EUTROPHICATION STATUS OF THE GREAT LAKES

by

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ABSTRACT

Data on four eutrophication indicators, collected in the years 1966 to 1975 by the Canada Centre for Inland Waters, have been summarized. The data for offshore, near-surface waters are condensed to summertime averages for each year, to search for trends. The parameters are: Secchi transparency, chlorophyll a, particulate organic carbon, and total phosphorus. Basins examined are: Lakes Superior, Huron and Ontario and Central Lake Erie. Lake Michigan is omitted.

A new trophic scale and classification scheme are developed to enhance the interpretation. Trophic indices for the four parameters have been assigned, based on observed relationships between the parameters. A medium or 'mesotrophic' range of 3 to 6 metres Secchi depth has been arbitrarily chosen, and corresponding ranges in the other parameters have been derived.

The new trophic scale is linear with respect to plankton concentration. All values are transformed to a scale on which 10 units is the lower limit for 'eutrophic'. The mean trophic indices for recent summers are: Lake Superior 2.7, Lake Huron 3.0, Central Lake Erie 8.0, and Lake Ontario 11.2.

The only trend that was found among these parameters and basins was an increasing Secchi "turbidity" value in Lake Ontario: the rate of increase was about 40% per 10 years.

The role of dissolved oxygen conditions in the typology of lakes is discussed.

INTRODUCTION

At the present time, the primary remedial activity being undertaken to improve water quality in the Great Lakes is the reduction of the phosphorus loadings to Lakes Erie and Ontario. This is being done to combat eutrophication, in particular to restore good dissolved oxygen conditions to Lake Erie and to decrease phytoplankton abundance and the associated surface-water turbidity in both of the lakes. The present paper contributes knowledge relevant to this management of trophic conditions, by summarizing some of the water quality data collected by the Canada Centre for Inland Waters since 1966, and by developing a trophic scale and classification for the same data. It is intended that trend graphs published herein will be kept up-to-date in future years to show the progress of trophic management.

A brief introduction to the problem of eutrophication of lakes can be found in Hutchinson (1973). Further background information can be found in a review by Stewart and Rohlich (1967), a study by Vollenweider (1968), and the proceedings of a symposium titled "Eutrophication: Causes, Consequences, Correctives" (1969).

The Great Lakes Water Quality Agreement

The Water Quality Agreement of 1972 between Canada and the United States established as a general water quality objective that Great Lakes waters should be free of nutrients in concentrations that create nuisance growths of algae, and further that dissolved oxygen conditions in Lake Erie should be improved (reference: Governments of Canada and the United States, 1972). The agreement includes a specific water quality objective for dissolved oxygen, approximately 50% saturation or greater. Phosphorus is identified as the key nutrient whose loadings are to be reduced in order to manage algal abundance and dissolved oxygen. For phosphorus, the quantitative objective is given in terms of annual loadings, rather than concentrations within each lake. The agreement calls for the phosphorus loadings to Lakes Erie and Ontario by 1976 to be one half of the loadings in 1971.

I hope that the present work will draw attention to actual lake conditions and perhaps help in the establishment of specific water quality objectives for eutrophication parameters such as chlorophyll, transparency, and total phosphorus.

Review of earlier Great Lakes work related to eutrophication

Beeton (1961, 1965, 1966, 1969) studied aspects of Great Lakes eutrophication for which data were available at the time: mainly historical changes in the concentrations of major ions and in the annual commercial fish catches. The major ion history was suggestive but not conclusive evidence of parallel changes in nutrients and plankton. The history of dissolved oxygen in central Lake Erie was just beginning to be observed and understood by Beeton and by Carr (1962).

The period of recent studies of dissolved nutrients in the Great Lakes began with Shiomi and Chawla's (1970) study of nutrients in Lake Ontario. They showed the large seasonal cycles in surface waters with depletion of phosphate and nitrate in summer.

Further descriptions of dissolved nutrients in surface waters of

Lakes Erie and Ontario were published by Gächter, Vollenweider, and Glooschenko (1974).

Dobson, Gilbertson and Sly (1974) published a summary of dissolved nutrient conditions in surface waters of the Great Lakes excluding Lake Michigan. The upper Great Lakes were shown to have abundant nitrate and silica in summer, which were not used due to an extreme shortage of phosphate. The two lower lakes had depletion of nitrate and silica in summer due to an abundant supply of phosphate.

Schelske and Stoermer (1971) discussed one consequence of eutrophication or increasing phosphorus loadings: silica concentrations show long-term depletion and become especially low each summer, which causes diatoms to be replaced in summer by green and blue-green algae. Lakes Erie and Ontario now show especially low silica concentrations (Dobson, Gilbertson, and Sly, 1974), and a diatom minimum in summer (Vollenweider, Munawar, and Stadelmann, 1974).

Dobson (1967) reported on dissolved oxygen conditions in Lake Ontario. There was only slight depletion in the hypolimnion during summer 1966. Such a deep lake is not likely to have an oxygen problem, even with considerable fertilization.

Dobson and Gilbertson (1971) reported the history of dissolved oxygen depletion each summer in the hypolimnion of central Lake Erie, in the period 1929 to 1970. In that period the depletion rate doubled; zero oxygen concentrations in late summer occurred after about 1960.

Chlorophyll a distributions in surface waters of Lake Huron during 1971 were reported by Glooschenko, Moore, and Vollenweider (1973).

They showed that Saginaw Bay had extremely high values. Saginaw Bay is excluded from the 'offshore' zone used in the present paper.

Distributions of chlorophyll *a* in surface waters of Lake Erie during 1970 were described by Glooschenko, Moore, and Vollenweider (1974). Their paper shows horizontal distributions in detail, including the eutrophic west basin. In the present paper only the cruise-mean values in the offshore part of central Lake Erie are reported for that lake.

Davi~~d~~s (1964) reported phytoplankton counts at a Cleveland water intake (Division Avenue Filtration Plant) over the years 1919 to 1963. Unfortunately, cell counts were used, rather than biomass estimates from counts and cell volumes. His conclusions were: the phytoplankton have increased in abundance; the seasonal maxima have become more pronounced; the seasonal minima have become less pronounced; the winter minimum did not occur in some recent years; and there were changes in species composition.

The direct study of Great Lakes phytoplankton has advanced to open-lake areas only recently. Also the useful "Utermöhl" technique has been introduced in the recent work (Utermöhl, 1931; Braarud, 1958). Due to the difficult and time-consuming nature of microscopical phytoplankton counting, and due to great geographical and seasonal variability, the phytoplankton distributions are just beginning to be observed and understood. It is only with great effort that long-term trends will be observed from microscopical counts over the next decade when the lower Great Lakes might recover from eutrophication.

Recent papers on phytoplankton in the Great Lakes include those of Munawar and Nauwerck (1971) on Lake Ontario, and Munawar and Munawar (1975) dealing with the phytoflagellates. The paper by Munawar, Stadelmann, and Munawar (1974) was a comprehensive study of a nearshore and an offshore station in Lake Ontario, including considerations of chlorophyll and dissolved nutrients in relation to the phytoplankton. Recent studies of phytoplankton abundance in all of the Great Lakes have been reviewed and synthesized by Vollenweider, Munawar, and Stadelmann (1974).

Zooplankton studies of the Great Lakes have been summarized by Watson (1974). There is little evidence for long-term trends due to the sparsity of sampling in earlier years.

A multi-parameter approach was taken by Stadelmann and Fraser (1974) in a study of a vertical north-south mid-lake section in Lake Ontario. Vertical structure throughout the year was emphasized, and parameters included temperature, dissolved inorganic nutrients, and organic particulate matter. For early summer, they showed that chlorophyll, particulate phosphorus, and particulate organic nitrogen had maxima near a depth of 10 metres. This places some limitation on the surface-layer average values calculated in the present work. The reader is asked to survey the depths of near-surface samples, listed in the appendix herein.

Another study by Stadelmann and Munawar (1974), based on data for various biomass parameters at two stations in Lake Ontario, emphasizes that much of the particulate organic carbon is in detritus or non-living particles. The paper discusses the usefulness and limitations of the various parameters such as chlorophyll, particulate organic carbon, and phytoplankton volume estimates, and therefore that paper is a useful background document for the present work.

Background for development of a trophic scale.

Two prominent limnologists in Europe during the 1920's were E. Naumann and A. Thienemann, who both began the field of lake 'trophic' typology or classification. Naumann characterized lakes by their phytoplankton abundance in surface waters in summer, whereas Thienemann emphasized the degree of depletion of dissolved oxygen in the deep waters in summer and the associated types of benthic organisms (Rodhe, 1969; Hutchinson, 1973). It was probably not understood at that time that these two major aspects of temperate lakes are not well-correlated in a series of lakes, dissolved oxygen being very dependent on the thickness of the hypolimnion. The two alternative classification schemes are sometimes contradictory. Also at that time practical methods for phytoplankton standing stock determination, such as the chlorophyll method, were not yet developed, and this made Naumann's classification procedure quite subjective. Classification of lakes has been quite unquantitative nearly to the present time, and many limnologists have used the 'trophic' scheme without clear quantitative definitions (Vallentyne, Shapiro, and others, 1969).

The usual definitions of words used in the 'trophic' system in limnology, as found in Webster's Seventh New Collegiate Dictionary (1970), are satisfactory as a starting point, although they contain the problem, still customary in limnology, that Naumann's and Thienemann's approaches are combined:

"Trophic: of or relating to nutrition.

Oligotrophic: of a lake: deficient in plant nutrients and usually having abundant dissolved oxygen with no marked stratification.

Meso - (prefix): middle, intermediate.

Eutrophic: of a lake: rich in dissolved nutrients but often shallow and with seasonal oxygen deficiency.

Hyper - (prefix): excessively.

Dystrophic: of a lake: brownish with much dissolved humic matter, a small bottom fauna, and a high oxygen consumption."

Naumann's concept of trophic status is contained in the following quotation published by Elster (1958) quoting from Naumann (1932), in translation from the German: "The term "eutrophic" can thus be used (for standing waters) only when a water rich in phytoplankton is involved which always shows from spring till autumn a coloring typical for vegetation, and in which water blooms start in summer a rather long period of high production. A contrast is presented by the concepts of oligotrophy and dystrophy, both referring to waters poor in plankton; in the first case there is clear water, in the second, brown water."

Naumann's approach to lake classification is also succinctly stated by Hutchinson (1973): "Naumann throughout his works gives the impression that he liked to draw limnological conclusions, expressible in schematic terms, merely from looking at lakes." For Naumann the appearance of a lake in summer was the fundamental property. For any human observer, clear waters are highly valued aesthetically and are judged to be the most beautiful. Further, there are fewer practical problems (for instance in municipal drinking water systems) with clear waters than with those having abundant phytoplankton. Thus Naumann's approach to classification has continuing value and usefulness.

But dissolved oxygen will not be neglected, it being also a fundamental parameter of water quality. The place of oxygen in lake typology is discussed later in this paper, and it is intended that dissolved oxygen conditions in the Great Lakes will be the subject of a later paper. In this present paper I advocate that dissolved oxygen in lakes should be studied for its own sake, and not primarily in relation to lake trophic classification, which concept will be narrowed to surface water quality only (see discussion in Järnefelt, 1958).

Some limnologists contend the traditional or classical system of lake trophic types (oligotrophic-mesotrophic-eutrophic) has failed (e.g. Shapiro, 1975). This present paper retains part of the old system by introducing four quantitative trophic class ranges of four easily measured and inter-related parameters indicating near-surface plankton abundance, thus renewing and quantifying the original stance of Naumann.

Parameters of eutrophication

For the measurement of trophic status and trends, useful parameters include standing stock of particulate organic matter, transparency of the water, dissolved inorganic nutrients, dissolved oxygen, phosphorus and nitrogen loadings to the lake, and others. Table 1 is a list of individual parameters that are being measured by the Canada Centre for Inland Waters in its ongoing Great Lakes program. The table was created by Dr. R. A. Vollenweider and a Eutrophication Committee under his chairmanship, the committee being attached to the Great Lakes Research Advisory Board of the International Joint Commission.

Standing stock of plankton and detritus, and specific fractions thereof, can be measured by a number of parameters, with the additional aid of filtration. The problem has been admirably discussed by Watson, Carpenter, and Munawar (1975). Two parameters for particulate organic matter are used in the present work: total chlorophyll _a_, which includes active and degraded chlorophyll _a_ and thus measures detritus from the phytoplankton as well as living cells; and particulate organic carbon, which includes all plankton and their detritus.

Transparency is obtained from the traditional Secchi-disc depth of disappearance.

One 'causative' variable is included in the present study, namely total phosphorus measured without any filtration.

The other variables in Table 1, especially dissolved oxygen and dissolved inorganic nutrients, are left for future research on trophic status and trends.

It should be noted that recently the phytoplankton production measurement using carbon 14 has been advocated for trophic assessment (e.g. Rodhe, 1969; Vallentyne, Shapiro, et al. 1969). That parameter is

Table 1. Parameters proposed for monitoring eutrophication of the Great Lakes: the work of Dr. R.A. Vollenweider and his Great Lakes Eutrophication Committee.

Primary resultant variables ("simplifying")	Secondary resultant variables ("integrating")	Causative variables	Related descriptive variables
Phytoplankton biomass*	Epilimnetic ΔP, ΔN, ΔSi (Δ winter - summer)	Measured nutrient (N and P) loading	Temperatures
Major algal groups and dominant species	Hypolimnetic O_2 and ΔO_2	Phosphorus - total - soluble reactive	Conductivity pH Turbidity (inshore)
Chlorophyll a	Zooplankton*	Nitrogen - total (Kjeldahl) - NO_3 + NH_3	Others
Particulate organic carbon	Bottom fauna	Reactive silica	
Secchi depth			

(*) Consideration has to be given to reference stations, and/or mixed samples for phyto- and zooplankton monitoring and counting.

__ Underlined parameters are those for which full agreement by committee members was reached.

an 'activity' of the phytoplankton rather than their standing stock or concentration. For the present research, the amount of a constituent, rather than its metabolic activity, is chosen for the trophic assessment.

METHODS

A pictorial introductory account of the methods is contained in a report by Carew and Williams (1975).

Secchi depth, 1966 to 1975.

The 'Secchi depth' was the depth of disappearance of a white disc 30 cm in diameter suspended on a line calibrated in metres. An approximate indication of precision is: at the 10 metre level, ± 1 metre; at the 3 metre level, ± 0.5 metres. The ships proceeded from station to station during night-time as well as daytime, but of course Secchi observations were only made at daylight stations. Thus the Secchi depth data are not as numerous as the other parameters.

Total chlorophyll *a*, 1967 to 1975.

"Total chlorophyll *a* " includes pheo-pigments (degraded chlorophyll) in forms such as zooplankton feces. A correction for pheo-pigments to give corrected or undegraded chlorophyll only, was not applied in the present work, it being thought that total chlorophyll *a* is the better indicator of water quality, though not of live phytoplankton biomass. Pheo-pigments in Lake Ontario were discussed by Glooschenko, Moore and Vollenweider (1972).

For the years 1967 to 1969, the fluorescence method of Lorenzen (1966) was used, with continuous measurement of _in vivo_ chlorphyll in a continuous flow system. Data for all 'stations' were extracted from the recorder-trace. Calibration was done by comparisons with a spectrophotometric method using the equations of Parsons and Strickland (1963). A correction for phaeopigments was not made; thus the result can be called 'total chlorophyll _a_'.

For the years 1970 to 1975, the spectrophotometric method of Strickland and Parsons (1968) was used except that the equation for computation of total chlorophyll _a_ was that of 'Unesco' (1966). Discrete samples were filtered through a Whatman GF/A glass filter to which 5 drops of a $MgCO_3$ suspension were added. Filters were kept, until analysis, at minus 10° C. Filters were ground with a teflon homogenizer for 1 minute in 3 ml 90% acetone, made up to 10.0 ml volume, and placed in the dark at room temperature for one hour to improve extraction. After centrifugation for 10 minutes at 3000 r.p.m., chlorophyll _a_ was spectrophotometrically determined. The volume that was filtered varied according to the chlorophyll and detritus content.

