Lake Simcoe Environmental Management Strategy

Implementation Program

Water Quality Trends in Lake Simcoe, 1972-1990

Implications For Basin Planning and Limnological Research Needs

Technical Report: Imp. B.13

1992

WATER QUALITY TRENDS IN LAKE SIMCOE 1972-1990, IMPLICATIONS FOR BASIN PLANNING AND LIMNOLOGICAL RESEARCH NEEDS [1]

Prepared by

K.H. Nicholls
Limnology Section
Water Resources Branch
Ontario Ministry of the Environment
October, 1991

for

The Lake Simcoe Environmental
Management Strategy
Technical Committee

LSEMS Implementation Technical Report No. B.13

---

[1] Based on a presentation made at the Lake Simcoe Conference and Festival, Baldwin, Ontario, June 7-8, 1991.

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 Committee, comprised of representatives of the following agencies:

- Ministry of Agriculture, Food and Rural Affairs;
- Ministry of the Environment and Energy;
- Ministry of Natural Resources; and
- Lake Simcoe Region Conservation Authority.

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 named lead agency to coordinate the LSEMS Implementation Program, a five year plan to improve the water quality of Lake Simcoe. The Conservation Authority will have overall coordination responsibilities as outlined in the LSEMS Cabinet Submission and subsequent agreement (Recommendation E.1). At the completion of the five year plan (1994) a report will be submitted to the Cabinet. This report will outline the activities and progress of the LSEMS Implementation Program during its five years. After reviewing the progress of the program the Cabinet may continue the implementation program.

The goal of the LSEMS Implementation Program is to improve the water quality and natural coldwater fishery of Lake Simcoe by reducing the phosphorus loading to the lake. The LSEMS Implementation Program will 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 of 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:

Supervisor of Environmental Services
Lake Simcoe Region Conservation Authority
120 Bayview Parkway
P.O. Box 282
Newmarket, Ontario.
L3Y 4X1

OR

Chief Administrative Officer
Lake Simcoe Region Conservation Authority
120 Bayview Parkway
P.O. Box 282
Newmarket, Ontario.
L3Y 4X1

DISCLAIMER

The material presented in these reports is analytical support information and does not necessarily constitute policy or approved management priorities of the Province or the Conservation Authority and/or the evaluation of the data and findings, should not be based solely on this specific report. Instead they should be analyzed in light of other reports produced within the comprehensive framework of this environmental management strategy and the implementation of the recommendations.

Reference to equipment, brand names or suppliers in this publication is not to be interpreted as an endorsement of that product or supplier by the authors, the Ministries of Agriculture, Food and Rural Affairs, Environment and Energy or Natural Resources or the Lake Simcoe Region Conservation Authority.

Abstract

An overview of recent limnological findings is presented with emphasis on the long-term record of dissolved oxygen, nutrients, phytoplankton, and chloride trends for Lake Simcoe. The main sampling efforts have included visits to 10-12 sites every 2-3 weeks during the May-October periods and weekly, year-round collections of nearshore samples from four municipal water supply intakes. Major improvements in water quality have not yet occurred in response to nutrient loading controls initiated during the last two decades. However, there is some evidence of lower total phosphorus concentrations at all lake locations during the late 1980s. Phosphorus release from anoxic bottom sediments during late summer may retard recovery of the lake. The rate of increase of chloride in the Lake Simcoe outflow and in samples collected from municipal water supply intakes averaged 0.4-0.6 mg/L/yr over the past 20 years and likely reflects expanding urbanization in the Lake Simcoe basin. Some thoughts on future surveillance, research and planning needs are also presented.

Table of Contents

Introduction

Excluding the Laurentian Great Lakes, Lake Simcoe is the largest lake in southern Ontario (Fig. 1). Because it is located within one hour's drive of more than one-half of Ontario's total population, it is an extremely valuable resource.

The first comprehensive set of water quality data on Lake Simcoe was collected during 1971-1974 (Ralston *et al.*, 1975). Monitoring continued at a less intensive level until 1979 when the Provincial Cabinet Committee for Resources Development called for an additional five years of monitoring. This 1980-1984 period of monitoring was incorporated into the LSEMS (Lake Simcoe Environmental Management Strategy) programme, which again included as one of its final recommendations the need for continued monitoring (LSEMS, 1985). Since 1985, the Ontario Ministry of the Environment, in collaboration with the Ministry of Natural Resources and the Lake Simcoe Region Conservation Authority, has continued to monitor the lake and has conducted a number of special studies designed to help understand aspects of the lake's biology and chemistry (Table 1). The purpose of this report is to provide a documentation of the information presented June 7, 1991 at the Lake Simcoe Conference and Festival (Baldwin), sponsored by the South Lake Simcoe Naturalists' Club, to which the author was invited as a program participant and speaker.

Methods

Sampling locations (Fig. 1) and analytical methods are as described by Humber and Foy (1985). In addition, the Ontario Ministry of the Environment has had a regular sampling programme at the Atherley "narrows" since 1982 in order to characterize the outflow water quality of the lake and to calculate the total mass of phosphorus and other materials exported from the lake. These data supplement longer term data collected less frequently at the same location under the Ministry's rivers monitoring programme (Harangoso, 1991). In 1982, an intake sampling programme was initiated at three municipal water supply intakes (Sutton, Beaverton and Brechin) with a fourth (Keswick) added in 1984 (Fig. 1). Weekly sampling of "raw" (untreated) water at these sites year-round enables data to be collected on near-shore water at times of the year when conventional, sampling is not possible.

Results and Discussion

Programme Overview

A number of monitoring and research activities have been completed or are still in progress (Table 1). All activities were initiated in order to track long-term water quality and to enhance understanding of the lake and its biota, thereby facilitating the interpretation of the long-term data.

Dissolved Oxygen

Dissolved oxygen is one of the most important water quality variables in Lake Simcoe. The effects of seasonal depletions in the bottom waters of the deeper areas of the lake are believed to influence the habits and health of fish populations, especially lake trout (MacLean *et al.*, 1981). Some details of the seasonality of oxygen depletion with reference to thermal stratification and temperature effects on depletion rates have been presented in Ralston *et al.* (1975), Willox (1982), Waring (1986) and Butterwick (1987). During the past decade, dissolved oxygen concentrations at the deep sites in Kempenfelt Bay and the main lake have declined steadily throughout the summer periods to levels of about 2 mg/L or less by late September of most years (Fig. 2).

Depletion rates during early summer in Cook's Bay (Fig. 3) have been nearly identical to those recorded for the deeper stations but an earlier breakdown of thermal stratification in late summer leads to earlier replenishment of bottom water dissolved oxygen levels in Cook's Bay (Fig. 3).

Depletion rates at the three deepest sampling locations have ranged from a low of 0.033 mg/L/day at Station K39 in 1982, to a high of 0.116 mg/L/day at Station K45 in 1987. While no long term trend is apparent, the year-to-year fluctuations are large, but consistent between stations (Fig. 4).

Predictive modelling of temperature, sediment oxygen demand, phosphorus loading and other factors influencing bottom water oxygen depletion rates is in progress (Table 1, Activity No. 10). The intent is to determine if phosphorus loading objectives can be developed which will achieve significantly reduced oxygen depletion rates.

Phosphorus and Related Variables

An account of the most important external sources of phosphorus for Lake Simcoe has been given in LSEMS (1985). In summary, total P loads from urban point-sources alone averaged 23 tonnes per year during the early 1980s. These inputs included treated sewage effluent (secondary treatment plus P removal) discharged directly to the lake as well as discharge from some municipalities to rivers and streams flowing into Lake Simcoe. Total phosphorus inputs to the lake from all external sources ranged between 68 and 103 tonnes and averaged 82 T/yr over the period 1982-1984. One additional source of phosphorus not included previously, is the release of P from lake bottom sediments.

Although not a true "source", because it represents a recycling of P previously supplied to the lake, the implications for lake recovery, as external supplies of P are reduced, may be significant. Phosphorus concentrations typically in the range of 40 to 100 µg P/L have been found at one metre above bottom at the deepwater stations in late summer after dissolved oxygen concentrations fall below about 2 mg/L (Fig. 5). As the lake mixes in the fall, this new supply of phosphorus is potentially available for algae growth. Indeed, the intake data have shown that the highest phytoplankton densities in Lake Simcoe have been in late fall (Fig. 6).

Under winter ice cover, most of this phytoplankton biomass sinks to the lake sediments where its decomposition contributes to dissolved oxygen depletion during winter and the following summer (augmented with fresh inputs of sedimenting phytoplankton grown on spring and summer supplies of P from the watershed). So, the cycle of P supply, phytoplankton growth, decomposition, dissolved about 15 µg/L by the mid-1980s (Fig. 8). This trend to declining concentrations was evident during the 1980s at all of the main lake sampling stations where the average May to October total P concentration during the latter half of the decade was between eight and 45 percent lower than during the 1980-85 period (Fig. 9). Although more detailed analysis of these trends is necessary, preliminary results suggest that the November to April levels may not have decreased because the intake data collected year-round since 1982 show no apparent trend (Fig. 10).

In Cook's Bay, it is possible that the declining total P concentrations during the ice-free periods of the 1980s has resulted in improved water quality since water clarity (Secchi disc visibility) has increased in recent years (Fig. 11). This trend reflects the decline in total phosphorus concentrations observed over the same time period (Fig. 12) and may be related to the diversion of treated sewage wastes from the towns of Aurora and Newmarket in 1984 (LSEMS, 1985). An additional response to improved water clarity in Cook's Bay may have been the apparent expansion of rooted macrophytes observed in 1987 over 1984 (Limnos Ltd., 1988a). These studies also demonstrated that the Cook's Bay macrophytes had not become phosphorus limited in response to the decreased phosphorus supplies from the Holland River, undoubtedly because these aquatic plants obtain most of their nutrient requirements through their root systems in the sediments.

