphorus (TP) outliers in the data sets from the four Lake Simcoe water intakes. Sampling at Brechin was discontinued after September, 1997 to accommodate curtailment of laboratory analytical capacity at the MOE's Laboratory Services Branch.

Water Intake Sampling Location	Date	Original TP Value(mg/L)	Replacement TP Value (mg/L)
Beaverton	16 August, 1982	0.108	0.03
Beaverton	7 September, 1982	0.177	0.04
Beaverton	10 January, 1984	0.130	0.013
Beaverton	27 July, 1987	0	0.016
Beaverton	16 September, 1991	0	0.008
Beaverton	14 December, 1994	0.108	0.03
Brechin	6 March, 1984	0	0.01
Brechin	22 May, 1984	0	0.013
Brechin	9 February, 1987	0	0.006
Brechin	27 July, 1987	0	0.016
Brechin	29 August, 1988	0	0.008
Brechin	12 December, 1994	0.088	0.03
Sutton	3 August, 1982	0.110	0.017
Sutton	17 August, 1982	0.093	0.013
Sutton	9 April, 1990	0	0.012
Sutton	12 August, 1991	0	0.006
Sutton	29 November, 1993	0	0.019
Sutton	13 December, 1994	0.138	0.05
Sutton	2 September, 1996	0.098	0.04
Sutton	2 July, 1997	0.140	0.014
Keswick	23 September, 1986	0	0.013
Keswick	29 November, 1993	0	0.036
Keswick	24 June, 1996	0	0.014