Particulate organic carbon, 1972 to 1975.

The sample was first well-mixed and a measured volume (300 ml to about 1 litre) was filtered through pre-ignited GF/C filters. The residue was washed with about 4 to 5 ml of 0.3% H_2SO_4 and then with about 4 to 5 ml of carbon-free water. The residue was dried and stored in a vacuum desiccator. For analyses, a Hewlett-Packard 185 CHN Analyzer was used. Prior to 1974, peak heights were read. From 1974 the Analyzer was equipped with an integrator. Analyses were done about 1 to 6 weeks after sampling. Blanks were prepared in the field by washing pre-ignited GF/C filters with about the same volume of the dilute H_2SO_4 and wash-water, and subjecting the filters to the same process as the samples received. Precision at the level of 20 μgC/litre was ±5 μg/litre.

Total phosphorus, 1967-1975

There was no filtration.

Before 1973, samples were acidified with 1.0 ml 30% H_2SO_4 per 100 ml sample and stored for up to one month in glass bottles.

The samples were digested in a sulfuric acid - potassium persulfate mixture and then analyzed by the Auto-Analyzer I (1967-1972) and AA II (1973-1975) ammonium molybdate-stannous chloride colorimetric method for reactive phosphate, using an acid baseline (wash) water (Philbert and Traversy, 1973). Up to 1972, the samples were digested by heating on a gas-heated hot plate until dense white fumes appeared. From 1973 samples were digested in an autoclave aboard ship and analyzed aboard ship. Blanks were prepared by subjecting deionized-distilled water to the same treatment as the samples. Approximately one in every 25 samples was a blank.

Before use, the glass containers for total phosphorus samples were washed with chromic acid or sulfuric acid, and then rinsed with tap and deionized-distilled water.

Working range was 0.5 to 50. µg P/litre. Detection limit was about 3.0 µg P/litre. The standard deviation near the detection limit was ±1.0 µg P/litre.

RESULTS

The data-base

The data for the four parameters are those from numerous discrete cruises, approximately monthly, of vessels of the Canada Centre for

Inland Waters in the years 1966 to 1975.

It is the strategy of this work to use summertime mean values in offshore, near-surface waters. But first the seasonal cycles will be examined to understand seasonal trends occurring in the summer period: thus all cruises having lake-wide water quality data are used. The cruise-mean values for offshore, near-surface waters are listed in the Appendix at the end of this paper: they are the foundation of the present work but also this data summary of cruise-mean values may be useful for other Great Lakes research such as plankton-modelling.

Only the "offshore" zones are considered in this work. Stations in the data-listings were selected on the basis of their soundings, according to the limits shown in Table 2. The offshore zones thus defined are illustrated in Figure 1.

Only the near-surface data are used. Samples were chosen from the upper 10 metres of the water column, where possible. In the earlier years, the only sample depth available was the 1-metre depth; in intermediate years, the depths 1, 5, and 10 metres were available; and in later years, integrated samples over the depth range 0 to 20 metres had to be used. These details are recorded in the data summary in the Appendix of this paper.

The regions chosen have a thermocline in summer which isolates the near-surface waters from the bottom sediments. Resuspension of sediments cannot be influencing the properties of the near-surface waters of the chosen regions in summer. This point is especially important for

Table 2. The sounding criteria used for classifying the "offshore" stations in the four Great Lakes basins. (See also Figure 1).

Basin	Soundings for "offshore" stations, in metres.
Lake Superior	> 100
Lake Huron	> 50
Central Lake Erie	> 20
Lake Ontario	> 50

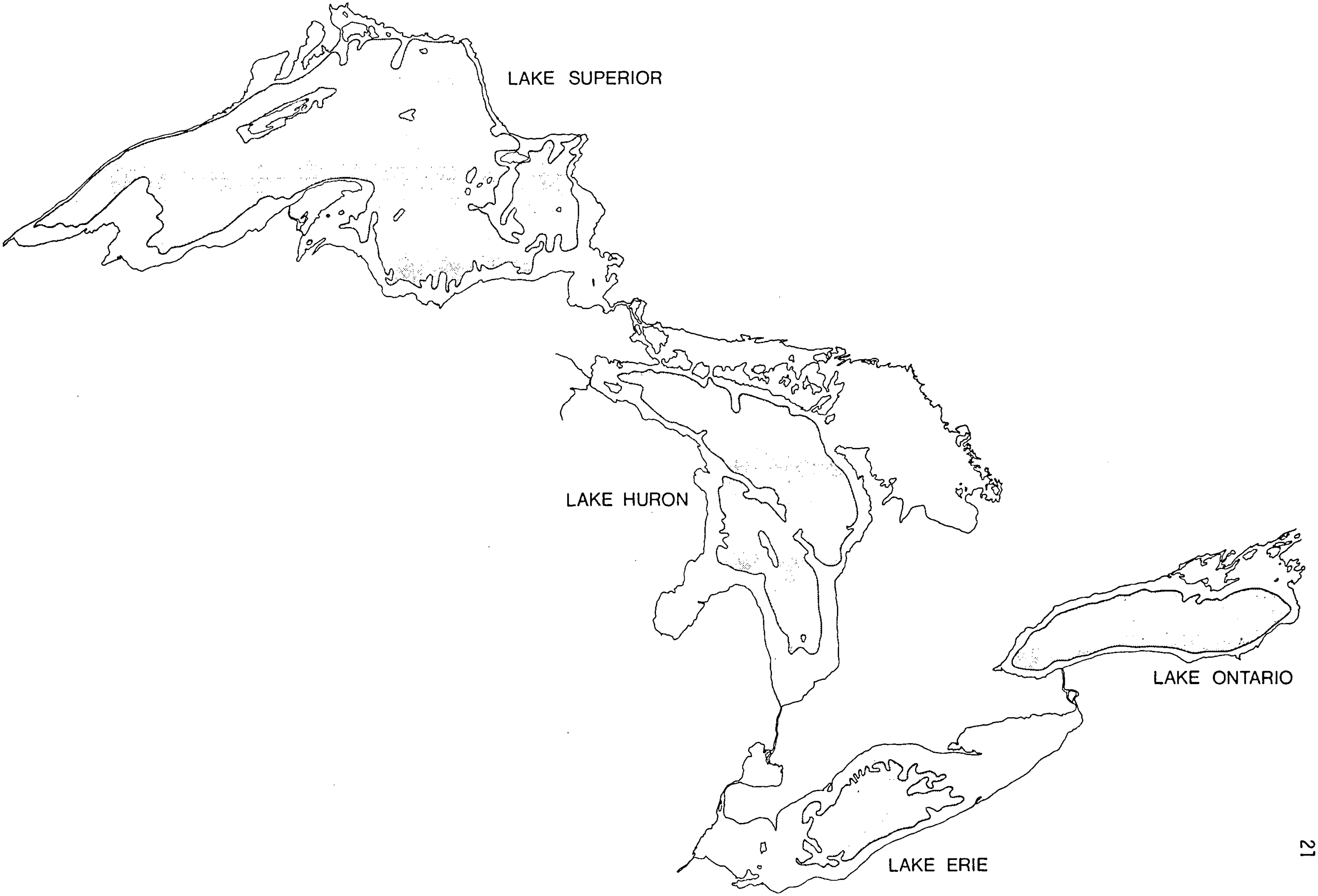

Fig. 1.

THE "OFFSHORE" ZONES OF LAKES SUPERIOR, HURON AND ONTARIO AND CENTRAL LAKE ERIE shallow Lake Erie, where a total phosphorus measurement outside the summer period is surely influenced by re-suspended sediment.

The use of data for 1 to 10 metres below the lake surface, or the nearest similar depths available for particular cruises, is an attempt to characterize near-surface waters only. It is not intended to include any thermoclinic maximum standing stock which may occur, at some times, deeper in the water column (Watson, Thompson, and Elder, 1975). Rather, it is intended to describe the mixed surface layer when it occurs. Especially at times in early summer when the uppermost waters are stratified in temperature and phytoplankton, a consistent set of depths would have been better, but this was not possible in the CCIW surveys. Inconsistent depths of samples are a limitation of the CCIW data when they are used to study trends.

For the offshore, near-surface waters of each basin, unweighted cruise-mean values were calculated (see the Appendix). The station spacing was usually regular enough for the unweighted means to be close to areally weighted mean values. Use of the latter would improve the mean values only slightly.

From the cruise-mean values for each of the four parameters and each basin, seasonal cycle graphs were made for each year, and from these graphs (not shown herein), summertime mean values were obtained as described later in this paper. The summer period is defined somewhat differently for each basin, and depends on the thermal and other cycles in the surface waters. For instance, the beginning of "summer" must be assigned to be after the disappearance of the "thermal bar" (Rodgers, 1965). The definitions of "summer" for each basin are listed in Table 3.

The Secchi-depth transformation.

The reader will easily understand that larger Secchi-depth readings accompany smaller standing stocks of particulate matter, so that some kind of transformation of the readings is necessary to make them directly proportional to standing stock. Postma (1961) experimentally determined the relations between Secchi-depths and suspended particle concentrations. For any one size of particles, their concentration was proportional to (k/Secchi depth). Postma's empirical work suggests that (k/Secchi depth) is an appropriate simple transformation of the Secchi-depth readings to get numbers approximately proportional to the concentration of particles. I have chosen {30./Secchi depth (metres)}, equals {100/Secchi depth (feet)}, to produce a medium range of 5 to 10 (m^{-1} x 30) corresponding to Secchi depths from 6 to 3 metres or 20 to 10 feet. The constant '30' is introduced to give, in practice, simple large numbers instead of decimal fractions. Table 4 is a list of some Secchi depths and their corresponding Secchi reciprocal values, and is intended to familiarize the reader with their relationships and to provide a conversion guide for some commonly-obtained readings.

All averaging of Secchi data in this paper was done on the reciprocal values, not on the untransformed readings. It is the reciprocal values that are additive: a mixture of two turbid samples

Table 3. Definitions of "summer", based on seasonal thermal and nutrient cycles of surface waters.

Basin	Dates
Superior	August and September
Huron	July 10 to September 30
Central Erie	June 15 to September 5
Ontario	July, August and September

Table 4. Conversion table for Secchi-disc observations.

Secchi depth (metres)	Secchi reciprocal value (m^{-1} x 30)
0.5	60.0
1.0	30.0
1.5	20.0
2.0	15.0
2.5	12.0
3.0	10.0
3.5	8.6
4.0	7.5
4.5	6.7
5.0	6.0
5.5	5.5
6.0	5.0
6.5	4.6
7.0	4.3
7.5	4.0
8.0	3.8
8.5	3.5
9.0	3.3
9.5	3.2
10.0	3.0
11.0	2.7
12.0	2.5
13.0	2.3
14.0	2.1
15.0	2.0
16.0	1.9
17.0	1.8
18.0	1.7

would have a reciprocal value equal to the mean of the two original reciprocals. The reciprocal values are proportional to the mass-concentrations of particles which are conserved during mixing.

To illustrate this averaging problem, I consider two readings of 3.0 m and 6.0 m. Obviously the straight-forward mean value is 4.5 m. But the corresponding original reciprocal values are 10.0 and 5.0 (m^{-1} x 30) whose mean value is 7.5 (m^{-1} x 30), giving a mean Secchi depth of 4.0 m, not 4.5 m.

Smoothed seasonal cycles.

With cruises at approximately monthly intervals, the seasonal cycle of a property in any one year is poorly defined. Seasonal cycle graphs for each year were drawn to calculate the summertime mean values, but those graphs are not shown herein.

Average smoothed seasonal cycle graphs for all years having data were drawn by plotting all cruise-mean values for one parameter and basin on one graph, and then drawing a curve through the numerous and scattered points. Only the curves themselves are illustrated here (Figures 2, 3 and 5).

In Figure 2, I show the average smoothed seasonal cycles of Secchi reciprocal values in the four basins. Lake Ontario has a peak in turbidity during August,whereas Central Lake Erie has a minimum value in July. Lake Huron, with lower Secchi reciprocal values than Ontario and Central Erie, has a broad minimum in August - October. Lake Superior, with the lowest reciprocal values, has no apparent seasonal variation.

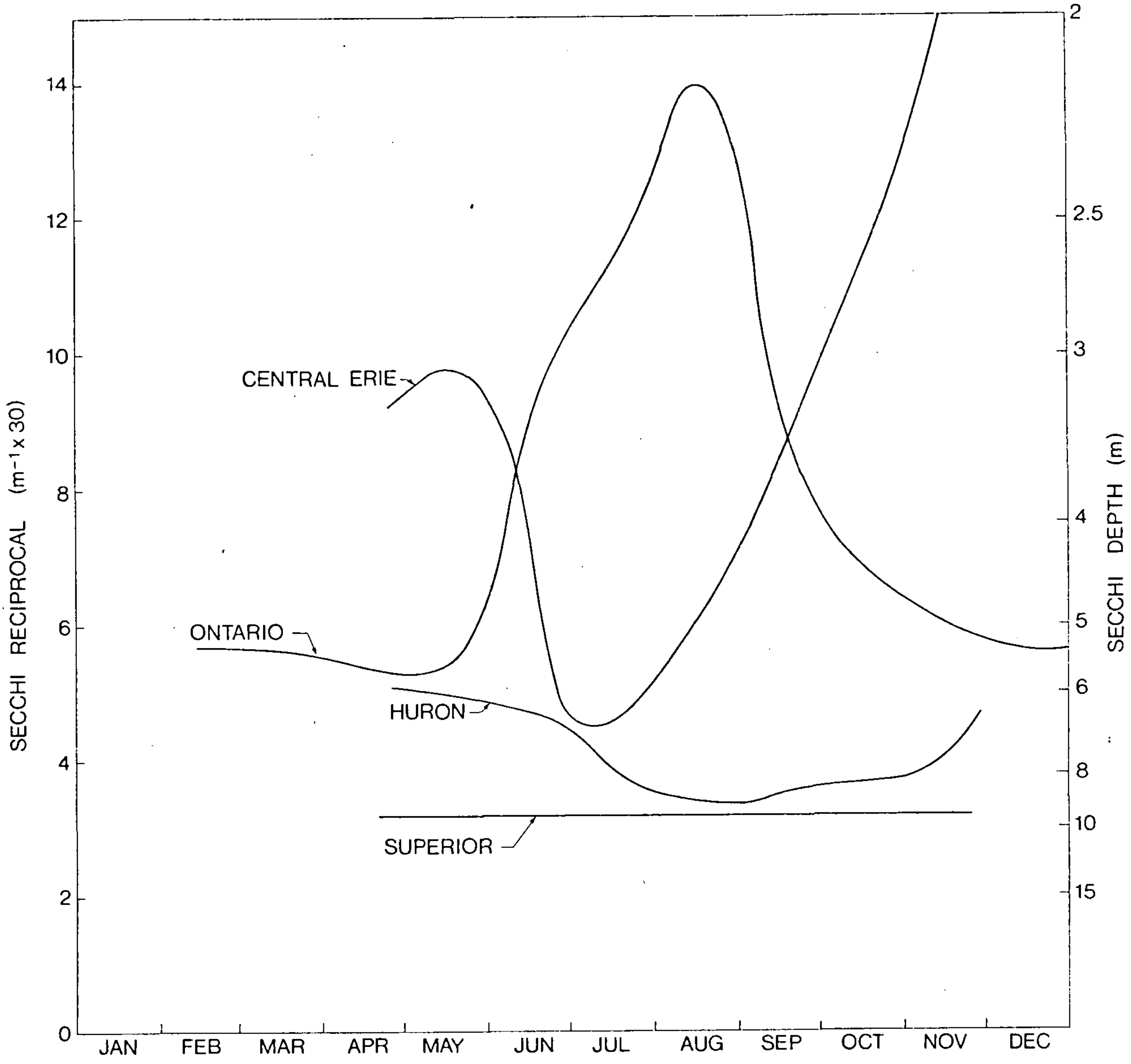

Fig. 2.
SEASONAL CYCLES OF SECCHI RECIPROCAL VALUES ($m^{-1} \times 30$) IN THE OFFSHORE PARTS OF 4 GREAT LAKES BASINS. THE SMOOTHED CURVES WERE DRAWN FROM MEAN VALUES ON CRUISES IN THE YEARS 1966 to 1974.