Continued urbanization of the Lake Simcoe basin in recent years has not resulted in a measurable increase in nutrient and algae levels probably because improved sewage treatment and phosphorus removal at major point-sources (LSEMS, 1985) to some extent balanced any additional loads associated with urbanization. One apparent effect of this urbanization in the basin has been a steady increase in the chloride concentrations of Lake Simcoe. Over the period 1971 to 1987, chloride concentrations in the Lake Simcoe outflow increased at about 0.6 mg/L per year (Fig. 13). This trend was also apparent at Lake Simcoe municipal water supply intakes (Fig. 14) where rates of increase were between 0.42 and 0.55 mg/L per year. This is in sharp contrast to the recently reported declines in Lake Erie of 0.7 mg/L per year (Whyte *et al.* 1990). Unlike the Lake Erie situation, where a significant portion of the total salt input was of industrial origin, there are no known industrial sources of chloride in the Lake Simcoe basin and it is presumed that the increased chloride concentrations in the lake reflect an expanding urban area and associated winter road de-icing operations.

While no major ecological damage can generally be anticipated from chloride increases of this magnitude, there have been a number of halophilic algal species, apparently of marine or brackish water origins, which have invaded local areas of the lower. Great Lakes (Sheath 1987), perhaps in response to chloride increases during this century of about 20 mg/L. One such species is the red alga *Bangia*, which is known to have a restricted presence in Lake Simcoe (Jackson, 1985). Its distribution and abundance may increase in the future in response to rising chloride concentrations, since other essential factors such as availability of suitable shoreline substrate and nutrient supplies presently appear adequate to support its growth in Lake Simcoe.

Future Directions

Limnological Monitoring and Surveillance

Like the patient with an illness who has been prescribed therapy and has been set on the road to recovery, regular checkups (sampling of key indices of lake ecosystem health) are mandatory. "**It is difficult to protect an ecosystem in the absence of a continual or regular flow of information about its 'health' and condition**" - John Cairns Jr.

The regular collection of environmental data on Lake Simcoe is essential. Monitoring and surveillance activities must be backed up by the scientific strengths to interpret and communicate the findings effectively. At the present time (1991), the agencies collaborating on the LSEMS programme are well along the path to implementing the more than 20 recommendations made in the final report of the Steering Committee (LSEMS, 1985), which range from specific remedial actions to policy and scientific issues. Commitments of staff time and funding have been made (within the constraints of the annual fiscal process) to continue this work until 1994.

Clearly, many of Lake Simcoe's anthropogenic stresses will still be in place by 1994. In the face of continued future pressures to urbanize the watershed, a longterm plan is needed for basin management and continued control of nutrient inputs beyond those short term phosphorus loading targets set down by LSEMS (1985). Limnological surveillance of the lake must become an accepted requirement for the 1990s and beyond.

Research

At the present time, there are many inadequacies in our understanding of the functioning of Lake Simcoe. The dividing line between research, especially time-trend research, and surveillance should not be a barrier between the two endeavours; one activity supports the other. Time-trend related research is a critical and integral part of the overall responsibility to protect Lake Simcoe. Some apparently simple relationships, for example the total P / chlorophyll / Secchi disc relationship so integral to assessments of lake trophic state (Dillon and Rigler, 1975; Canfield and Bachman, 1981), require special care in interpretation in Lake Simcoe's case. This is because Lake Simcoe is a marl lake (its sediments are 50% $CaCO_3$ by weight), which experiences summertime "whitings" when water clarity is influenced by calcite precipitation.

Calcite precipitation in Lake Simcoe likely plays some role in phosphate binding and sedimentation (House, 1990), but the factors controlling calcite precipitation in Lake Simcoe are not known. In other lakes, the phenomenon is closely tied to plant and algae growth and is even indirectly influenced by fish predation and aquatic food web interactions (Hanson *et al.*, 1990). An understanding of the role of calcite precipitation as it interacts with trophic status regulation (Koschel *et al.*, 1983) would seem to be critical to any interpretation of trends in total P concentrations and water clarity in Lake Simcoe.

One of the most critical research needs for Lake Simcoe is the development of a clearer understanding of the causal relationships between phosphorus loading, organic matter production and decomposition and hypolimnetic dissolved oxygen deficits. The prediction of dissolved oxygen depletion is a challenge facing limnologists worldwide (Cornett and Rigler, 1979) and is certainly not a problem peculiar to Lake Simcoe. The links to phosphorus loading (Welch and Perkins, 1979; Rydberg *et al.*, 1990; Chapra and Canale, 1991) are especially critical because predictive modelling successes in this area will offer a framework for setting tolerable phosphorus loading limits to lakes.

Research specific to Lake Simcoe is needed on the role of the deepwater sediments as a long term sink and short term source of nutrients and contaminants (Johnson and Nicholls, 1988, 1989) with special attention on finding the critical P sedimentation rate associated with redox-related P release (Nurnberg, 1991). Understanding of the sediment-water interface as a regulator of lakewater concentrations of dissolved materials (especially microbiologically mediated transformations) is still rather poor (Daumas, 1990). Sediment oxygen demand and its carry-over effects from season to season and from year to year (Graneli, 1978) may need to be experimentally defined for Lake Simcoe under different phosphorus loading / primary production Simcoe is the development of a clearer understanding of the causal relationships between phosphorus loading, organic matter production and decomposition and hypolimnetic dissolved oxygen deficits.

The prediction of dissolved oxygen depletion is a challenge facing limnologists worldwide (Cornett and Rigler, 1979) and is certainly not a problem peculiar to Lake Simcoe. The links to phosphorus loading (Welch and Perkins, 1979; Rydberg *et al.*, 1990; Chapra and Canale, 1991) are especially critical because predictive modelling successes in this area will offer a framework for setting tolerable phosphorus loading limits to lakes.

Research specific to Lake Simcoe is needed on the role of the deepwater sediments as a long term sink and short term source of nutrients and contaminants (Johnson and Nicholls, 1988, 1989) with special attention on finding the critical P sedimentation rate associated with redox-related P release (Nurnberg, 1991). Understanding of the

sediment-water interface as a regulator of lakewater concentrations of dissolved materials (especially microbiologically mediated transformations) is still rather poor (Daumas, 1990). Sediment oxygen demand and its carry-over effects from season to season and from year to year (Graneli, 1978) may need to be experimentally defined for Lake Simcoe under different phosphorus loading / primary production scenarios to facilitate the P loading - oxygen deficit modelling.

At the present time, the complexity of these modelling efforts sometimes appears to result in progress at a frustratingly slow pace. But what are the alternatives? Uncovering the hidden processes involved in the functioning of a lake can be painstakingly slow because water residence times, adjustments in sediment-water exchange equilibria and life histories of key biota are often in the order of years, as opposed to time frames of hours or days for the critical parameters in most laboratory research. In the absence of long term ecological research, serious misjudgements can occur in attempts to manage natural systems (Magnuson, 1990). It is also evident that limnological research that produces better information on the relationships between structure and function of aquatic ecosystems has clear cost benefits for monitoring and lake and watershed management (Forsberg, 1982).

Longterm Planning

In the absence of scientifically defensible longterm objectives for phosphorus loading to Lake Simcoe, the LSEMS Implementation programme has established an interim requirement for no net increase in loadings to the lake from point-sources in the basin beyond those inputs presently set by the design capacity of existing sewage treatment plants and present-day phosphorus removal technology (for the Lake Simcoe basin, 0.3 mg P/L or less in treated effluent). As well, Provincial agricultural pollution control initiatives, such as "Land Stewardship II" and "Food Systems 2000" programmes, should result in decreased use of agricultural chemicals and control of manure leachate and streambank erosional inputs to Lake Simcoe.

However, a longer term basin planning framework is needed which will ensure that nutrient and sediment inputs are further reduced and that watershed protection and enhancement initiatives are stimulated, especially with regard to the rejuvenation of natural vegetation along water courses. Further urbanization in the Lake Simcoe basin must be consistent with the spirit and intent of the "environmentally sustainable development" philosophy with due respect for the preservation of natural areas (Epp, 1990) and the development of innovative technologies for waste treatment *(e.g.* Teal and Peterson, 1991).

The control of phosphorus loading may have immediate benefits for Lake Simcoe in terms of lower densities of suspended and attached algae, with resultant improvements in aesthetic values, drinking water quality and fish habitat, but the history of experiences with phosphorus control suggests that results are not always predictable (Cullen and Forsberg, 1988). Additional and perhaps more immediately effective remedial measures, such as direct supplementation of the presently seasonally limited bottom water dissolved oxygen reserves with hypolimnetic injection techniques may be required. While the capital and operating costs of such a system may appear daunting (Limnos Ltd., 1991), the costs of not attempting to correct damages caused by previous decades of abuse and neglect may be even more formidable in the long term.

Acknowledgements

Lynda Nakamoto computerized much of the Lake Simcoe database and prepared some of the figures used in this report. The Atherley chloride and total phosphorus data were compiled by staff of the Watershed Management Section, Ministry of the Environment and the trend lines for these data (Figs 8 and 13) were developed by Bill Snodgrass of Beak Consultants Ltd. Gord Hopkins provided data and computer generated plots from the Lake Simcoe water supply intake monitoring program. Many staff of the Lake Simcoe Region Conservation Authority, Central Region of the Ministry of the Environment, and the Fisheries Assessment Unit, Ministry of Natural Resources have assisted over the years in sample collection and other aspects of the Lake Simcoe programme. All chemical analysis have been performed by staff of the Laboratory Services Branch, Ontario Ministry of the Environment.

References

Angelow, R., and G.W. Robinson. 1985. *"Summer Nutrient Conditions in the Lower Holland River Prior to Diversion of Municipal Inputs."* LSEMS Technical Report No. B.3, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Beak Consultants Ltd. 1987. *"The Predictability of Hypolimnetic Dissolved Oxygen Depletion in Lake Simcoe as Related to Water Temperature, Nutrient Loading and Other Environmental Variables."* LSEMS Implementation Technical Report No.IMP.B2, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Beak Consultants Ltd. 1990. *"Hypolimnetic Oxygen Dynamics in Lake Simcoe: Part 2-Evaluation Using Time Trend and Model Simulation Techniques."* LSEMS Implementation Technical Report No.IMP.B8, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Butterwick, D. 1987. *"Dissolved Oxygen and Temperature Regimes for Lake Simcoe, 1984-1986."* Report No. 1987-3, Lake Simcoe Fisheries Assessment Unit, Ontario Ministry of Natural Resources, Toronto. 46p.