The graph (Figure 2) indicates that Central Lake Erie and especially Lake Ontario require numerous cruises in summer to precisely define the summertime mean value of each year. The number of cruises can be seen in the Appendix; in some years there were judged to be too few to define the summertime mean value.

Figure 3 illustrates the smoothed seasonal cycle of total chlorophyll *a* in the surface waters of the four basins. For Lake Ontario, the curve rises in April-May-June. During that interval the data are from both sides of the thermal bar (Rodgers, 1965), so that the curve describes neither inshore nor offshore water-masses. Inshore waters at that time have the higher values. For other times of year including summer, the curve for Lake Ontario more nearly describes the whole lake-surface.

Total chlorophyll *a* in Lake Ontario passed through a minimum in August (Figure 3), whereas Secchi reciprocal values had a single peak in August (Figure 2). It might seem that turbidity in August was due partly to something other than phytoplankton, such as suspended calcium carbonate. However, it can be noted that phytoplankton biomass had a single peak in August during 1970: this was reported by Munawar and Nauwerck (1971). Perhaps the chlorophyll minimum was due to nutrient deficiency and low chlorophyll values in the phytoplankton at that time, or incomplete extraction of chlorophyll from the species of phytoplankton occurring at that time.

Seasonal cycles of particulate organic carbon in Central Lake Erie, Lake Huron, and Lake Superior cannot be shown because of too few data.

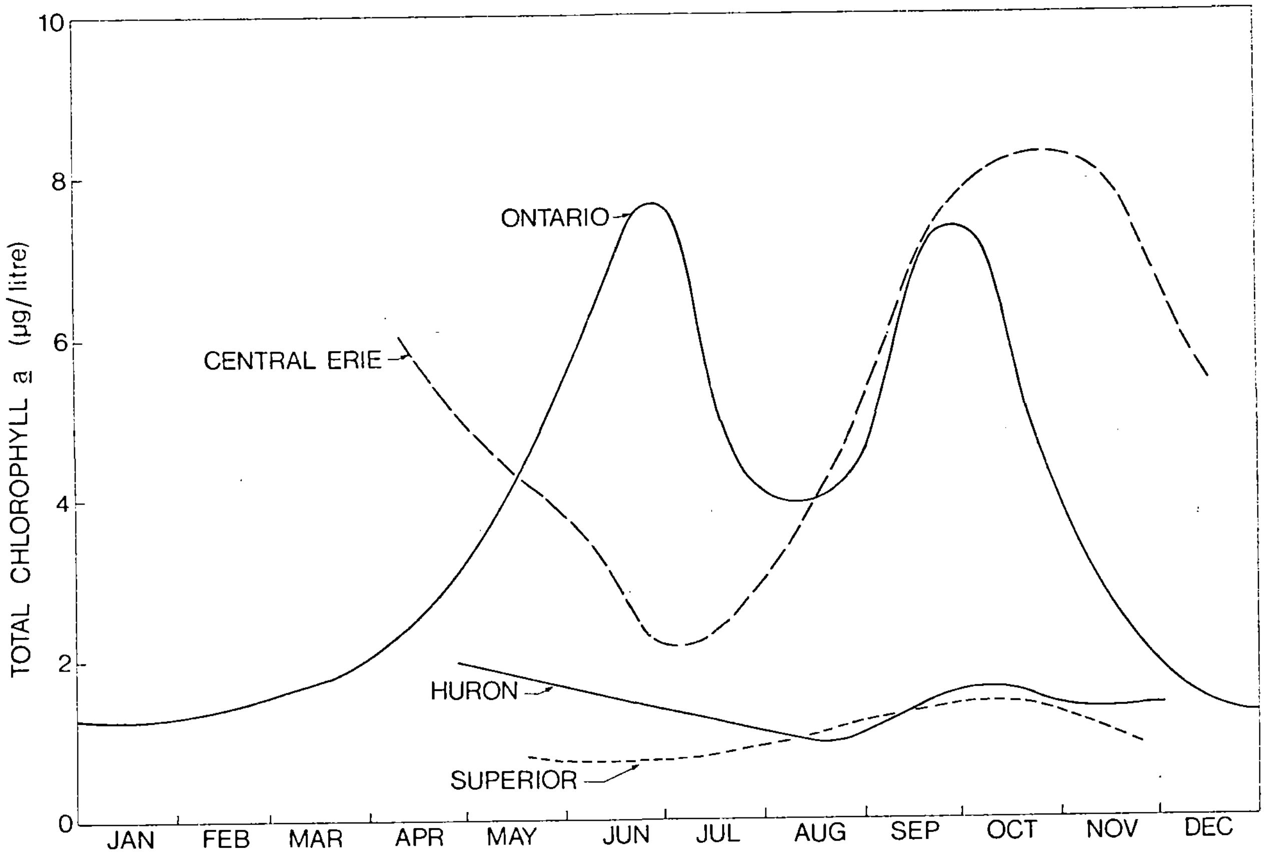

Fig. 3.

SEASONAL CYCLES OF TOTAL CHLOROPHYLL a (µg/LITRE) IN OFFSHORE, SURFACE WATERS OF 4 GREAT LAKES BASINS. THE SMOOTHED CURVES WERE DRAWN FROM MEAN VALUES ON CRUISES IN THE YEARS 1967 to 1975.

Figure 4 illustrates the unsmoothed seasonal cycles of POC in Lake Ontario. The values of summertime were highest in 1972 (see also Figure 11, below). In that year there was a strong wind on June 23, associated with the passage of Hurricane Agnes (Phillips, 1974). Total chlorophyll a in Lake Ontario during summer was also highest in that year (Figure 10). The strong wind moved the thermocline downwards and entrained deep water into the epilimnion. This may also have entrained dissolved nutrients and thus caused an unusually high phytoplankton stock in the summer of 1972.

Average smoothed seasonal cycles of total phosphorus are shown in Figure 5. Lake Ontario has a long period of unchanging values in late winter (February to May). Data for that interval in Lake Ontario will be examined separately (Figure 13, below). In Lake Ontario during summer the total phosphorus values of surface waters are declining due to sedimentation of plankton. (For the duration of the summer-thermocline, lakes become more stratified chemically.) Central Lake Erie had a minimum total phosphorus content in surface waters during June-September, and higher values in the unstratified periods before and after. Seasonal changes in total phosphorus are not apparent in Lakes Huron and Superior, from the cruise-mean values in all years. The time of sampling for total phosphorus in those two lakes may not be important.

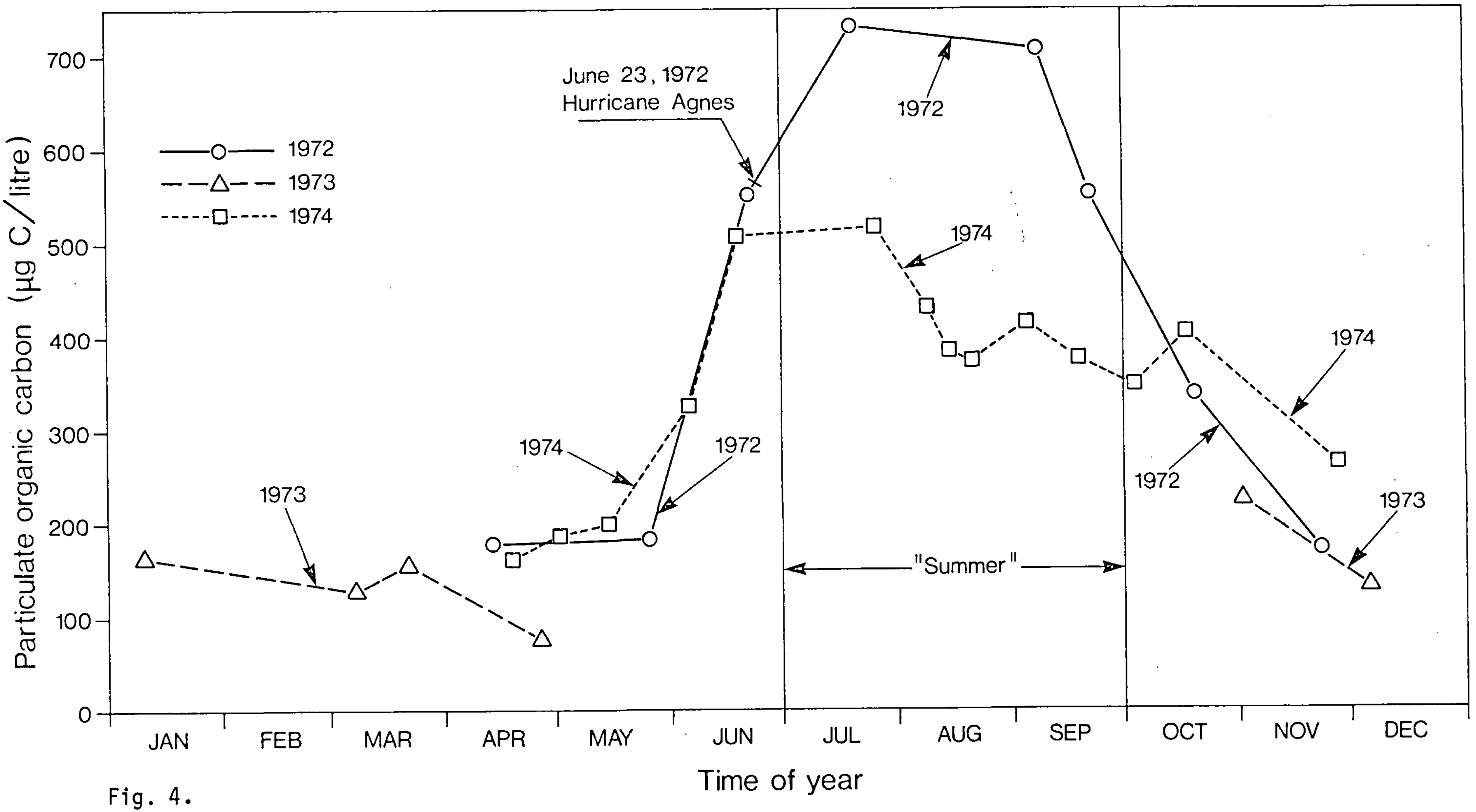

Fig. 4.

PARTICULATE ORGANIC CARBON IN OFFSHORE SURFACE WATERS OF LAKE ONTARIO: CRUISE-MEAN VALUES OBSERVED IN THE YEARS 1972 – 1974. UNITS ARE MICROGRAMS CARBON PER LITRE

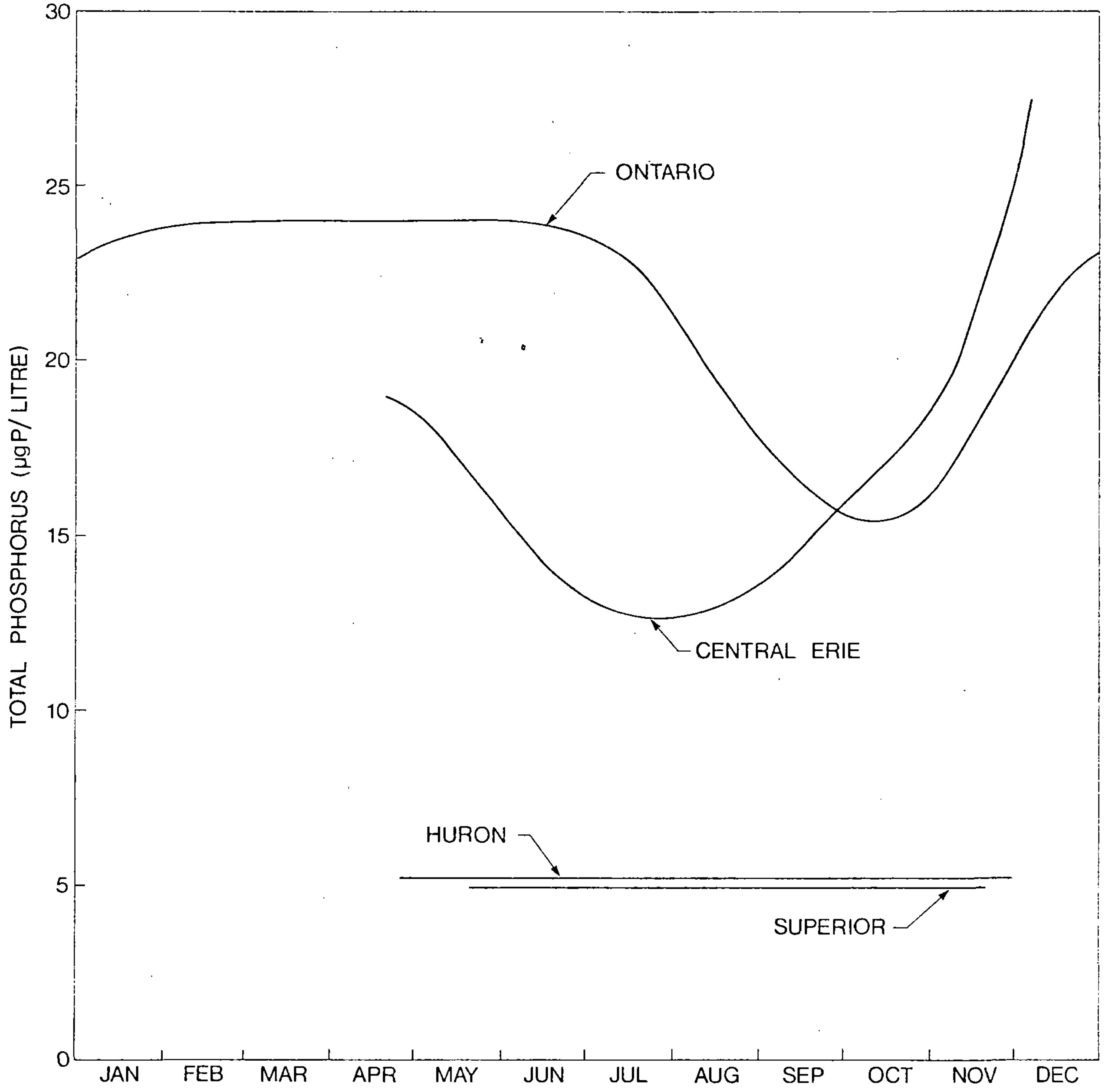

Fig. 5.
SEASONAL CYCLES OF TOTAL PHOSPHORUS (µg P/ LITRE) IN OFFSHORE, SURFACE WATERS OF 4 GREAT LAKES BASINS. THE SMOOTHED CURVES WERE DRAWN FROM MEAN VALUES ON CRUISES IN THE YEARS 1967 to 1974.

Summertime mean values in each year.

For assigning trophic indices and for the study of trends, I calculated the summertime mean values of Secchi reciprocals, total chlorophyll *a*, particulate organic carbon, and total phosphorus, all in offshore, near-surface waters. The resulting data are listed in Tables 5 to 8. To calculate the summertime mean values, first the cruise-mean values were calculated. (Results are listed in the Appendix, Tables A-1 to A-16). Then for each year the cruise-mean values were plotted against time of year. With linear interpolation between the points, values were extracted at 10-day intervals throughout the summer period, and these extracted values were averaged (arithmetic mean value calculated) to give the summertime mean value. The number of cruises associated with each summertime mean value can be ascertained from the Appendix. The "trophic indices" listed in the right-hand column of Tables 6 to 8 will be explained and used later in the paper.

Development of a trophic scale.

It was found that summertime mean values of total chlorophyll *a*, particulate organic carbon, and total phosphorus were all approximately proportional to Secchi reciprocal values (see Figures 6 to 8). To derive a simple relationship of the form $(x = a.y)$, the grand mean values for Central Lake Erie and Lake Ontario in summer were calculated. Then the mean value for the two lakes together was calculated, with equal weight being given to each of the two lakes. A straight line was

Table 5. Trophic status of the four Great Lakes basins indicated by Secchi reciprocals (m^{-1} x 30) in offshore waters during summer in the years 1966 to 1975.