Canfield, D. E., and L. M. Hodgson. 1983. "Prediction of Secchi disc depths in Florida lakes: impact of algal biomass and organic color." *Hydrobiologia,* 99: 51-60.

Chapra, S. C., and R. P. Canale. 1991. Long-term phenomenological model of phosphorus and oxygen for Stratified lakes. *Water Res.* 25: 707-715.

Cornett, R. J., and F. H. Rigler. 1979. "Hypolimnetic oxygen deficits: their prediction and interpretation." *Science,* 205: 580-581.

Cullen, P. and C. Forsberg. 1988. "Experiences with reducing point sources of phosphorus to lakes." *Hydrobiologia,* 170: 321-336.

Cumming-Cockburn and Associates Ltd. 1987. *"Estimated Monthly Flows at Atherley, 1982-1986."* LSEMS Implementation Technical Report No.IMP.B3, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Cumming-Cockburn and Associates Ltd. 1991. "*Estimated Monthly Flows and Exports of Total Nitrogen and Phosphorus From Lake Simcoe at Atherley."* LSEMS Implementation Technical Report No.IMP.B12, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Dumas R. 1990. "Contribution of the water-sediment interface to the transformation of biogenic substances: application to nitrogen compounds." *Hydrobiologia,* 207: 15-29.

Dillon, P. J., and F. H. Rigler. 1975. "A simple method for predicting the capacity of a lake for development based on lake trophic status." *J. Fish. Res. Bd. Canada.,* 32: 1519-1531.

Epp, H. T. 1990. "Role of natural areas in river basin management." *Canadian Water Resources* Journal,15: 345355.

Forsberg, C. 1982. "Limnological research can improve and reduce the cost of monitoring and control of water quality." *Hydrobiologia,* 86: 143-146.

Graneli, W. 1978. " Sediment oxygen uptake in South Swedish lakes." *Oikos,* 30: 7-16.

Hanson, M. A., M. G. Butler, J. L. Richardson, and J. L. Anndt. 1990. "Indirect effects of fish predation on calcite supersaturation precipitation and turbidity in a shallow prairie lake." *Freshwater Biology,* 24:547556.

Harangoso, S. 1991. *"Water Quality Data for Ontario Lakes and Streams,* 1987." Water Resources Branch, Ontario Ministry of the Environment, Toronto. 489p.

House, W. A. 1990. "The prediction of phosphate coprecipitation with calcite in freshwaters." *Water Research,* 24: 1017-1023.

Hopkins, G. J., and L. Webb. 1990. *"Lake Simcoe Water. Quality Monitoring at Water Supply Intakes, 1982-1989."* LSEMS Implementation Technical Report No.IMP.B10, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Humber, J. and M. G. Foy. 1985. *"Water Quality Characteristics of Lake Simcoe, 1980-1984."* A report to the Steering Committee of the Lake Simcoe Environmental Management Strategy, *Technical Report No. B.1.* Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Jackson, M. B. 1982. "*Cladophora* in Lake Simcoe, 1976 and 1980." In *Water Quality Characteristics of Lake Simcoe 1980.* Chapter Three, pp. 67-97. Ontario Ministry of the Environment, Toronto.

Jackson, M. B. 1985. "The red alga *Bangia* in Lake Simcoe". *J. Great Lakes Res.,* 11: 179-181.

Johnson, M. G., and K. H. Nicholls. 1988. "Temporal and spatial trends in metal loads to sediments of Lake Simcoe, Ontario." *Water, Air and Soil Pollution,* 39:337-354.

Johnson, M. G., and K. H. Nicholls. 1989. "Temporal and spatial variability in sediment and phosphorus loads to Lake Simcoe, Ontario." *J. Great Lakes Res.,* 15: 265-228.

Limnos Ltd. 1988a. *"Aquatic Plants of Cook's Bay, Lake Simcoe, 1987."* LSEMS Implementation Tech. Report No. IMP. B4, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Limnos Ltd. 1988b. *"Duckweed Harvest From the Holland River - Recommendations for Harvesting Strategies, Disposal Options and Assessment of Benefits."* LSEMS Implementation Technical Report No. IMP. B5, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Limnos Ltd. 1988c. *"Assessment and Control of Duckweed in the Maskinonge River, Keswick, Ontario."* LSEMS Implementation Technical Report No.IMP.B6, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Limnos Ltd. 1990. *"Lake Simcoe Hypolimnion Aeration: An Assessment of the Potential for Direct Treatment of Oxygen Depleted Hypolimnetic Waters in Lake Simcoe."* LESEMS Implementation Technical Report No .IMP. B9, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Limnos Ltd. 1991. *"Dichotomosiphon tuberosus, a dominant benthic alga in Lake Simcoe: status in 1990."* LSEMS Implementation Technical Report No.IMP.B11, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

LSEMS (Lake Simcoe Environmental Management Strategy). 1985. *Final Report and Recommendations of the Steering Committee.* Government of Ontario / Lake Simcoe Region Conservation Authority, Newmarket, Ont.

MacLean, J. A., D. O. Evans, N. V. Martin, and R. L. Desjardine. 1981. "Survival, growth, spawning distribution and movements of introduced and native lake trout *(Salvalinus namaycush)* in two inland Ontario lakes." *Can. J. Fish. Aquat. Sci.,* 38: 1685-1700.

Magnuson, J. J. 1990. "Long-term ecological research and the invisible present." *BioScience,* 40: 496-501.

Neil, J.H., G.A. Kamaitus, and G.W. Robinson. 1985. "Aquatic *Plant Assessment in Cook's Bay, Lake Simcoe."* LSEMS Technical Report No. B.4, Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority, Newmarket, Ont.

Nicholls, K. H., F. M. Forbes, R. Shaw, J. Humber, and L. Nakamoto. 1985. "Phytoplankton of Lake Simcoe during the ice-free periods of 1980-82 and potential response to reduced phosphorus loadings." *J. Great Lakes Res.,* 11: 3-12.

Nurnberg, G. K. 1991. "Phosphorus from internal sources in the Great Lakes, and the concept of threshold external load." *J. Great Lakes Res.,* 17: 132-140.

Ontario Ministry of the Environment. 1978. *Mercury in the Lake Simcoe Aquatic Environment.* Ontario Ministry of the Environment, Water Resources Branch, Toronto, Ont. 31p.+ Appendices.

Ontario Ministry of the Environment. 1982. *Water Quality Characteristics of Lake Simcoe, 1980.* Ontario Ministry of the Environment, Toronto. 97p.

Ralston, J. G., S. M. Irwin, and D. M. Veal. 1975. *"Lake Simcoe Basin, a Water Quality and Use Study."* Ontario Ministry of the Environment, Toronto. 143p.

Rydberg, L., L. Edler, S. Floderus, and W. Graneli. 1990. "Interaction between the supply of nutrients, primary production, sedimentation and oxygen consumption in SE Kattegat." *Ambio,* 19: 134-141.

Sheath R. 1987. "Invasions into the Great Lakes by marine algae." *Arch. Hydrobiol. Beih.,* 25: 165-186.

Teal, J. M., and S. B. Peterson. 1991. "The next generation of septage treatment." *Research Journal WPCF,* 63: 84-89.

Waring, P. 1986. *"Dissolved Oxygen and Temperature Profiles at Two Lake Simcoe Limnological Stations, 1981-1983."* Lake Simcoe Fisheries Assessment Unit Report No. 1986-2. Ontario Ministry of Natural Resources, Toronto. 42p.

Whyte, R. S., J. H. Hartig, and G. J. Hopkins. 1990. "Decreasing chloride trends observed at Lake Erie municipal water intakes." *J. Great Lakes Res.,* 16: 233-240.

Welch, E. B., and M. A. Perkins. 1979. "Oxygen deficit-phosphorus loading relation in lakes." Journal WPCF,51:2823-2828.

Willox, C. 1982. *"The Dissolved Oxygen and Temperature Regimes of Lake Simcoe During the Summer of 1980."* Lake Simcoe Fisheries Assessment Unit, Report No. 82-1. Ontario Ministry if Natural Resources, Toronto. 92p.

Wilson, J. P. 1986. *"The Use of Statistical Models to Document Environmental Change in the Lake Simcoe Basin."* Ph.D. Thesis, Dept. of Geography, University of Toronto. 345p.

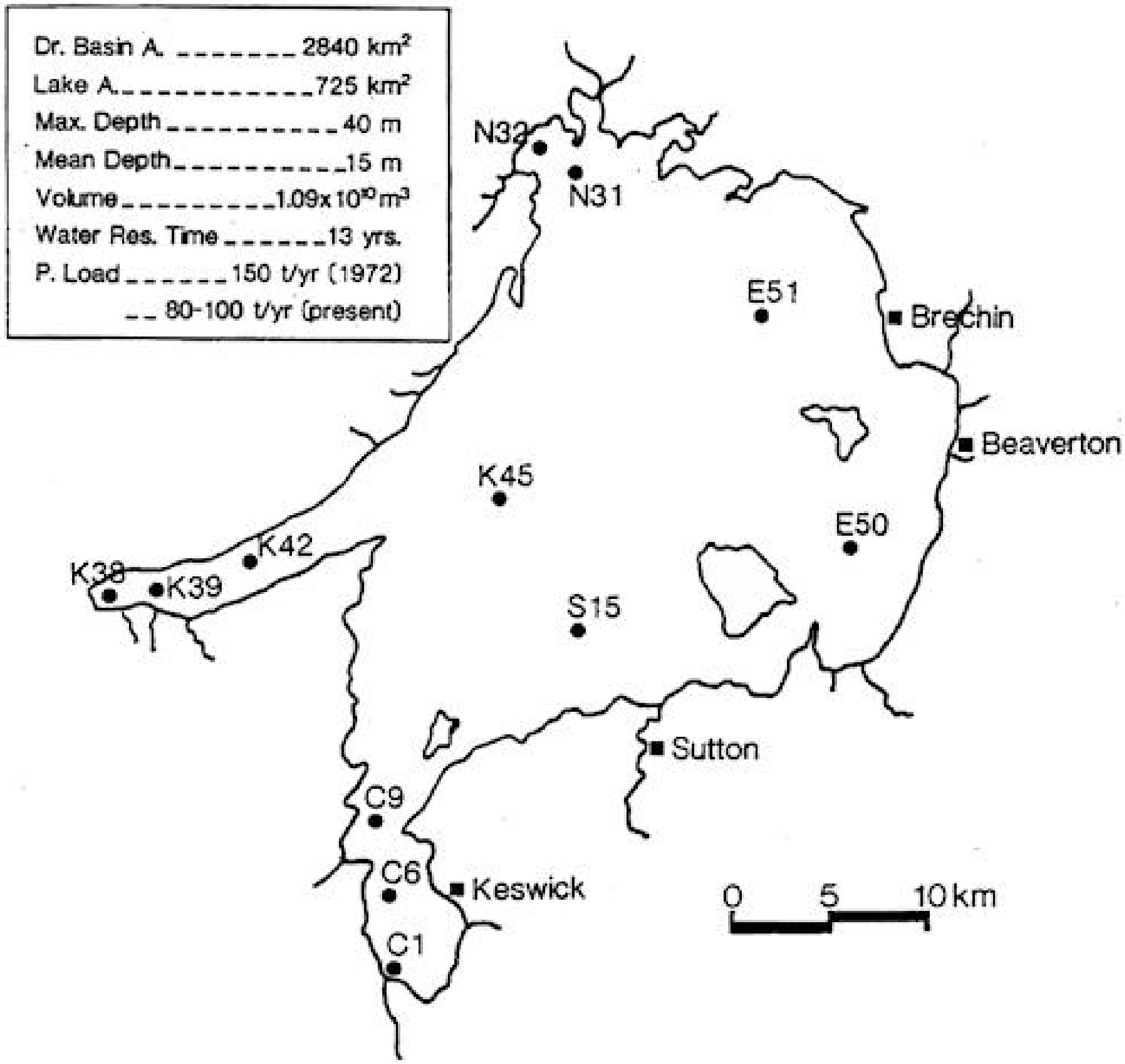

Fig. 1. Map of Lake Simcoe, showing the locations of the sampling stations and of the four locations (Keswick, Sutton, Beaverton and Brechin) where municipal water supplies (intake samples) are monitored regularly.

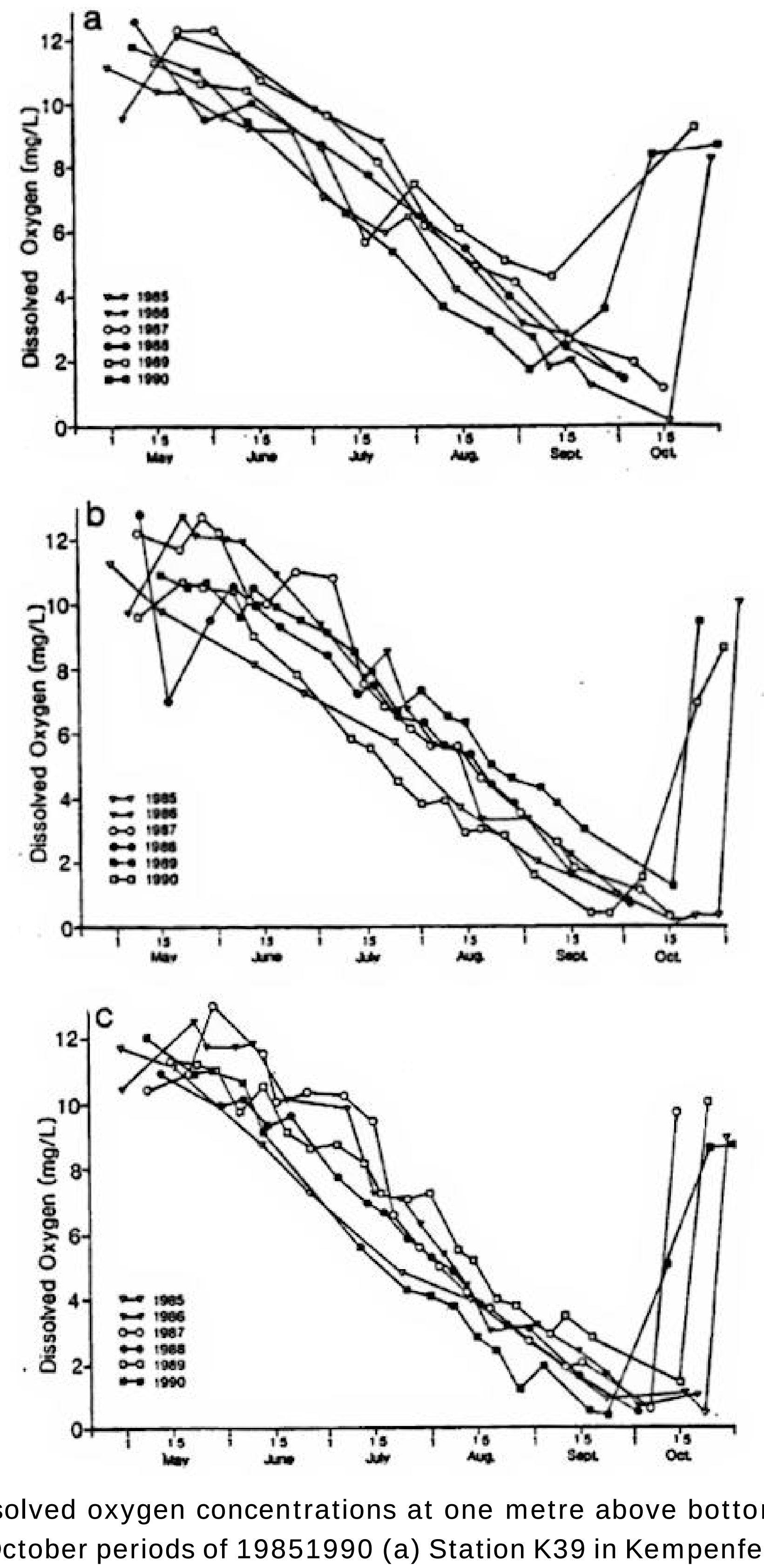

Fig. 2. Dissolved oxygen concentrations at one metre above bottom during the May to October periods of 19851990 (a) Station K39 in Kempenfelt Bay, (b) Station K42 in Kempenfelt Bay, and (c) Station K45 in the main lake.

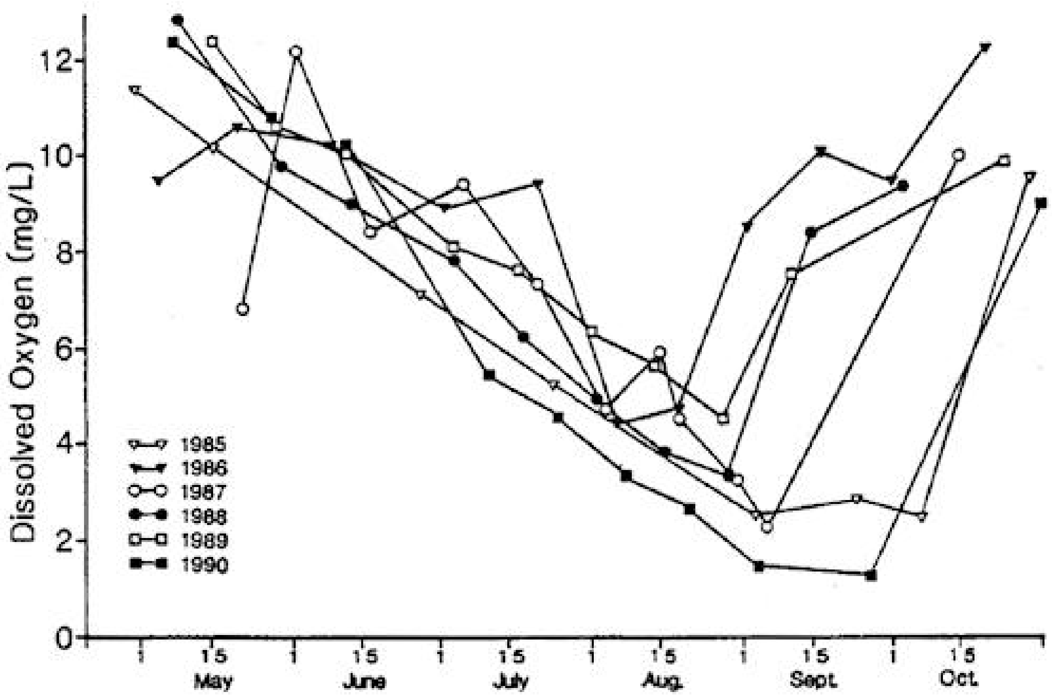

Fig. 3. Dissolved oxygen concentrations at one metre above bottom at Station C9 in Cook's Bay.