Lake	Year	Summer - mean Secchi reciprocal (m^{-1} x 30)	Grand mean Secchi reciprocal (m^{-1} x 30)
Superior	1967	2.6	
	1968	3.5	
	1969	2.6	3.1
	1970	3.0	
	1973	3.8	
Huron	1966	2.8	
	1968	3.7	
	1969	4.7	
	1970	3.0	3.7
	1971	4.1	
	1972	3.9	
	1974	3.5	
Central Erie	1966	5.2	
	1967	4.4	
	1968	8.0	
	1969	6.9	
	1970	6.0	6.3
	1971	6.6	
	1972	6.6	
	1973	8.1	
	1975	5.1	
Ontario	1966	9.4	
	1967	9.5	
	1968	9.5	
	1969	10.8	10.8
	1970	11.7	
	1974	12.0	
	1975	12.6	

Table 6. Trophic status of the four Great Lakes basins indicated by total chlorophyll a in offshore, near-surface waters during summer in the years 1967 to 1975.

Lake	Year	Summer -mean TCa (μg/litre)	Grand mean TCa (μg/litre)	Trophic index (μg/litre x 2.0)
Superior	1968	0.7	1.0	2.0
	1973	1.3		
Huron	1968	1.1	1.2	2.4
	1971	1.3		
	1972	0.7		
	1973	1.8		
	1974	1.1		
Central Erie	1968	4.0	3.9	7.8
	1970	3.8		
	1972	3.8		
	1973	4.2		
	1975	3.6		
Ontario	1967	5.2	5.3	10.6
	1969	4.6		
	1970	5.9		
	1972	6.4		
	1974	4.8		
	1975	4.8		

Table 7. Trophic status of the four Great Lakes basins indicated by particulate organic carbon in offshore, near-surface waters during summer in the years 1972 to 1975.

Lake	Year	Summer -mean POC (μg/litre)	Grand mean POC (μg/litre)	Trophic index (μg/litre x 0.020)
Superior	1973	147.	147.	2.9
Huron	1974	187.	187.	3.7
Central Erie	1972	450.	464.	9.3
	1973	525.		
	1974	400.		
	1975	480.		
Ontario	1972	676.	526.	10.5
	1974	436.		
	1975	465.		

Table 8. Trophic status of the four Great Lakes basins indicated by total phosphorus in offshore, near-surface waters during summer in the years 1968 to 1975.

Lake	Year	Summer -mean Total P (µg P/litre)	Grand mean Total P (µg P/litre)	Trophic index (µg P/litre x 0.56)
Superior	1971	3.1	4.6	2.6
	1973	6.0		
Huron	1968	4.3	4.8	2.7
	1969	6.3		
	1971	3.6		
	1972	5.0		
	1974	4.6		
Central Erie	1970	11.2	14.2	8.1
	1971	15.4		
	1972	14.9		
	1974	14.3		
	1975	15.4		
Ontario	1968	18.7	19.5	11.1
	1969	17.5		
	1970	21.5		
	1971	22.2		
	1972	18.9		
	1974	19.7		
	1975	17.8		

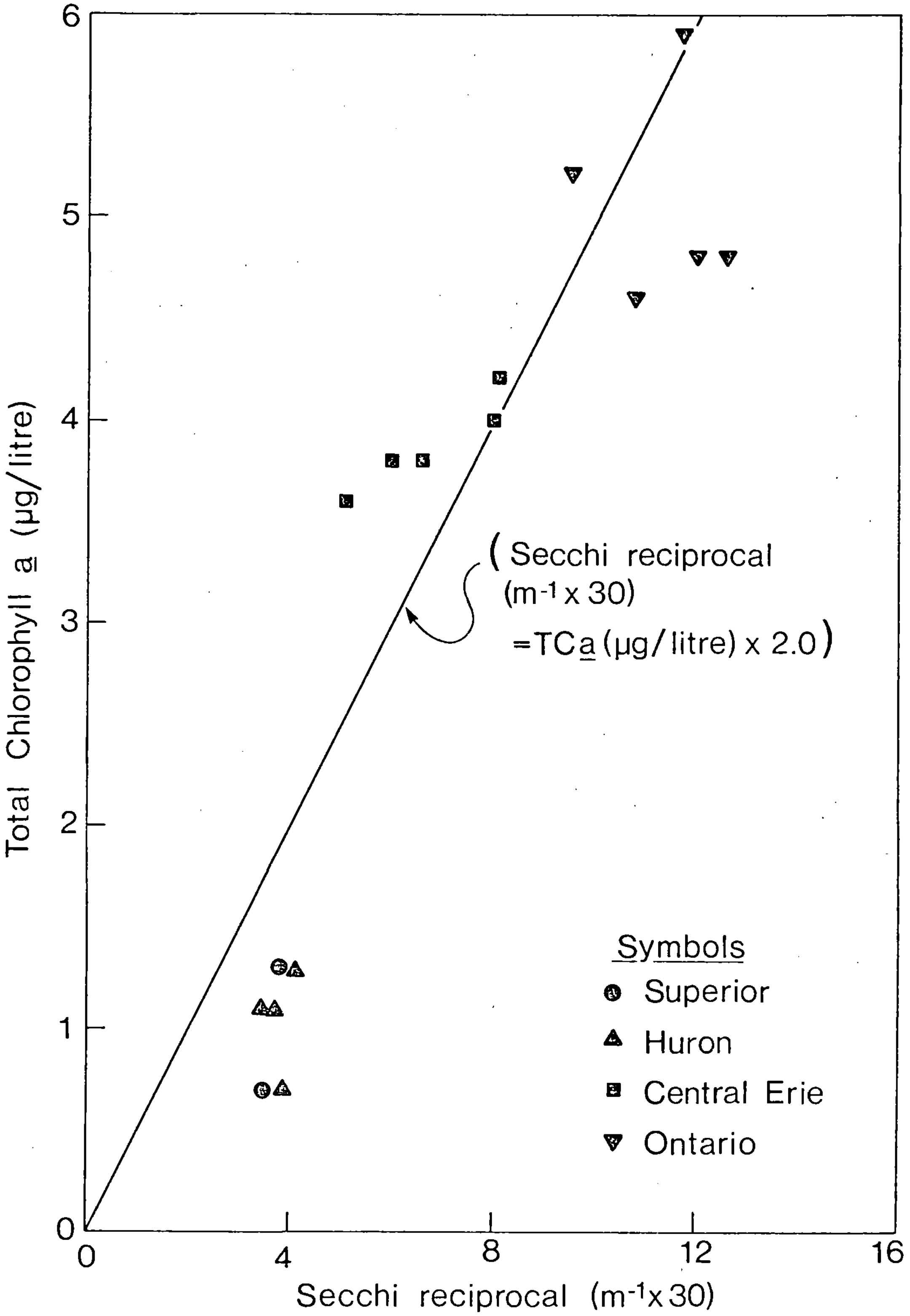

Fig. 6.

SECCHI RECIPROCAL VS. TOTAL CHLOROPHYLL a IN THE GREAT LAKES: SUMMERTIME MEAN VALUES AND A SIMPLE STRAIGHT - LINE RELATIONSHIP.

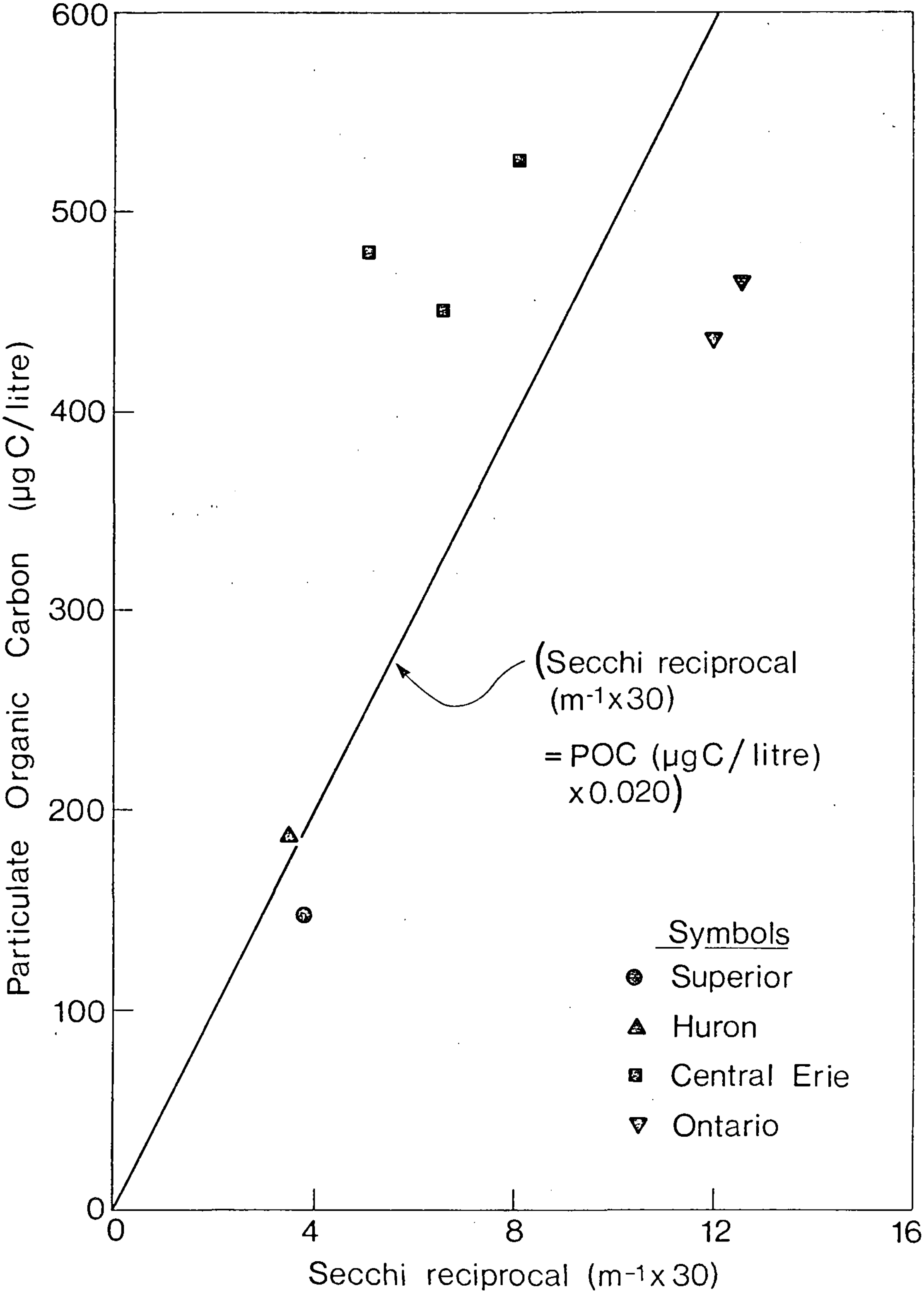

Fig. 7.

SECCHI RECIPROCAL VS. PARTICULATE ORGANIC CARBON IN THE GREAT LAKES: SUMMERTIME MEAN VALUES AND A SIMPLE STRAIGHT-LINE RELATIONSHIP.

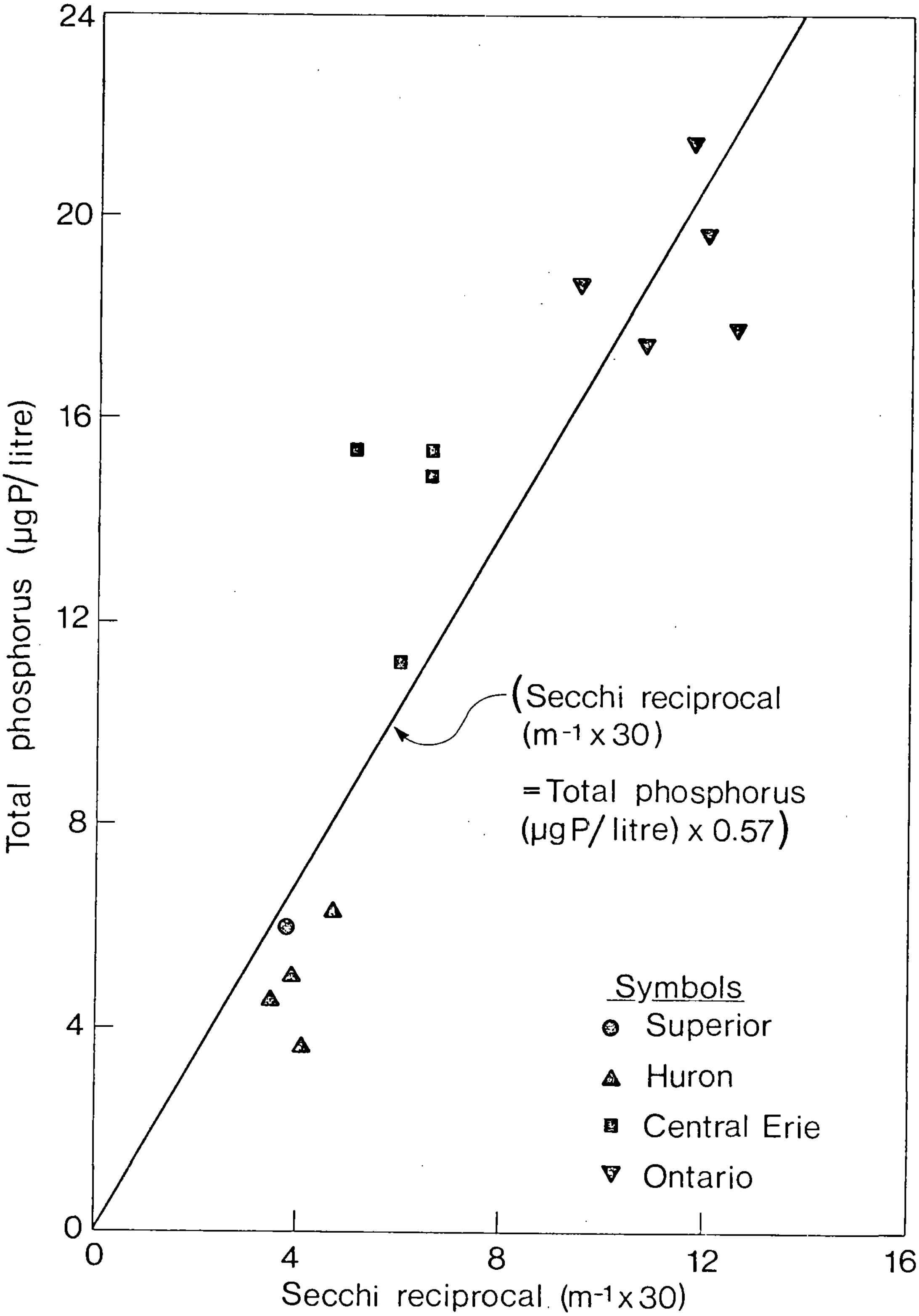

Fig. 8 ·

SECCHI RECIPROCAL VS. TOTAL PHOSPHORUS IN THE GREAT LAKES: SUMMERTIME MEAN VALUES AND A SIMPLE STRAIGHT-LINE RELATIONSHIP.

derived that passed through the point for the pair of grand mean values and the origin. Sophisticated curve-fitting as by the least-squares method was not used, in order to obtain the most simple relationship and a zero intercept.

Cruise-mean values in summer, rather than summertime means, were used to calculate the grand-mean values for each of the two lakes, to give more weight to the summers having more data.

At this place in the paper, I will introduce the four trophic classes: oligotrophic, mesotrophic, eutrophic, and hypereutrophic. Their quantitative ranges will be defined and derived. (1) <u>Secchi reciprocal values for each trophic class</u>: The limits of Secchi reciprocal values for each trophic class are chosen arbitrarily, and then the equivalent values for the 3 other parameters are calculated from their mean ratios with Secchi reciprocal in Central Lake Erie and Lake Ontario (Tables 9 to 12). The Secchi reciprocal values have the following class limits, by definition:

oligotrophic	0 to 5 (m^{-1} x 30)
mesotrophic	5 to 10 (m^{-1} x 30)
eutrophic	10 to 30 (m^{-1} x 30)
hypereutrophic	>30 (m^{-1} x 30)

(2) <u>Total chlorophyll *a*, limits for each trophic class</u>: Equivalent ranges for total chlorophyll *a* are calculated in Table 9. By chance the class-limits for chlorophyll turned out to be quite simple numbers, (0, 2.5, 5, and 15 µg/litre) that are easy to remember.

(3) <u>Particulate organic carbon, limits for each trophic class</u>: Class-

Table 9. Computation of the trophic class ranges for total chlorophyll a in summer in the Great Lakes.

(a) The mean values of total chlorophyll a and Secchi reciprocals in Central Lake Erie during summer (June 15 - September 5):

Mean date of cruise	Cruise - mean TCa (μg/litre)	Cruise - mean Secchi reciprocal (m^{-1} x 30)
Aug. 1, 1968	3.7	8.0
Sept. 2, 1968	6.5	9.5
July 5, 1970	2.0	4.8
July 30, 1970	4.5	6.5
Aug. 27, 1970	4.9	5.9
Aug. 19, 1971	2.4	6.7
Aug. 30, 1972	6.3	6.2
July 27, 1973	4.4	7.0
Aug. 30, 1973	5.8	9.2
Aug. 23, 1974	3.4	4.2
June 27, 1975	2.0	4.1
Aug. 9, 1975	4.0	5.0
Grand mean summertime values:	4.2 μg/ℓ	6.4 (m^{-1} x 30)

Table 9 (Cont'd)

(b) The mean values of total chlorophyll a and Secchi reciprocal in Lake Ontario during summer (July - September):

Mean date of cruise		Cruise-mean TCa (μg/litre)	Cruise-mean Secchi reciprocal (m^{-1} x 30)
July 12,	1967	3.2	9.3
July 27,	"	5.5	12.0
Aug. 7,	"	3.2	10.6
Aug. 23,	"	4.8	10.5
Sept. 7,	"	5.6	8.3
Sept. 18,	"	8.4	7.4
July 4,	1968	9.0	13.0
July 10,	1969	5.5	11.7
Aug. 7,	"	3.9	11.1
Sept. 7,	"	3.5	10.5
July 18,	1970	5.8	11.0
Aug. 19,	"	3.9	16.3
Sept. 17,	"	7.4	8.1
Aug. 11,	1971	4.8	22.2
July 19,	1972	8.1	8.8
Sept. 7,	"	6.5	14.5
July 25,	1974	4.1	10.6
Aug. 8,	"	4.0	14.8
Aug. 14,	"	4.4	14.4
Aug. 20,	"	3.3	23.1
Sept. 5,	"	4.8	10.1
Sept. 18,	"	6.8	9.6
July 4,	1975	5.5	8.4
July 23,	"	2.9	18.9
Aug. 14,	"	4.5	16.2
Sept. 5,	"	6.0	10.2
Sept. 25,	"	5.6	6.6
Grand mean summertime values:		5.2 μg/ℓ	12.2 (m^{-1} x 30)

Table 9 (Cont'd)

(c) Computation of grand mean values, Central Lake Erie and Lake Ontario in summer:

	Mean total Chlorophyll a (μg/litre)	Mean Secchi reciprocal (m^{-1} x 30)
Central Lake Erie	4.2	6.4
Lake Ontario	5.2	12.2
Grand mean values:	4.7	9.3

(d) Computation of the lower limit of total chlorophyll a for each trophic class:

(1) mesotrophic class, Secchi reciprocal

= 5.0 (m^{-1} x 30) :

$4.7 \times \frac{5.0}{9.3} = 2.5$ μg/litre.

(2) eutrophic class, Secchi reciprocal

= 10.0 (m^{-1} x 30) :

$4.7 \times \frac{10.0}{9.3} = 5.1 \simeq 5.0$ μg/litre.

(3) hypereutrophic class, Secchi reciprocal

= 30. (m^{-1} x 30) :

$4.7 \times \frac{30.}{9.3} = 15.2 \simeq 15.0$ μg/litre.

limits for POC are derived in Table 10. Again by chance the class limits are easy to remember (0, 250, 500, 1500 μg/litre).

(4) Total phosphorus in summer, limits for each trophic class: Class-limits for total phosphorus in surface waters during summer are derived in Table 11.

(5) Total phosphorus in late winter, limits for each trophic class: Total phosphorus in late winter has been measured in Lake Ontario only. The values are quite constant in the interval February to May (Figure 5). Therefore data from cruises in that period in each year are used to derive trophic class ranges, from the relationship with summer-mean Secchi reciprocal values (Table 12). The class-limits for total phosphorus in winter are only slightly higher than the corresponding ranges for total phosphorus in summer. Again, by chance, they are simple numbers that are easy to remember (0, 10, 20, 60 μg/litre).

The trophic system just derived is summarized in Table 13. Conversion factors for placing observed values on a common scale with Secchi reciprocals (m^{-1} x 30) are given in Table 14.

The trophic scale and classification scheme just developed is linear with respect to plankton abundance, although the classes are not all of the same width.

Trends in summer, 1966 to 1975

Summertime mean values for each parameter, year and basin have been listed in Tables 5 to 8; they are now illustrated in Figures 9 to 12. Along with the data-points and linear interpolation

Table 10. Computation of the trophic class ranges for particulate organic carbon in summer in the Great Lakes.

(a) The mean values of particulate organic carbon and Secchi reciprocal in Central Lake Erie during summer (June 15 - September 5):

Mean date of cruise		Cruise-mean POC (μg/litre)	Cruise-mean Secchi reciprocal (m^{-1} x 30)
Aug. 3,	1972	337.	5.9
Aug. 30,	"	564.	6.2
July 27,	1973	510.	7.0
Aug. 30,	"	540.	9.2
Aug. 23,	1974	400.	4.2
June 27,	1975	416.	4.1
Aug. 9,	"	545.	5.0
Grand mean summertime values:		473. μg/litre	5.9 (m^{-1} x 30)

Table 10 (Cont'd)

(b) The mean values of particulate organic carbon and Secchi reciprocal in Lake Ontario during summer (July - September):

Mean date of cruise		Cruise-mean POC (μg/litre)	Cruise-mean Secchi reciprocal (m^{-1} x 30)
July 19,	1972	733.	8.8
Sept. 7,	"	708.	14.5
Sept. 21,	"	552.	12.3
July 25,	1974	518.	10.6
Aug. 8,	"	432.	14.8
Aug. 14,	"	385.	14.4
Aug. 20,	"	374.	23.1
Sept. 4,	"	415.	10.1
Sept. 18,	"	376.	9.6
July 4,	1975	614.	8.4
July 23,	"	336.	18.9
Aug. 14,	"	474.	16.2
Sept. 5,	"	516.	10.2
Sept. 25,	"	412.	6.6
Grand mean summertime values:		489. μg/litre	12.8 (m^{-1} x 30)

Table 10 (Cont'd)

(c) Computation of grand mean values, Central Lake Erie and Lake Ontario in summer:

	Mean POC (μg/litre)	Mean Secchi reciprocal (m^{-1} x 30)
Central Lake Erie	473.	5.9
Lake Ontario	489.	12.8
Grand mean values:	481.	9.4

(d) Computation of the lower limit of particulate organic carbon for each trophic class:

(1) mesotrophic class, Secchi reciprocal

= 5.0 (m^{-1} x 30):

$$481. \times \frac{5.0}{9.4} = 256. \simeq 250.\ \mu g/litre$$

(2) eutrophic class ,Secchi reciprocal

= 10.0 (m^{-1} x 30):

$$481. \times \frac{10.0}{9.4} = 512. \simeq 500.\ \mu g/litre$$

(3) hypereutrophic class, Secchi reciprocal

= 30. (m^{-1} x 30):

$$481. \times \frac{30.}{9.4} = 1530. \simeq 1500.\ \mu g/litre$$

Table 11. Computation of the trophic class ranges for total phosphorus in summer in the Great Lakes.

(a) The mean values of total phosphorus and Secchi reciprocal in Central Lake Erie during summer (June 15 - Sept. 5):

Mean date of cruise		Cruise-mean total P (μg/litre)	Cruise-mean Secchi reciprocal (m^{-1} x 30)
July 5,	1970	10.2	4.8
July 30,	"	10.9	6.5
Aug. 27,	"	10.4	5.9
Aug. 19,	1971	11.2	6.7
Aug. 3,	1972	13.7	5.9
Aug. 30	"	15.2	6.2
Aug. 23,	1974	14.3	4.2
Grand mean summertime values:		12.3 μg/litre	5.7 (m^{-1} x 30)

Table 11 (Cont'd)

(b) The mean values of total phosphorus and Secchi reciprocal in Lake Ontario during summer (July - September):

Mean date of cruise		Cruise-mean total P (μg/litre)	Cruise-mean Secchi reciprocal (m^{-1} x 30)
July 3,	1968	21.0	13.0
July 11,	1969	19.8	11.7
Aug. 7,	"	17.0	11.1
Sept. 7,	"	16.1	10.5
July 18,	1970	28.4	11.0
Aug. 19,	"	20.4	16.3
Sept. 17,	"	14.4	8.1
Aug. 11,	1971	22.2	22.2
July 18,	1972	20.3	8.8
Sept. 7,	"	17.8	14.5
Sept. 21,	"	17.0	12.3
Sept. 5,	1974	18.5	10.1
July 5,	1975	20.4	8.4
Sept. 5,	"	16.2	10.2
Sept. 25,	"	15.9	6.6
Grand mean summertime values:		19.0 μg/litre	11.7 (m^{-1} x 30)

Table 12. Computation of the trophic class ranges for total phosphorus in late winter in Lake Ontario.

(a) The mean values of total phosphorus in late winter (Feb. - May) and Secchi reciprocal in summer, in Lake Ontario:

Year	Late winter mean value of total P (μg/litre)	Summertime mean value of Secchi reciprocal (m^{-1} x 30)
1968	24.0	9.5
1969	22.2	10.8
1970	23.5	11.7
1974	24.3	12.0
1975	21.1	12.6
Grand mean values:	23.0 μg/litre	11.3 (m^{-1} x 30)

Table 12 (Cont'd)

(b) Computation of the lower limit of total phosphorus in late winter for each trophic class:

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(1) mesotrophic class, Secchi reciprocal

$= 5.0\ (m^{-1} \times 30)$:

$$23.0 \times \frac{5.0}{11.3} = 10.2 \approx 10.0\ \mu g/\text{litre}$$

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(2) eutrophic class, Secchi reciprocal

$= 10.0\ (m^{-1} \times 30)$:

$$23.0 \times \frac{10.0}{11.3} = 20.4 \approx 20.\ \mu g/\text{litre}$$

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(3) hypereutrophic class, Secchi reciprocal

$= 30.\ (m^{-1} \times 30)$:

$$23.0 \times \frac{30.0}{11.3} = 61.1 \approx 60.\ \mu g/\text{litre}$$

Table 13. Ranges defining the trophic system.

	Classification			
Parameter	Oligotrophic	Mesotrophic	Eutrophic	Hypereutrophic
Secchi depth	> 6 m	6 to 3 m	3 to 1 m	< 1 m
Secchi reciprocal	0 to 5 (m^{-1} x 30)	5 to 10 (m^{-1} x 30)	10 to 30 (m^{-1} x 30)	> 30 (m^{-1} x 30)
Total chlorophyll a	0.0 to 2.5 µg/litre	2.5 to 5.0 µg/litre	5.0 to 15. µg/litre	> 15. µg/litre
Particulate organic carbon	0 to 250. µg/litre	250. to 500. µg/litre	500. to 1500. µg/litre	> 1500. µg/litre
Total phosphorus in summer	0 to 9.0 ≈0 to 10 µg/litre	9.0 to 18.0 ≈ 10 to 20 µg/litre	18.0 to 50. µg/litre	> 50. µg/litre
Total phosphorus in winter	0 to 10.2 ≈0 to 10. µg/litre	10.2 to 20.4 ≈ 10. to 20. µg/litre	20 to 60 µg/litre	> 60 µg/litre

Table 14. Conversion factors for transforming observed values to the scale of Secchi reciprocals (m^{-1} x 30).

Parameter	Conversion factor
Total chlorophyll a (μg/litre)	$\times \frac{10.0}{5.0} = \times\ 2.0$
Particulate organic carbon (μg/litre)	$\times \frac{10.0}{500} = \times\ 0.020$
Total phosphorus in summer (μg P/litre)	$\times \frac{10.0}{18.} = \times\ 0.56$
Total phosphorus in winter (μg P/litre)	$\times \frac{10.0}{20} = \times\ 0.50$

to give trends, I have shown the trophic class limits according to the trophic system just developed.

Figure 9 shows the trends and classifications for Secchi reciprocal values. Lake Ontario had increasing turbidity; the rate of increase from 1968 to 1975 was about 4% per year. Central Lake Erie was highly variable in those years. The Secchi reciprocal values can be influenced by particle size, as well as by mass concentration of particles. Larger particles produce smaller Secchi reciprocal values (Postma, 1961). Changes in particle size might perhaps have influenced the Secchi reciprocal variability observed in Central Lake Erie. Lakes Huron and Superior fall in the oligotrophic range of Secchi reciprocal values.

In Figure 9 and following figures, synonyms are introduced for the trophic classes, oligotrophic, mesotrophic, eutrophic, and (off scale, not shown) hypereutrophic, as follows:

hypereutrophic = very high = very poor
eutrophic = high = poor
mesotrophic = medium = fair
oligotrophic = low = good.

The middle set of synonyms, 'very high', etc., are only non-technical descriptive words intended for the layman. The right-hand set, 'very poor', etc., are value-judgment words being assigned to the quantitative trophic classes, intended to describe the current general thinking about the value of trophic status in the two areas of aesthetic worth and associated practical problems. Similar value-judgment words were introduced by Vollenweider (1968): he described specific external

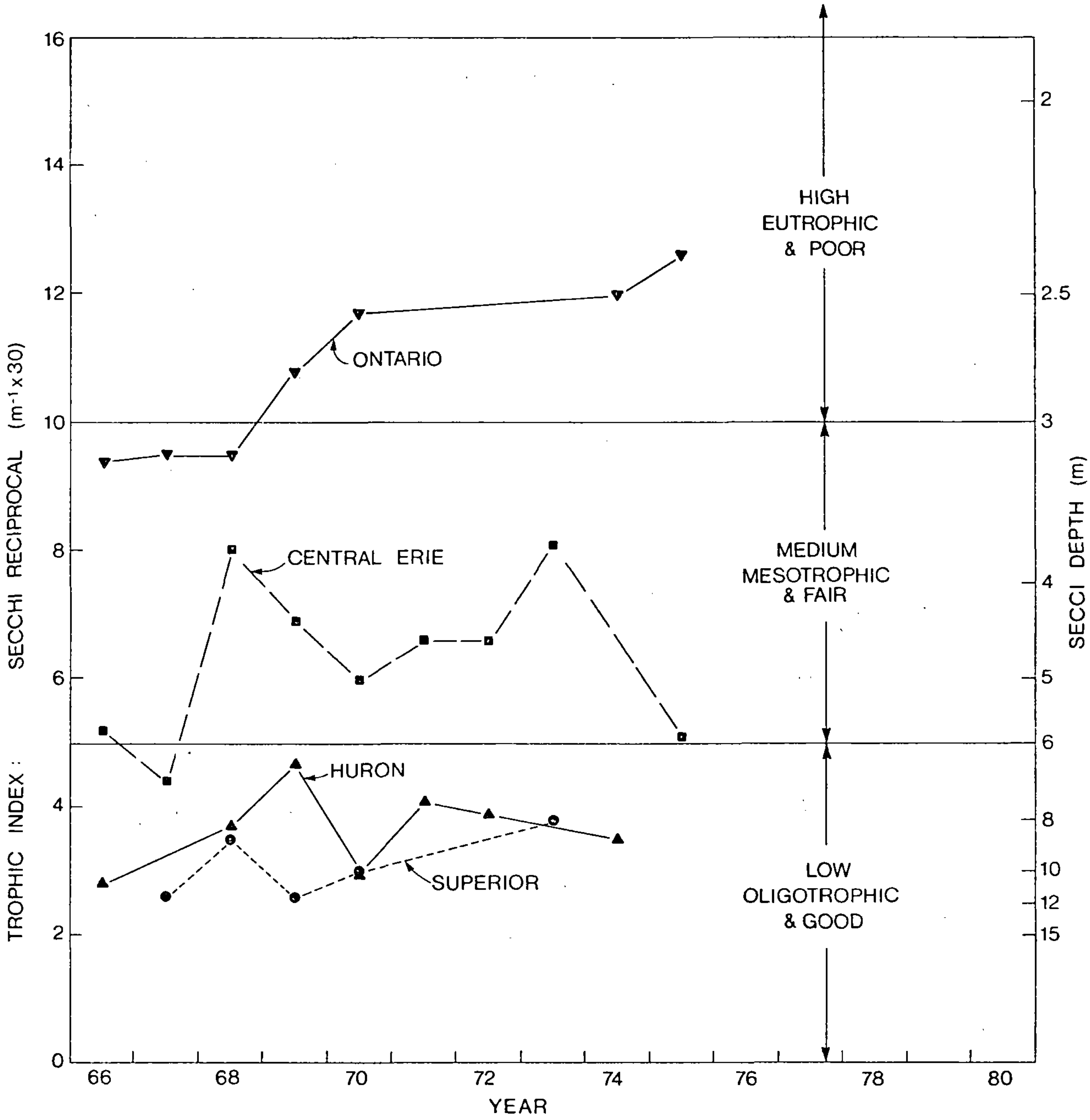

Fig. 9.