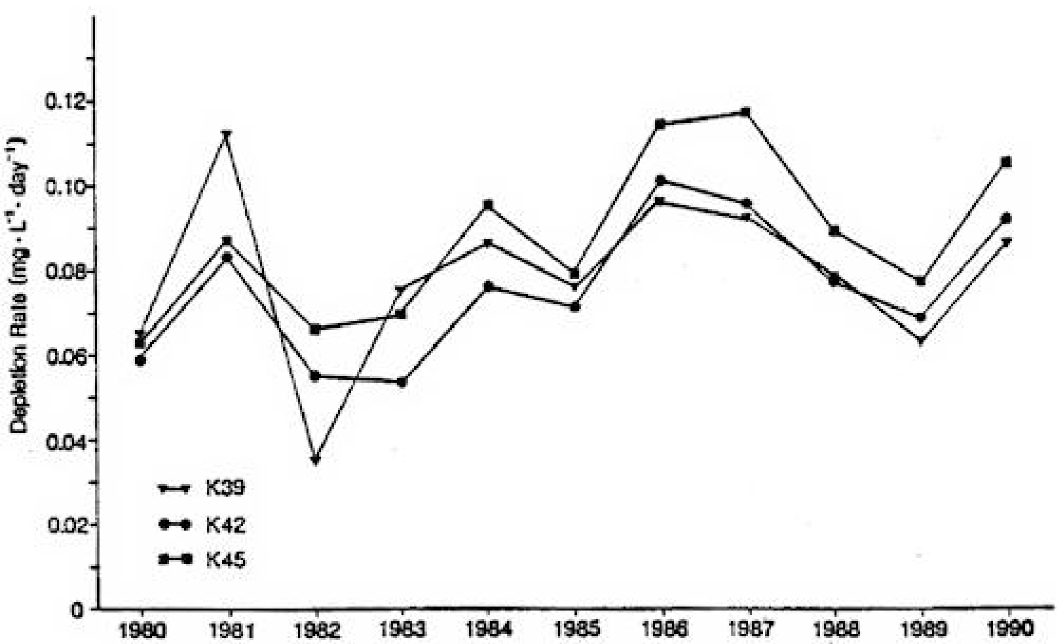

Fig. 4. Dissolved oxygen depletion rates at one metre above bottom at the three deepwater Stations in Lake Simcoe, 1980-1990. Rates were determined from the slopes of linear regression lines calculated from the June to September concentrations during each year.

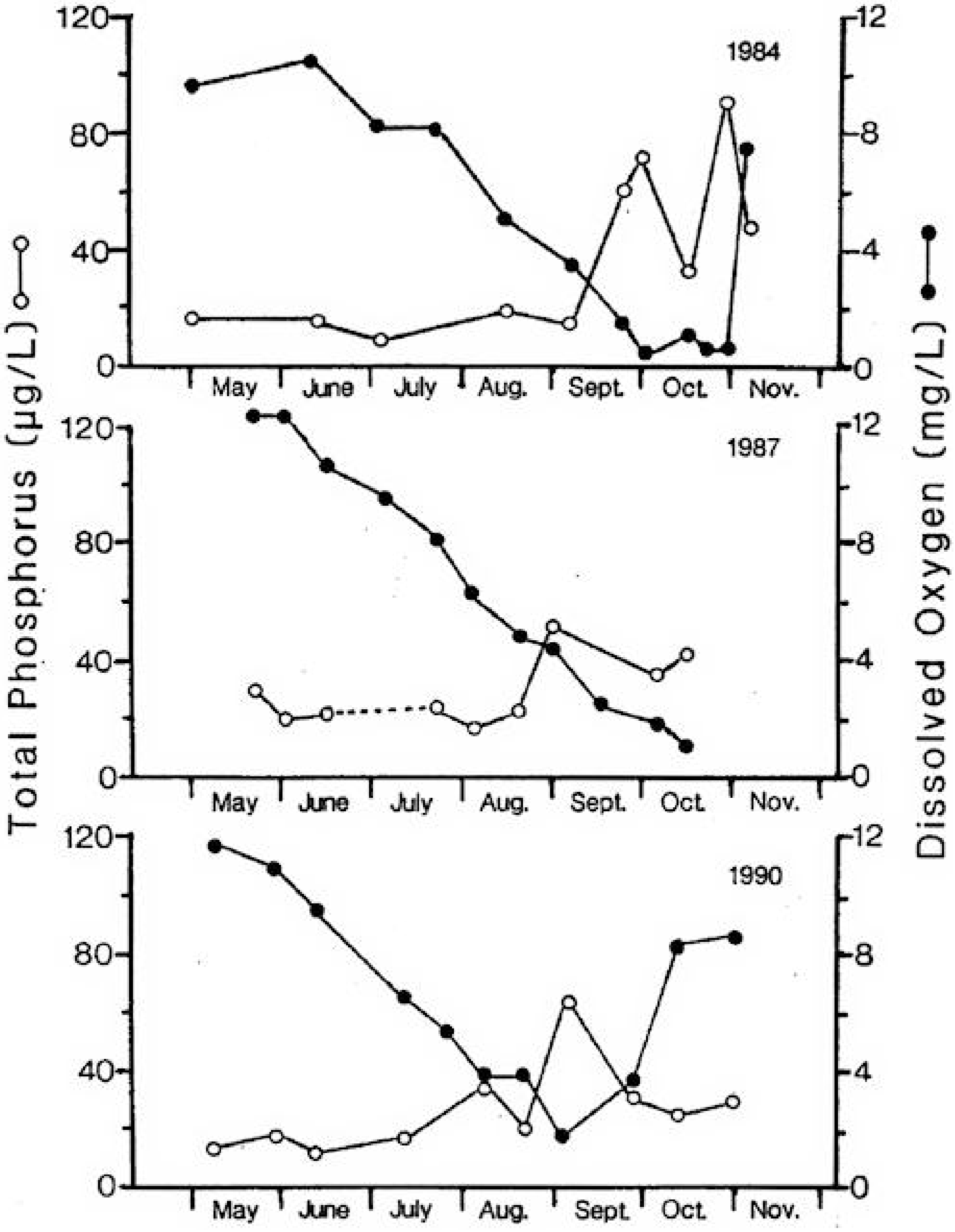

Fig. 5. Total phosphorus and dissolved oxygen concentrations at one metre above bottom at Station K39 in Kempenfelt Bay during 1984, 1987 and 1990.

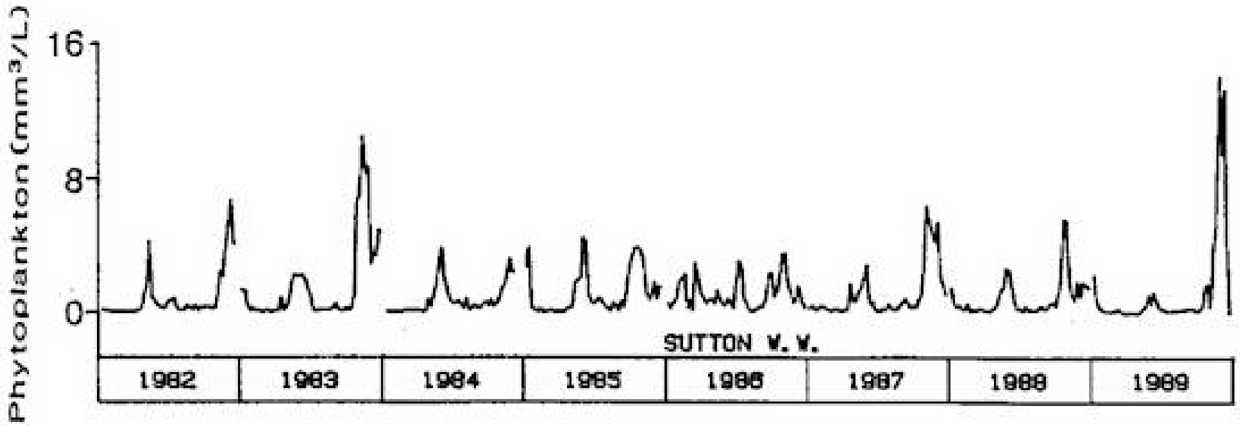

Fig. 6. Phytoplankton biovolume (mm^3/L) in samples collected weekly from the Sutton water supply intake, 1982 through 1989. Note that in most years the annual peaks are greatest in late fall.

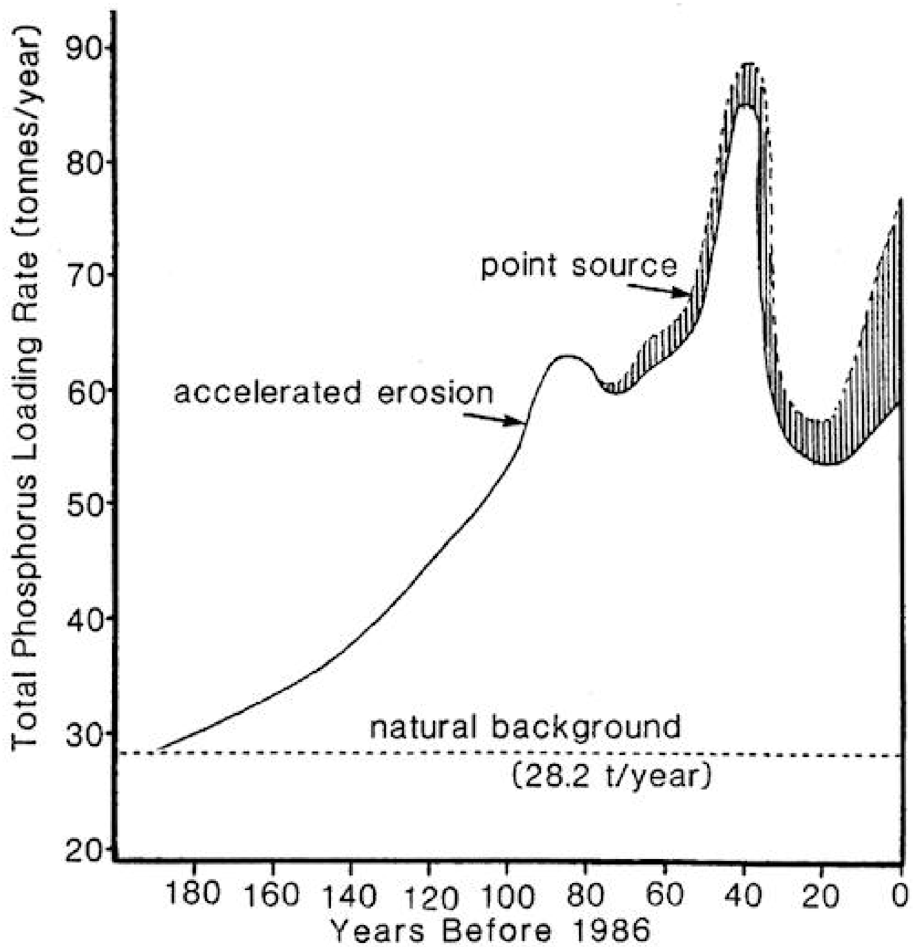

Fig. 7. Phosphorus loading rates (tonnes/year) from natural background, accelerated erosional and point sources to Lake Simcoe over the past two centuries (after Johnson and Nicholls (1989).