MEAN VALUES OF SECCHI RECIPROCAL DURING SUMMER IN THE OFFSHORE PART OF 4 GREAT LAKES BASINS: DATA FOR THE YEARS 1966 TO 1975. UNITS ARE $(m^{-1} \times 30)$.

loadings of nitrogen and phosphorus as 'permissible' and 'dangerous'. Such value judgments are a positive step towards defining goals in trophic management.

Figure 10 shows trends and classifications for total chlorophyll _a_. Lake Ontario was highly variable whereas Central Lake Erie's values were nearly constant, in the middle of the mesotrophic class. Lakes Huron and Superior are oligotrophic in their chlorophyll content.

Figure 11 illustrates the summertime mean values of particulate organic carbon. The high value for Lake Ontario in 1972 has already been discussed in connection with Figure 4. Lakes Ontario and Central Erie fell near the mesotrophic/eutrophic boundary for POC. Lakes Huron and Superior are oligotrophic. There are too few years with data on POC to ascertain trends in any of the basins, except perhaps Central Lake Erie for which it is fairly constant.

Figure 12 shows trends and classes for summertime total phosphorus. Lake Ontario was in the lower part of the eutrophic class; Central Lake Erie was mesotrophic with constant values from 1971 to 1975; Lakes Huron and Superior are oligotrophic. The low levels of total phosphorus in Huron and Superior are not accurately defined in these data. Note for instance the apparent doubling of summertime mean total phosphorus in Lake Superior, from 3 μg P/litre in 1971 to 6 μg/litre in 1973.

Lake Ontario: total phosphorus trend in the late-winter period.

Total phosphorus mean values in Lake Ontario in February to May of a series of years were listed in Table 12. They are illustrated

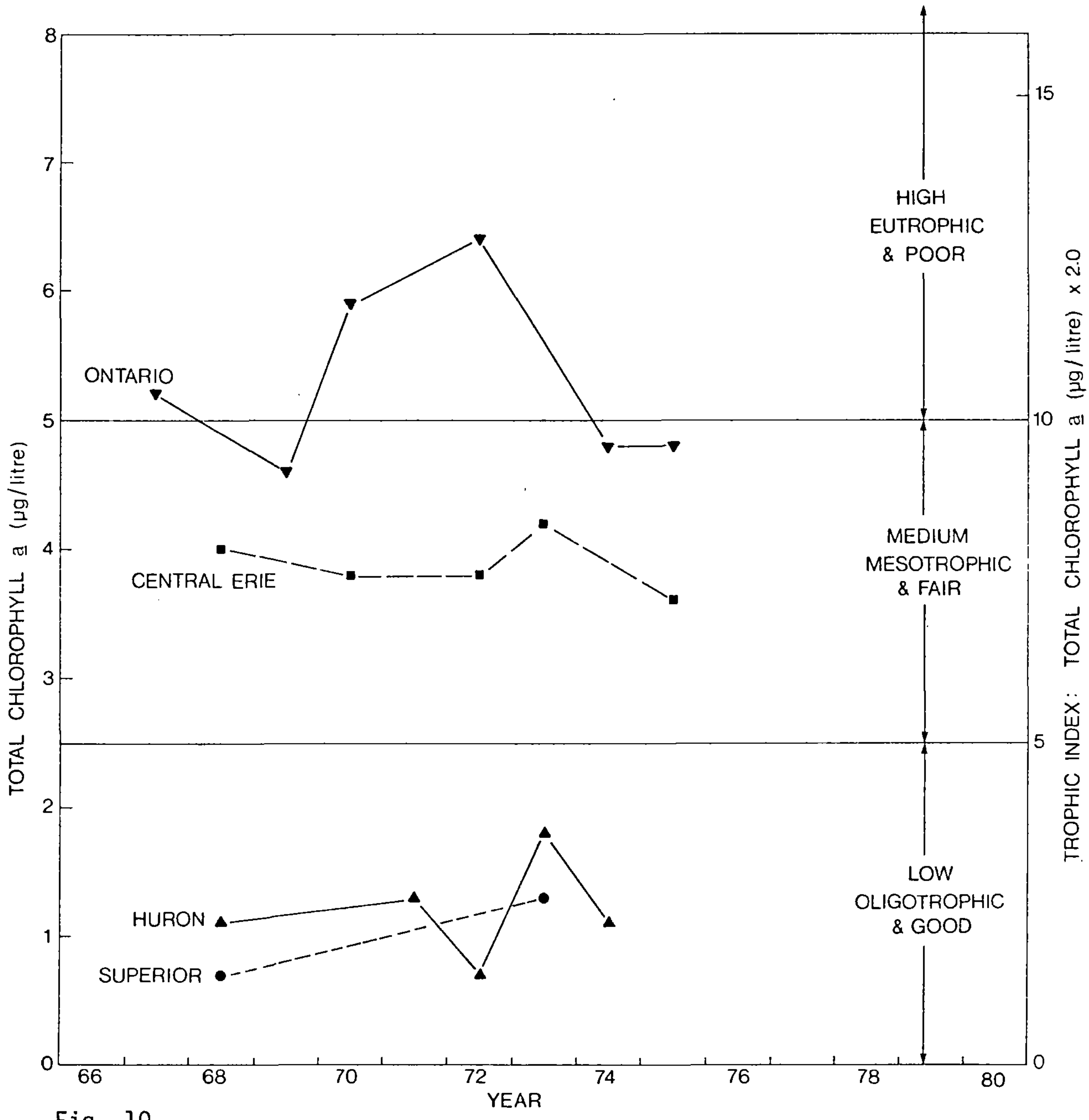

Fig. 10.
MEAN VALUES OF TOTAL CHLOROPHYLL a DURING SUMMER IN THE OFFSHORE, SURFACE WATERS OF 4 GREAT LAKES BASINS: DATA FOR THE YEARS 1967 to 1975. UNITS ARE MICROGRAMS PER LITRE.

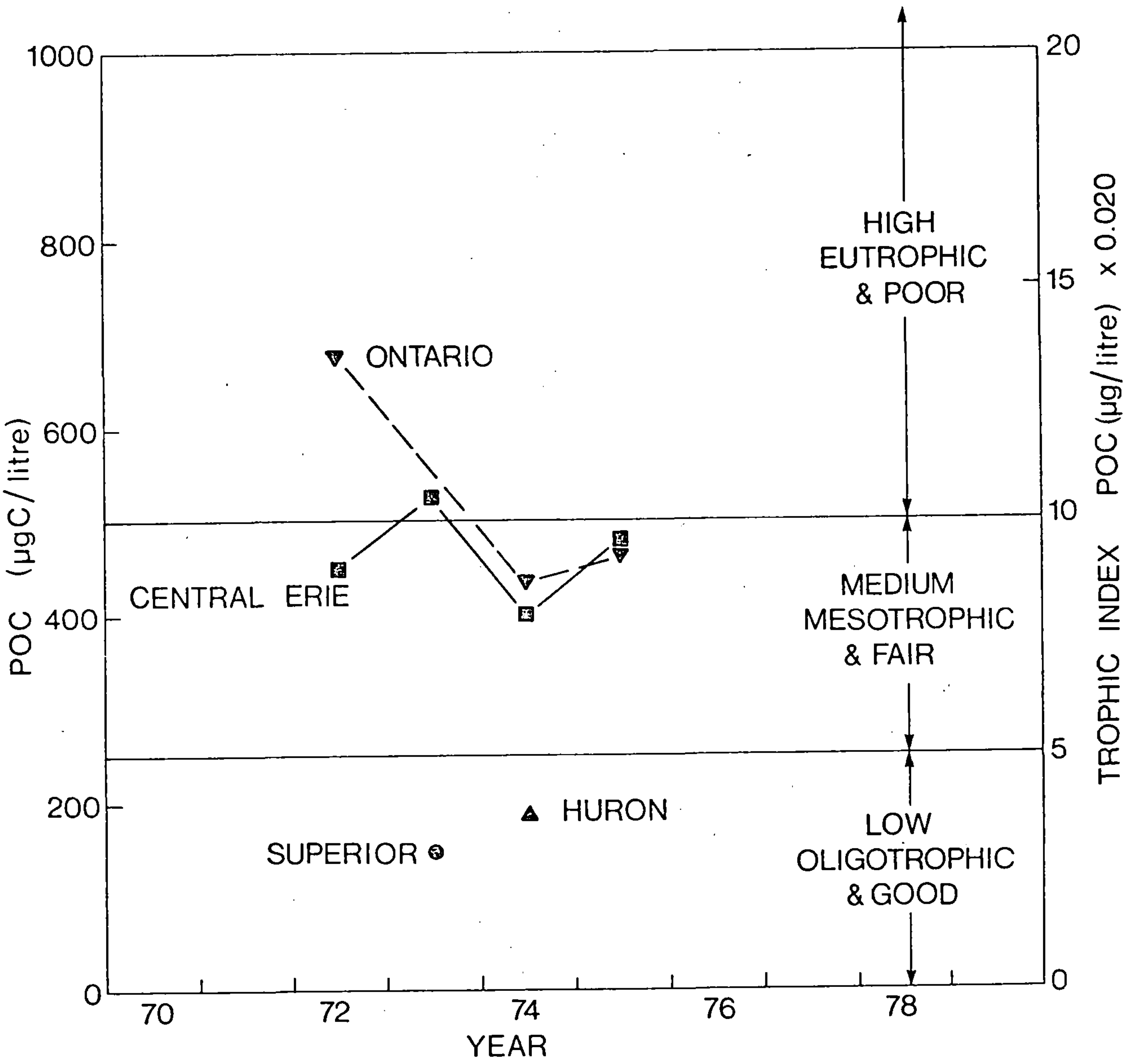

Fig. 11.
MEAN VALUES OF PARTICULATE ORGANIC CARBON DURING SUMMER IN THE OFFSHORE, SURFACE WATERS OF 4 GREAT LAKES BASINS: DATA FOR THE YEARS 1972 to 1975. UNITS ARE MICROGRAMS CARBON PER LITRE.

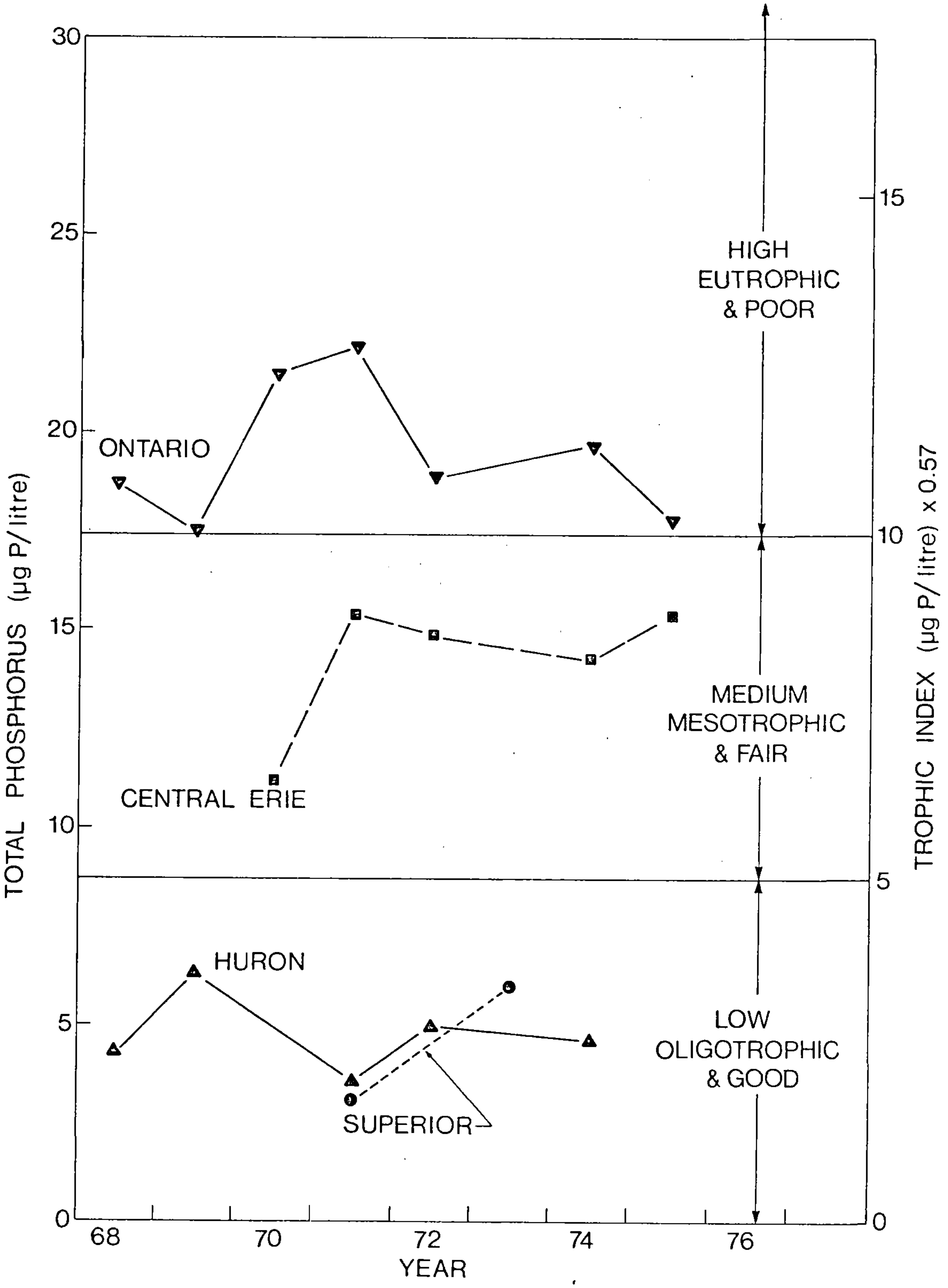

Fig. 12.

MEAN VALUES OF TOTAL PHOSPHORUS DURING SUMMER IN THE OFFSHORE, SURFACE WATERS OF 4 GREAT LAKES BASINS: DATA FOR THE YEARS 1968 to 1975. UNITS ARE MICROGRAMS PHOSPHORUS PER LITRE.

now in Figure 13; they were nearly constant at about 23 μg P/litre from 1968 to 1975, and fell in the lower part of the eutrophic class.

Summary of trends.

Among these parameters, basins, and years, only Secchi 'turbidity' in Lake Ontario was increasing. The other values in Lake Ontario and Central Lake Erie surface waters were either steady and constant over the years, or too variable to allow any trend or constancy to be seen. These conclusions are listed in Table 15.

The rate of change of Secchi reciprocal values in Lake Ontario (Figure 9) was about 38% per 10 years, whereas total phosphorus in that lake was not changing (Figure 13). Additional information about dissolved nutrients in Lake Ontario was contributed by A. Fraser (Can. Cent. Inland Waters, personal communication): dissolved inorganic phosphate in late winter was constant since 1968, but nitrogen in the forms nitrate and ammonia in late winter was increasing at a rate, quite similar to summertime Secchi reciprocals, of about 47% per 10 years. Apparently Lake Ontario's summertime plankton have been limited by nitrogen, not phosphorus. This suggests the question: how much of a reduction in phosphorus loading will be necessary to restore growth-limitation by phosphorus in Lake Ontario?

Remarks on confidence limits.

In Figures 9 to 13 are shown trends of four parameters in four basins. No confidence limits or estimates of probable error of each

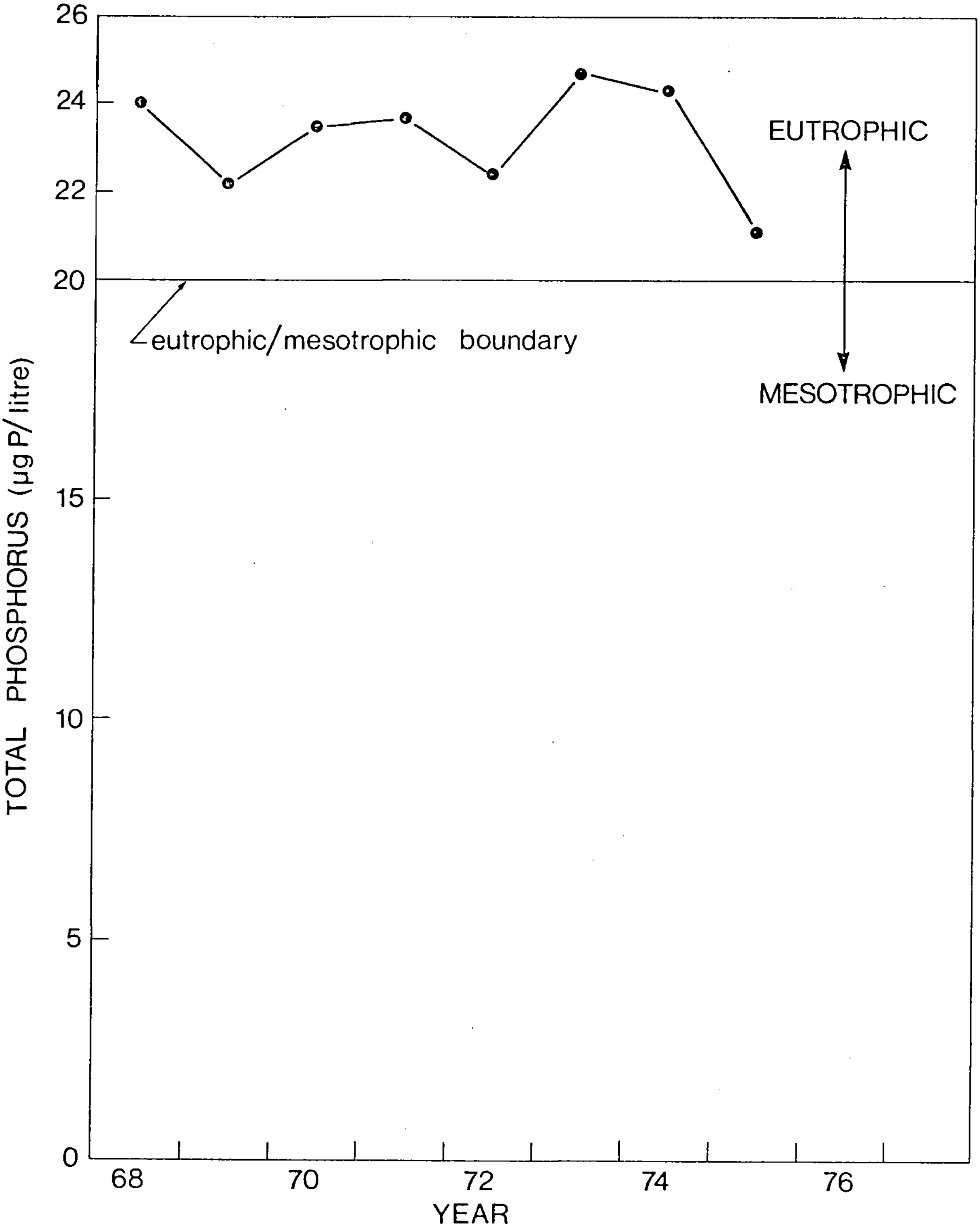

Fig. 13.

MEAN VALUES OF TOTAL PHOSPHORUS DURING LATE WINTER (FEBRUARY to MAY) IN THE OFFSHORE, SURFACE WATERS OF LAKE ONTARIO: DATA FOR THE YEARS 1968 to 1975. UNITS ARE MICROGRAMS PHOSPHORUS PER LITRE.

Table 15. Summary of trends of summertime mean values in Lakes Erie and Ontario, ≃1968 to 1975.

Parameter	Central Lake Erie	Lake Ontario
Secchi "turbidity"	variable	increasing, 4% per year
Total chlorophyll <u>a</u>	constant	variable
Particulate organic carbon	constant	variable
Total phosphorus	constant	constant

(annual) point are shown. Therefore some remarks are necessary.

The points represent mean values for a variable number of stations and cruises, and it seems likely that geographical and temporal variations, and likely some analytical inaccuracies, determine the degree of dispersion of the set of data used to derive each point. Therefore it seems that any 'standard deviation' summarizes the variability within each data-set without indicating what really needs to be known: the uncertainty of each summertime mean value. Because of this reasoning no error limits are shown. They would only be misleading.

However there is another consideration that is more constructive: the meaning of the relation of the plotted points to each other. Subjectively, the sets of points appear fairly random (eg. Figure 10: the curve for chlorophyll in Lake Ontario) or fairly regular without much scatter (eg. Figure 10: the curve for chlorophyll in Central Lake Erie). Points falling between adjacent points are probably more certain than points not between adjacent points, at least for the indication of trends. No attempt has been made to quantify this idea (say, by looking at the second derivative of the trend - curve), but this subjective approach gives the reader some insight for viewing these graphs of trends.

Mean trophic status, ~1970-1975.

Mean values of four trophic indicators in the four Great Lakes basins, for the years 1970 to 1975 approximately, are listed in their conventional units in Table 16. For interpretation, they are listed

Table 16. Four trophic status indicators for near-surface waters: mean summertime values for the offshore parts of 4 Great Lakes basins in the years 1970-1975. Units in this table are the conventional ones, in contrast with the "indices" of Table 17.

	Basin			
Parameter	Superior	Huron	Central Erie	Ontario
Secchi depth (metres)	8.8	8.3	4.4	2.5
Total chlorophyll *a* (μg/litre)	1.0	1.2	3.9	5.3
Particulate organic carbon (μg/litre)	147.	187.	464.	526.
Total phosphorus (μg P/litre)	4.6	4.4	14.0	20.6

again in Table 17 and illustrated in Figures 14 to 17, with their values transformed onto the common scale developed in this paper, for which 'mesotrophic' is 5 to 10 units in every case. Labels can now be assigned for trophic classification, as follows: Lake Superior, oligotrophic; Lake Huron, oligotrophic; Central Lake Erie, mesotrophic (despite its dissolved oxygen problem); and Lake Ontario, slightly eutrophic (despite the absence of an oxygen problem). Also the numerical trophic indices put each basin somewhere on the trophic continuum.

Table 17. Four trophic status indicators for near-surface waters: mean summertime values for the offshore parts of 4 Great Lakes basins in the years 1970-1975. Values are transformed to a common scale on which the 'mesotrophic' range is 5 to 10 units.

	Basin			
Parameter	Superior	Huron	Central Erie	Ontario
Secchi reciprocal (m^{-1} x 30)	3.4	3.6	6.8	11.8
Total chlorophyll a (μg/l x 2.0)	2.0	2.4	7.8	10.6
Particulate organic carbon (μg/l x 0.020)	2.9	3.7	9.3	10.5
Total phosphorus (μg P/l x 0.57)	2.6	2.5	8.0	11.7
Mean trophic index from 4 parameters:	2.7	3.0	8.0	11.2

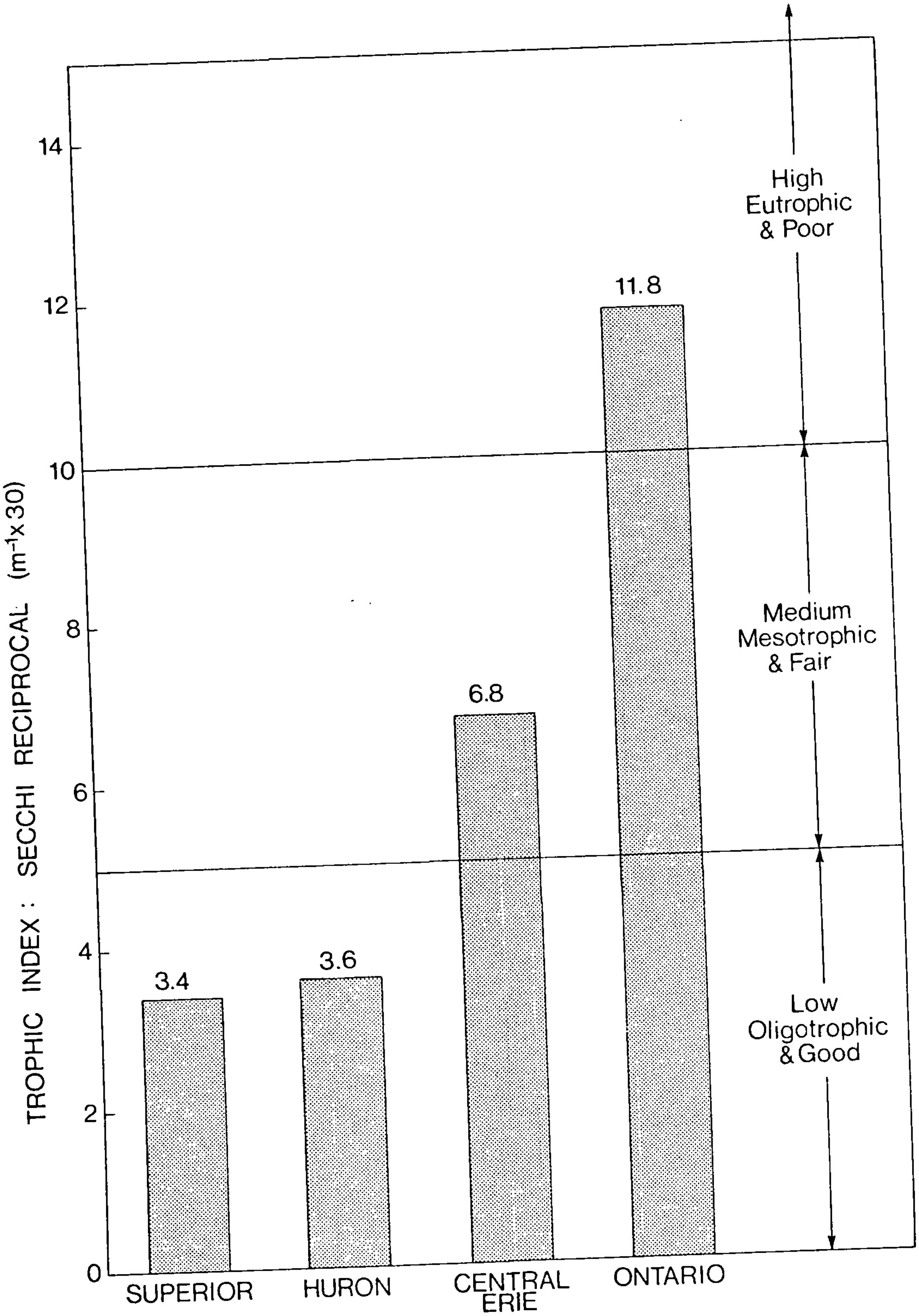

Fig. 14.
TROPHIC STATUS OF THE INTERNATIONAL GREAT LAKES INDICATED BY MEAN SECCHI RECIPROCALS ($m^{-1} \times 30$) IN OFFSHORE WATERS DURING SUMMER IN THE YEARS 1970 to 1974.

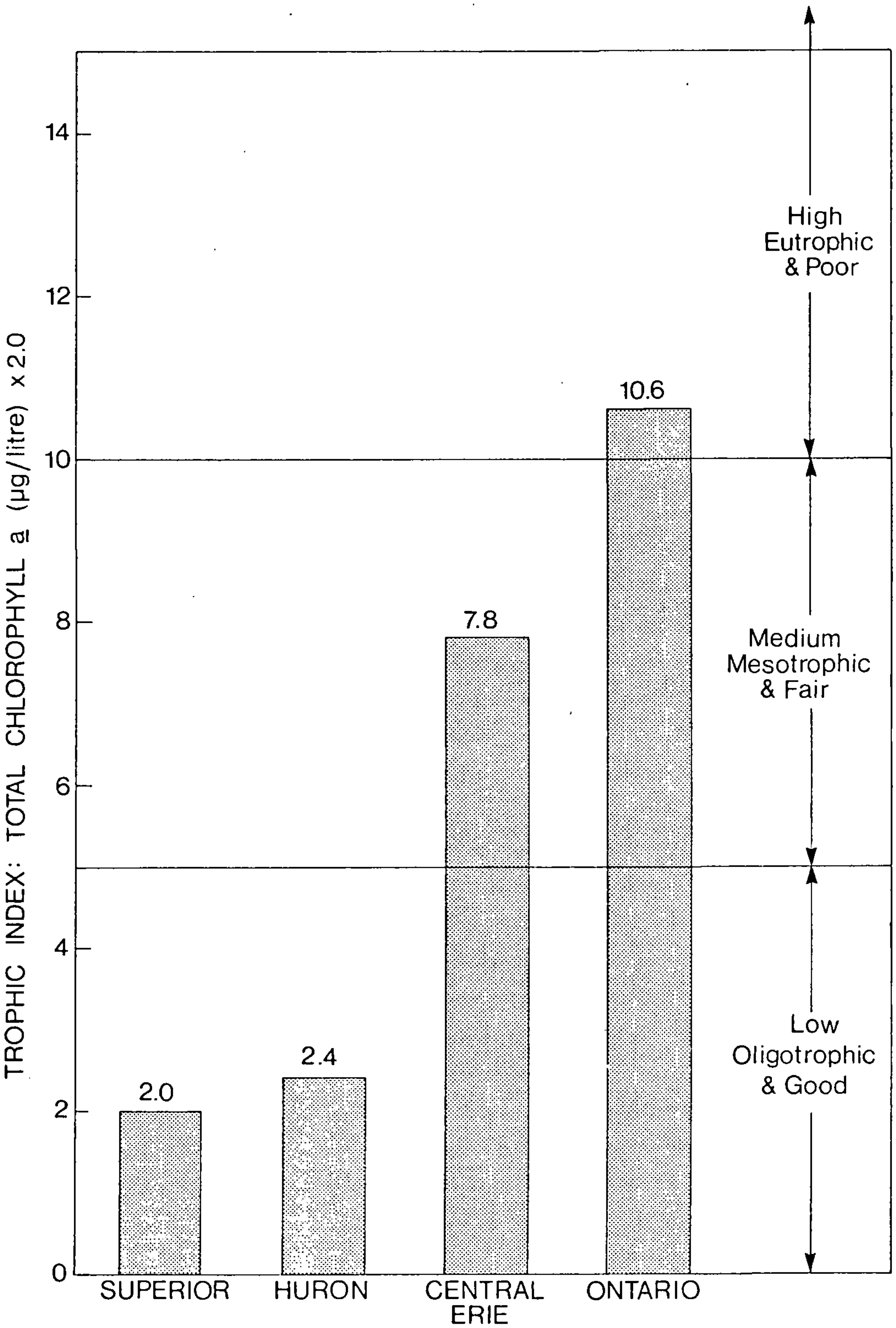

Fig. 15.

TROPHIC STATUS OF THE INTERNATIONAL GREAT LAKES INDICATED BY THE MEAN VALUES OF {TOTAL CHLOROPHYLL a (μg/LITRE) x 2.0} IN OFFSHORE, SURFACE WATERS DURING SUMMER IN THE YEARS 1967 to 1975.