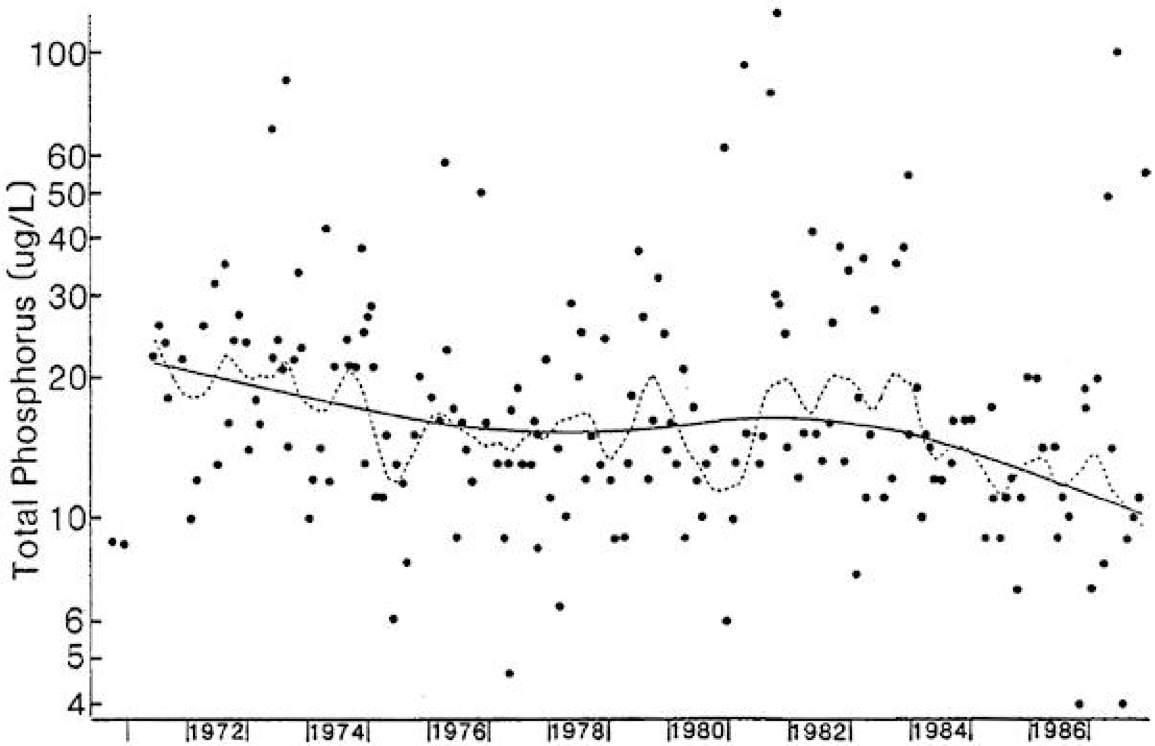

Fig. 8. Total phosphorus concentrations measured approximately monthly in the Lake Simcoe outflow at Atherley. The solid line is an overall smoothed trend line based on annual regression trend lines (the dotted line).

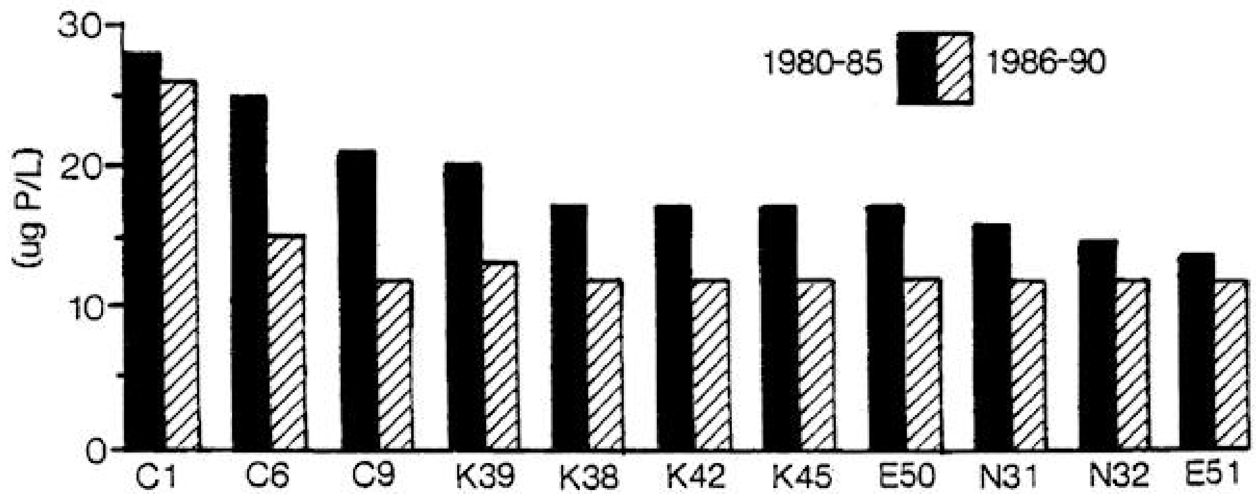

Fig. 9. May to October average total phosphorus concentrations at all Lake Simcoe sampling stations, 1980-1990.

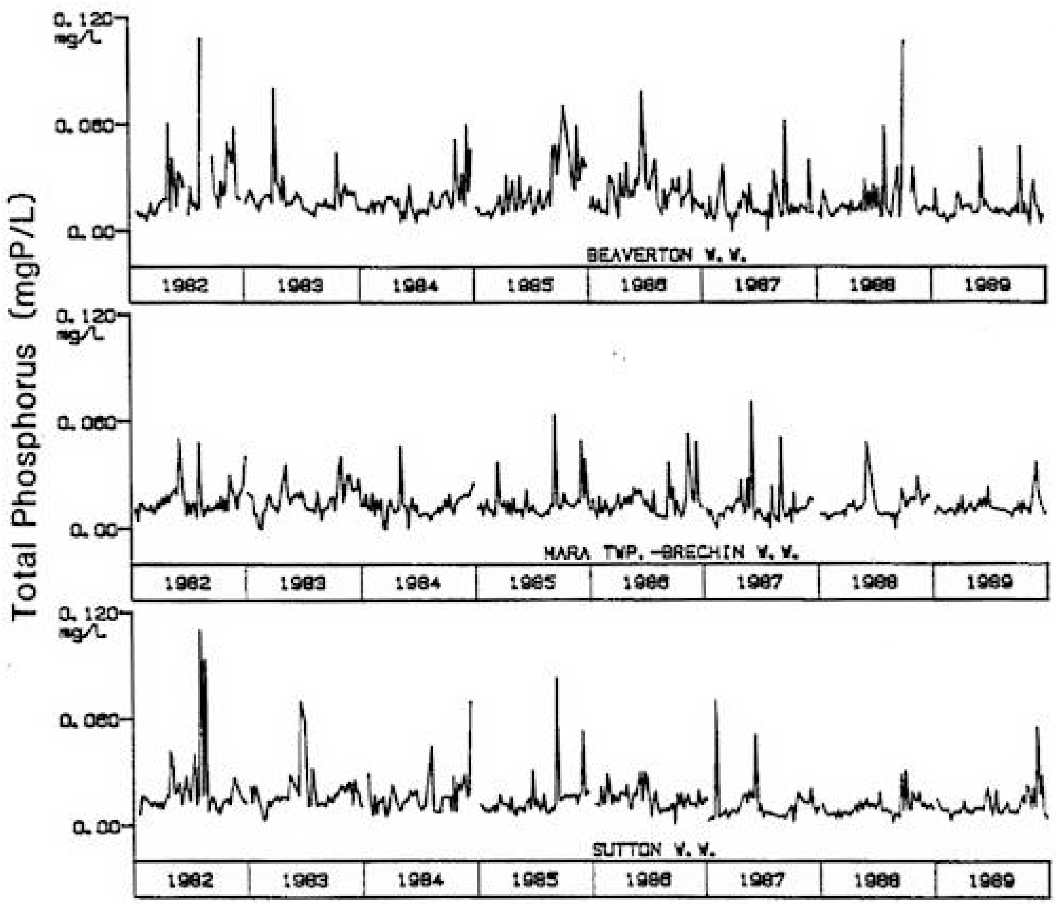

Fig. 10. Total phosphorus concentrations in samples collected weekly at the three main Lake Simcoe municipal water supply intakes, 1982-1989.

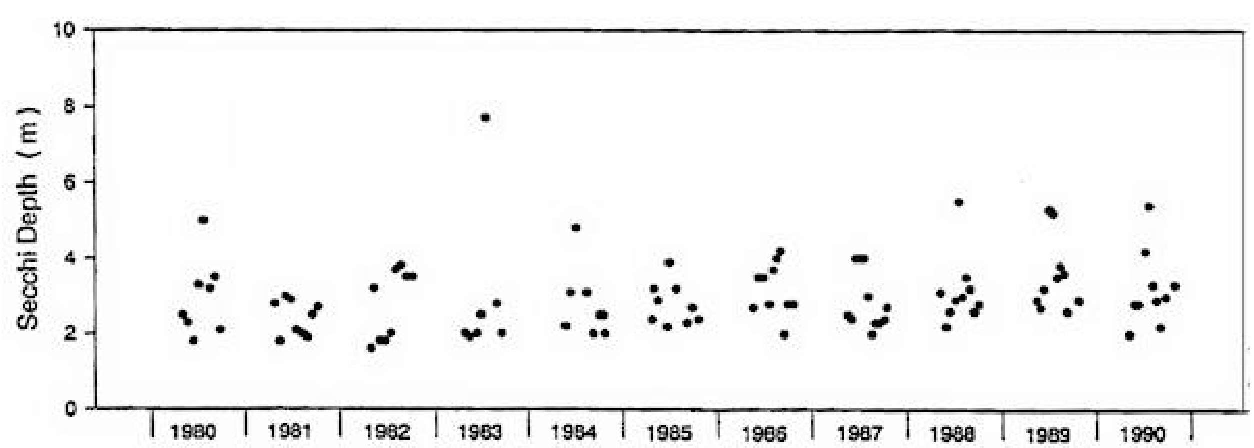

Fig. 11. May to October Secchi disc visibilities at Station 6 in Cook's Bay of Lake Simcoe, 1980-1990.

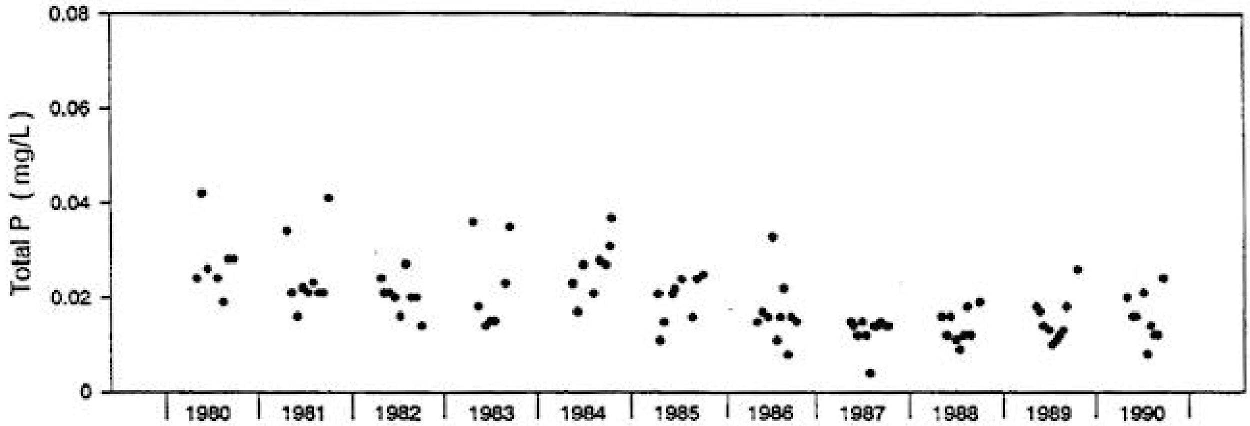

Fig. 12. May to October total phosphorus concentrations at Station 6 in Cook's Bay of Lake Simcoe, 1980-1990.

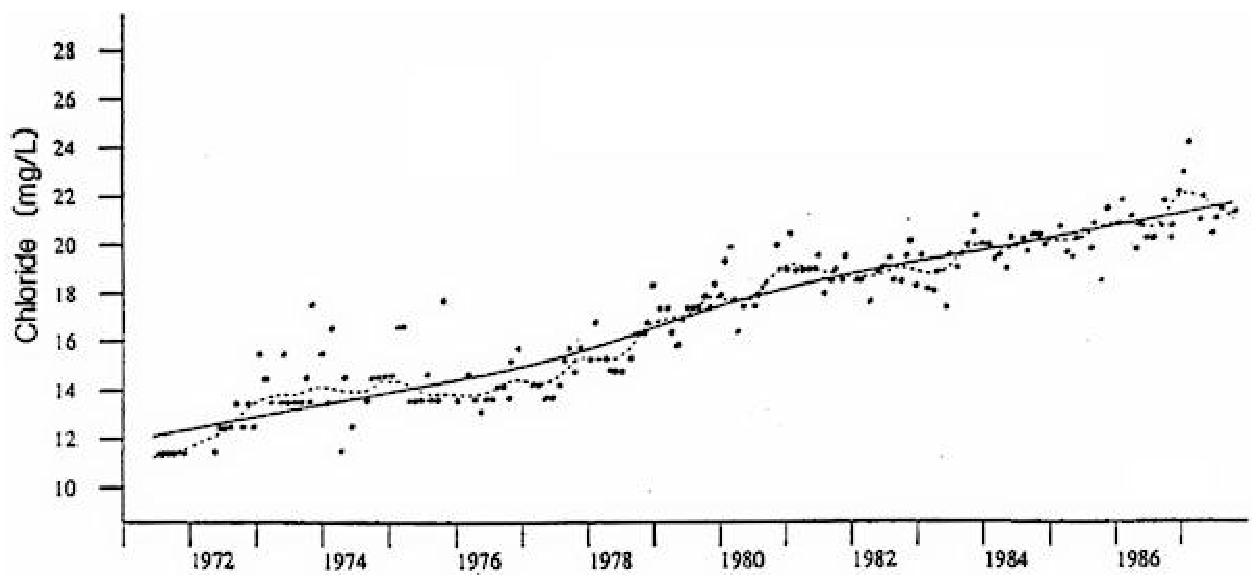

Fig. 13. Chloride concentrations measured approximately monthly in the Lake Simcoe outflow at Atherley, 1971-1987. The solid line is an overall smoothed trend line based on annual regression trend lines (the dotted line).

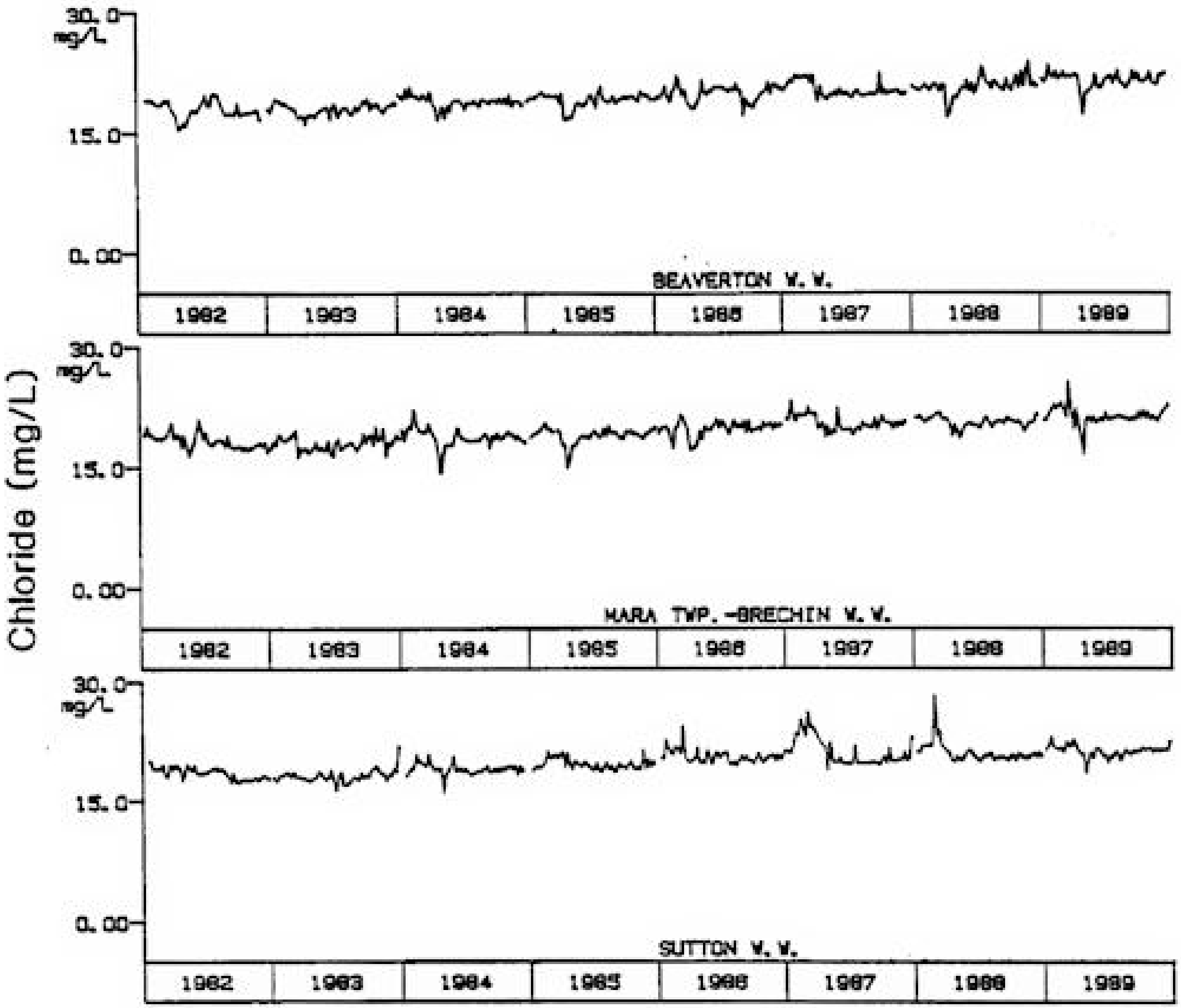

Fig. 14. Chloride concentrations in samples collected weekly at the three main Lake Simcoe municipal water supply intakes, 1982-1989.

TABLE 1. List of water quality monitoring and special study activities undertaken in Lake Simcoe by the Ontario Ministry of the Environment, 1971-1991.[1]

	ACTIVITY	PROGRAMME YEARS and Status of Data	REPORTS
1.	Tri-weekly sampling, May-October at fixed stations in the main lake, Kempenfelt Bay and Cook's Bay; temperature and dissolved oxygen profiles, phytoplankton and zooplankton (1980s only), chlorophyll a, dissolved and total forms of nitrogen and phosphorus, spec. conductance, pH, alkalinity, chloride	1971-1974; Water Resources Branch; data summaries only still exist. 1975-1979; Central Region; less intensive data. 1980-1984; Central Region; LSEMS Programme; all original data computerized. 1985-1990; Water Resources Branch, Inland Lakes Programme; all original data computerized. 1991-1994; Water Resources Branch; LSEMS Implementation Program in progress.	Ralston *et al.* (1975), Ont. Ministry of the Environment (1982), Nicholls *et al.* (1985), Humber and Foy (1985)
2.	Shoreline *Cladophora* survey (distribution, N, P, Hg and Pb levels)	1976 and 1980	Jackson (1982, 1985)
3.	Contaminants in sediments	1977 (mercury only) 1986 (phosphorus and several metals)	Ont. Ministry of the Environment (1978); Johnson and Nicholls (1988, 1989)
4.	S. Cook's Bay macrophyte surveys	1984, 1987	Neil *et al.* (1985); Limnos Ltd. (1988a)
5.	Main lake surveys of benthic algae (*Dichotomosiphon*)	1983, 1986, 1990	Neil, J.H., and Robinson (1985); Limnos Ltd. (1987, 1991)
6.	Initiation of municipal water intake sampling (weekly, year-round)	1982 at Beaverton, Brechin and Sutton, and 1983 at Keswick	Hopkins and Webb (1990)
7.	Intensive sampling at Atherley and estimates of N and P export	1983-present	Cumming Cockburn Ltd. (1987, 1991)
8.	Weekly sampling of the Lower Holland River and S. Cook's Bay-(parameter list as for Activity 1.)	1982-present	Angelow and Robinson (1985)
9.	Duckweed assessment, Holland and Maskinonge Rivers	1987	Limnos Ltd. (1988b, 1988c)
10.	Hypolimnetic dissolved oxygen modelling	1986-present	Beak Consultants Ltd. (1987, 1990)
11.	Feasibility study of hypolimnetic aeration	1989-1990	Limnos Ltd. (1990)

[1] Several of these activities have involved the cooperation and assistance of the Lake Simcoe Region Conservation Authority and the Ministry of Natural Resources.

APPENDIX

MEMBERSHIP ON THE STEERING COMMITTEE FOR THE LAKE SIMCOE ENVIRONMENTAL MANAGEMENT STRATEGY IMPLEMENTATION PROGRAM

D. Marquis, Lake Simcoe Region Conservation Authority (Chairman)
J. Barker, Maple District, Ministry of Natural Resources
E. Cavanagh, York County, Ministry of Agriculture and Food
R. DesJardine, Central Region, Ministry of Natural Resources (past member)
J. Kinkead, Watershed Management Branch, Ministry of the Environment (past member)
J. Merritt, Director - Central Region, Ministry of the Environment
P. Miller, Watershed Management Branch, Ministry of the Environment
A. Morton, Lake Simcoe Region Conservation Authority (past member)
B. Noels, Lake Simcoe Region Conservation Authority (Secretary)

APPENDIX

MEMBERSHIP ON THE TECHNICAL COMMITTEE FOR THE LAKE SIMCOE ENVIRONMENTAL MANAGEMENT STRATEGY IMPLEMENTATION PROGRAM

B. Noels, Lake Simcoe Region Conservation Authority (Chairman)
J. Beaver, Central Region, Ministry of the Environment (past member)
I. Buchanan, Maple District, Ministry of Natural
R. DesJardine, Central Region, Ministry of Natural Resources (past member)
J. Dobell, Huronia District, Ministry of Natural Resources
H. Farghaly, Central Region, Ministry of the Environment
D. Green, Resources Management Branch, Ministry of Agriculture and Food (past member)
B. Kemp, Lake Simcoe Region Conservation Authority
J. Kinkead, Watershed Management Section, Ministry of the Environment (past member)
R. MacGregor, Central Region, Ministry of Natural Resources (past member)
N. Moore, Victoria-Haliburton County, Ministry of Agriculture and Food
K. Nicholls, Water Resources Branch, Ministry of the Environment
B. Peterkin, Central Region, Ministry of Natural Resources
T. Rance, Maple District, Ministry of Natural Resources
B. Stone, Northumberland County, Ministry of Agriculture and Food
M. Walters, Lake Simcoe Region Conservation Authority
C. Willox, Lake Simcoe Fisheries Assessment Unit, Ministry of Natural Resources
K. Willson, Watershed Management Section, Ministry of the Environment

LAKE SIMCOE ENVIRONMENTAL MANAGEMENT STRATEGY

REPORTS

A. Land Sub-Group. 1985. Overview of Phosphorus Sources, Loads and Remedial Measures Studies.

A.1 Frank, D., D. Henry, J. Antoszek and F. Engler. 1985. " Lake Simcoe Tributary Water Quantity and Quality Data Report."

A.2 Frank, D., D. Henry, T. Chang and B. Yip. 1985. "Newmarket Urban Test Catchment Data Report."

A.3 Antoszek, J., T. Stam and D. Pritchard.1985. "Streambank Erosion Inventory. Volume I."

A.3 Antoszek, J., S. Meek, K. Butler and O. Kashef. 1985. "Streambank Erosion Inventory. Volume II."

A.4 Rupke and Associates. 1985. "Calibration Summary of Holland Marsh Polder Drainage Pumps."

A.5 Limnos Limited. 1985. "Phosphorus Control by Duckweed Harvest -Holland Marsh Polder Drainage System."

A.6 Land Sub-Group. 1985. "Phosphorus and Modelling Control Options."

B. Lake Sub-Group. 1985. "Overview of Lake Simcoe Water Quality and Fisheries Studies."

B.1 Humber, J.E. 1985. "Water Quality Characteristics of Lake Simcoe - 1980-1984."

B.2 Neil, J.H. and G.W. Robinson.1985. "*Dichotomosiphon tuberosus*, a benthic algal species widespread in Lake Simcoe."

B.3 Angelow, R. and G. Robinson. 1985. "Summer Nutrient Conditions in the Lower Holland River prior to Diversion of Municipal Inputs."

B.4 Neil, J.H., G.A. Kormaitas and G.W. Robinson.1985. "Aquatic Plant Assessment in Cook’s Bay, Lake Simcoe."

Gault, H.D. 1985. "Community Relations Report."

LAKE SIMCOE ENVIRONMENTAL MANAGEMENT STRATEGY IMPLEMENTATION PROGRAM

REPORTS

Imp. A.1	Lower Holland River Erosion Control Study. 1992. Harrington & Hoyle Ltd.
Imp. A.2	Lake Simcoe Tributary Monitoring Data Report, 1982 to 1992. May, 1994. G. Peat & M. Waiters.
Imp. A.3	
Imp. A.4	Annual Water Balances And Phosphorus Loading for Lake Simcoe (1990 - 1998). circa 1998. L.D. Scott *et al.*
Imp. A.5	Phosphorus Loading To Lake Simcoe, 1990 - 1998: Highlights and Preliminary Interpretation in Historical and Ecosystem Contexts. May, 2001. K.H. Nicholls.
Imp. A.6	Development and Implementation of a Phosphorus Loading Watershed Management Model for Lake Simcoe. Sept., 1994. Beak Consultants Ltd.
Imp. B.1	The Benthic Alga "*Dichotomosiphon tuberosus* in Lake Simcoe, 1986, 1987. Limnos Ltd.
Imp. B.2	The Predictability of Hypolimnetic Dissolved Oxygen Depletion in Lake Simcoe, Part 1. 1987. Beak Consultants Ltd.
Imp. B.3	Estimated Outflow from Lake Simcoe at Atherley, 1982-1986. 1987. Cumming-Cockburn and Associates Ltd. 1987.
Imp. B.4	Aquatic Plants of Cook's Bay, Lake Simcoe, 1987. 1988. Limnos Ltd.
Imp. B.5	Duckweed Harvest from Holland River. 1988. Limnos Ltd.
Imp. B.6	Assessment and Control of Duckweed in the Maskinonge River, Keswick, Ontario. 1988. Limnos Ltd.
Imp. B.7	The History of Phosphorus, Sediment and Metal Loadings to Lake Simcoe from Lake Sediment Records. Dec. 1989. Johnson and Nicholls.
Imp. B.8	Hypolimnetic Oxygen Dynamics in Lake Simcoe, Part 2: Evaluation Using Time Trend and Model Simulation Techniques. April, 1990. Beak Consultants Ltd.
Imp. B.9	Lake Simcoe Hypolimnion Aeration: An Assessment of the Potential for Direct Treatment. Aug. 1990. Limnos Ltd.
Imp. B.10	Lake Simcoe Nearshore Water Quality Monitoring at Water Supply Intakes, 1982-1989: Data Report. Oct. 1990. Hopkins, G.J. and L Webb.
Imp. B.11	Status in 1990 of the Dominant Benthic Alga, *Dichotomosiphon tuberosus*, in Lake Simcoe. Jan. 1991. Limnos Ltd.
Imp. B.12	Estimated Monthly Flows and Exports of Total Nitrogen and Phosphorus from

Lake Simcoe at Atherley. April, 1992. Cumming-Cockburn and Associates Limited.

Imp. B.13 Water Quality Trends in Lake Simcoe 1972-1990 and the Implications for Basin Planning and Limnological Research Needs. Oct. 1991. Nicholls, K.H.

Imp. B.14 Hydrodynamic Computer Model of Major Water Movement Patterns in Lake Simcoe. June 1992. "Hydroflux Engineering.

Imp. B.15 Estimation of Phosphorus Loadings and Evaluation of Empirical Oxygen Models for Lake Simcoe for 1970 - 1990. Dec., 1992. Beak Consultants Ltd.

Imp. B.16 Hypolimnetic Oxygen Dynamics in Lake Simcoe, Part 3: Model Confirmation and Prediction of the Effects of Management. Dec., 1992. Beak Consultants Ltd.

Imp. B.17 A Limnological Basis for a Lake Simcoe Phosphorus Loading Objective. July, 1995. K.H. Nicholls.

Imp. B.18 Lake Simcoe Water Quality Update, with Emphasis on Phosphorus Trends. Nov., 1998. K.H. Nicholls.

Imp. B.19 Lake Simcoe Water Quality Update: LSEMS Phase II Progress Report, 1995-1999. May, 2001. K.H. Nicholls.

Imp. B.20 Lake Simcoe Water Quality Update 2000 - 2003. Implementation Program 2005. Jan., 2005. M.C. Eimers & J.G. Winter.