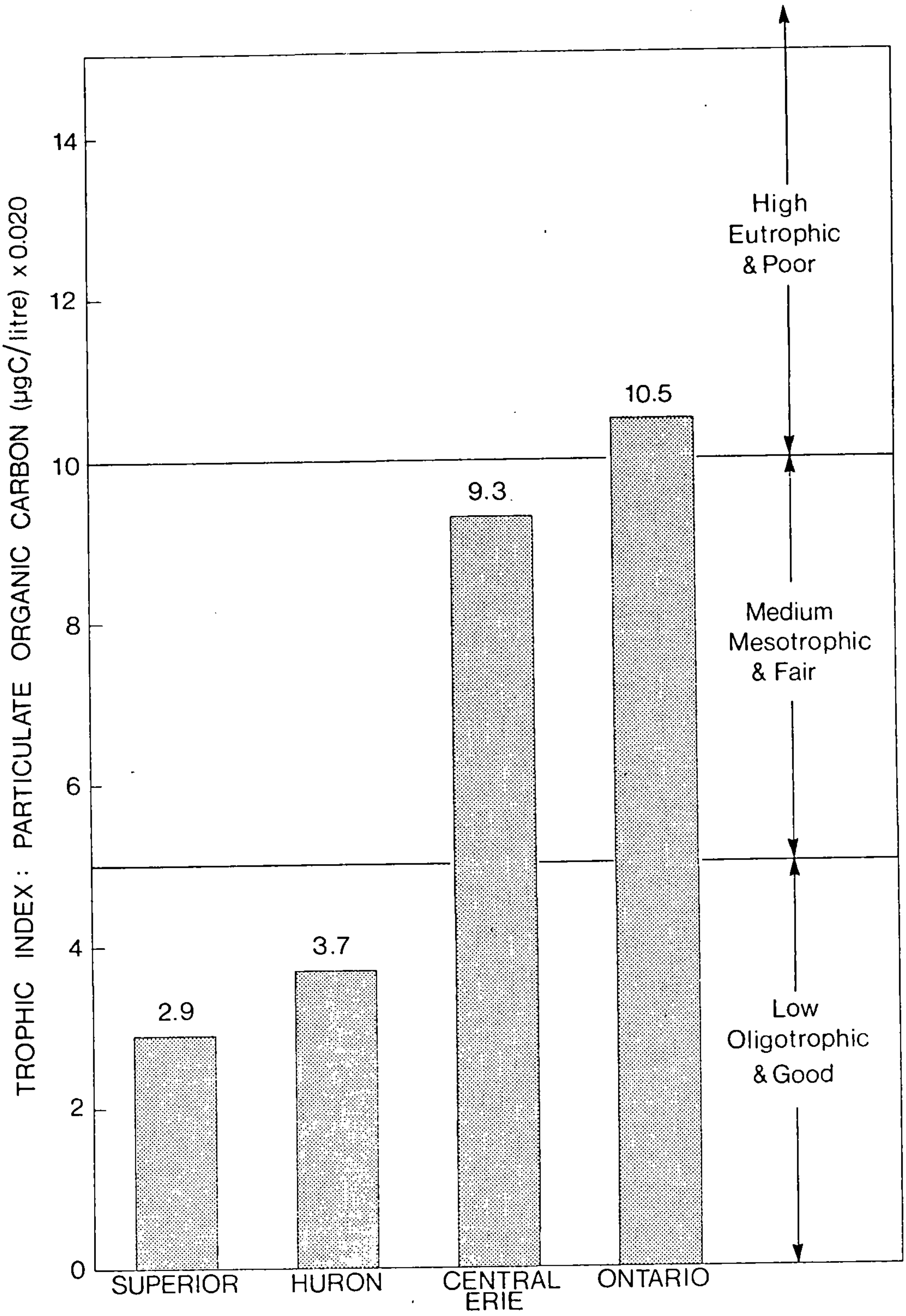

Fig. 16.
TROPHIC STATUS OF THE INTERNATIONAL GREAT LAKES INDICATED BY THE MEAN VALUES OF {PARTICULATE ORGANIC CARBON (µgC/LITRE) x 0.020} IN OFFSHORE, SURFACE WATERS DURING SUMMER IN THE YEARS 1972 to 1975.

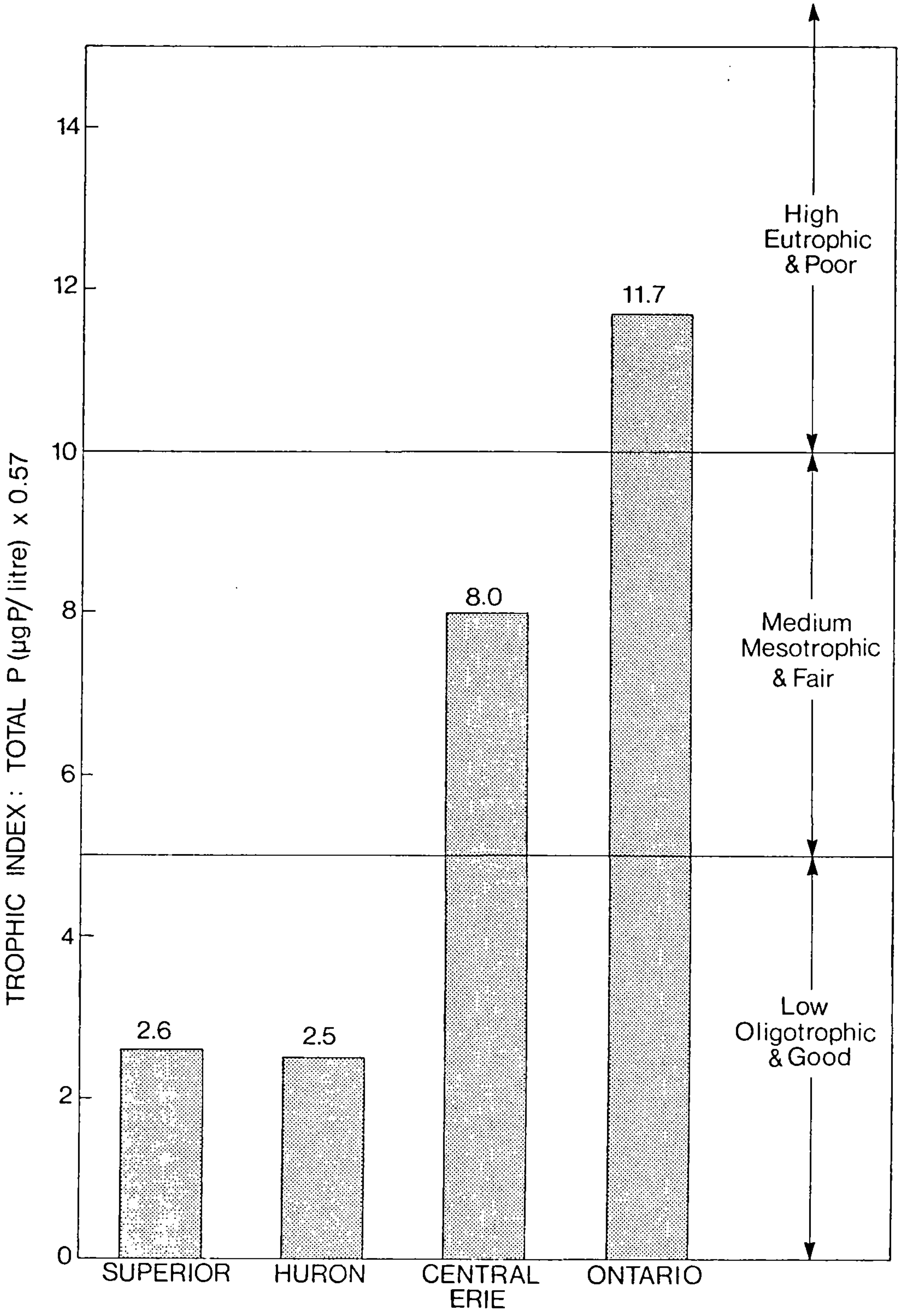

Fig. 17.

TROPHIC STATUS OF THE INTERNATIONAL GREAT LAKES INDICATED BY THE MEAN VALUES OF {TOTAL PHOSPHOROUS (µgP/LITRE) x 0.57} IN THE OFFSHORE SURFACE WATERS DURING SUMMER IN THE YEARS 1970 to 1974.

The trophic indices for particulate organic carbon in Central Lake Erie and Lake Ontario are nearly equal (Figure 16), in contrast to the other parameters. One can speculate that there is relatively more transparent plankton (zooplankton) in Central Lake Erie than in Lake Ontario, or alternatively, there may be relatively more suspended detritus, containing carbon, in Central Lake Erie.

DISCUSSION

Some adverse effects of eutrophication are: floating scums of algae on lake-surface and shoreline; difficulties in filtration and deodorization of municipal water supplies; and disappearance of valuable fish species (Hasler, 1947; and Vollenweider, 1968). These aspects justify the value judgement and associated terminology that I apply to trophic classes (oligotrophic = good; mesotrophic = fair; eutrophic = poor; hypereutrophic = very poor). It is hoped that this terminology and value judgement will contribute to development of specific water quality criteria for eutrophication of surface waters.

The trophic labels 'good', 'fair' and 'poor' are assigned without any implication intended for fishery potential: fish ponds, in practice, are deliberately fertilized, and their labels may have to be in the reverse order. It is not clear from the literature on fish production in large lakes that increased fertilization enhances fish production; it may result in coarse fish replacing highly-valued types. For consideration of this fishery aspect see, for example, Moyle, 1949.

Findenegg (1955) contended for a trophic system based upon plankton parameters such as I use in the present paper, but Findenegg's proposal was not very specific. He discussed the importance of dissolved oxygen and concluded that it confused the picture, especially for tropical lakes.

Elster (1958) wrote that after Naumann's death the focus of typology shifted more to the hypolimnion with its oxygen deficit and faunal types. The definition of trophic status became more and more obscured. Then in an interesting passage related closely to the present work, Elster (1958) wrote: "... it is the unavoidable task of limnological research to seek a standard enabling us to fit the individual lakes or the individual water body into this scale. This can never be done on the basis of a complex combination of factors, unless the combined features are related to each other unequivocally. Thus, it is necessary to select from the complex concept of trophic conditions a single, naturally occurring, quantitatively graded feature measurable by us directly or indirectly, and to establish it not only as indicator but as a definite content of the concept." Elster favours the use of production, rather than standing stock of plankton, whereas I favour plankton standing stock as a valid trophic factor and water quality indicator: that is, how much plankton and detritus are there, rather than some measure of its activity.

Returning to Thienemann's position, hypolimnetic oxygen depletion rates can be adjusted to "areal" rates to compensate for morphometric effects and allow lakes to be compared (Elster, 1958; Hutchinson, 1938) yet there may still be difficulty with oxygen comparisons due to different fallout from the epilimnion and different ratios of hypolimnetic metabolism versus permanent burial of the plankton and detritus.

Elster (1958) concludes: "... in limnology new achievements will have to assert themselves by proving that they can confirm and explain the "classic" types."

The discussion - paper of Vallentyne, Shapiro et al. (1969) set down the problem of trophic classification in a provocative way which stimulated the development of indices and classes in the present work.

Shannon and Brezonik (1972) defined trophic classes by means of groups of actual lakes (so-called "cluster analysis") in Florida. My method of assigning class ranges is more arbitrary and no doubt results in groups of various sizes in different regions: it is the absolute level of trophic status that is emphasized rather than statistical group size in some geographical region.

Dillon and Rigler (1974) reported total phosphorus at spring overturn, summer mean chlorophyll a, and summer mean Secchi depth, for 17 lakes in southern Ontario. Mean values were: total phosphorus 8.3 μg/litre; summer mean chlorophyll a 1.38 μg/litre; and summer mean Secchi reciprocal 5.5 (m^{-1} x 30). Then the values corresponding to 10.0 (m^{-1} x 30), the mesotrophic/eutrophic boundary, would be: total phosphorus at spring overturn, 15.1 μg/litre [compared to 20. for Lake Ontario]; and summer mean chlorophyll a, 2.5 μg/litre [compared to 5.0 for Lakes Erie and Ontario]. It seems plausible that humic substances are more abundant in their lakes than in Lakes Erie and Ontario, because ratios of chlorophyll to Secchi reciprocal are relatively higher in Lakes Erie and Ontario. This suggests that the lower Great Lakes may safely be used for equivalent trophic ranges for the four parameters of the present study.

Norvell and Frink (1975) studied Connecticut lakes in a manner quite similar to the present work on the Great Lakes. They listed ranges for trophic classes, as herein, but their ranges were overlapping ones for the different classes. They studied relationships among parameters, using more parameters than does the present study. But their correlation coefficients confirm that relationships are strongest among the parameters used herein.

Shapiro (1975) has reviewed trophic scales and indices, especially ones developed recently. There are many unique systems, and many of them use numerous, unrelated parameters. Some of the schemes only place lakes on a relative scale.

An initial stage in the development of the present work was reviewed by Shapiro: he listed its advantages and disadvantages. He critized the use of value judgements in trophic classification such as the terms good, fair, poor, and very poor, applied in this work to trophic classes. The present writer feels that these terms enhance communication with the public, which Shapiro advocates.

Shapiro, Lundquist, and Carlson (1975) described a program in Minnesota in which lakes were assessed by Secchi disc measurements. They affirmed that the Secchi disc method is elegantly suited to limnological assessment carried out by non-limnologists, that is, by the lay public. However, their 'trophic state index' is more complex than the one used herein: their index is 10 (6 - $\log_2$ SD(m)) whereas mine is 30/SD(m). They also mention that chlorophyll and total phosphorus are useful parameters. Their trophic scale is non-linear with respect to plankton abundance, whereas mine is linear and therefore easier to understand.

Carlson (in press, 1976, "Limnology and Oceanography") presented his system of numerical classification of lakes using primarily Secchi depths but also chlorophyll and total phosphorus. His strategy is quite similar to that of the present paper, except that he establishes a logarithmic scale rather than a linear one. Also he does not retain the classical terminology for lake types. The reader can choose one of the two systems.

The dystrophic lake type: a suggestion for classification.

A two-dimensional lake type system can be constructed with trophic status along one axis and humic content along the other axis. Euhumic (= dystrophic) lakes can be either oligotrophic or eutrophic (Hansen, 1962). To establish a quantitative scale and classes for humic content, one can use the Secchi depth criteria again: given a lake for which the transparency is caused by humic content and not by suspended plankton, mesohumic can be defined as humic contents giving Secchi depths from 3 to 6 metres, and hyperhumic can be defined as those humic contents giving Secchi depths of one metre or less. If a pure humic lake cannot be found for calibrating the scale, then the Secchi reciprocal for a mixed type can be adjusted by subtracting the fraction caused by plankton as measured by chlorophyll content, and the residual Secchi reciprocal value can be correlated with humic content.

A similar approach could be taken for shallow lakes with frequent resuspension of sediments. It is useful to keep the four parameters separate in assessing the conditions: suspended sediment will cause a high ratio of Secchi reciprocal/chlorophyll. Secchi depth and water clarity are, in general, not pure indicators of trophic status.

Dissolved oxygen in temperate lakes.

Dissolved oxygen is another very important parameter of eutrophication. A serious study of oxygen is not attempted for the present paper, but some remarks will be made to make the author's position clear.

A lake with a thin hypolimnetic layer may have an oxygen problem in summer even when the surface waters are quite clear: for example, Lake Erie's central basin (see Dobson and Gilbertson, 1971, and Dobson, Gilbertson and Sly, 1974).

For assessment of trophic status, the depletion rate of dissolved oxygen per unit area in the hypolimnion can be studied. Hutchinson (1938) helped to develop the use of the areal oxygen depletion rate in limnology. The rate of disappearance from the hypolimnion in summer was expressed as mg/cm^2/month and this was found to be proportional to plankton stocks in surface waters. Hutchinson suggested that a small but fairly constant fraction of the falling plankton is represented by the hypolimnetic oxygen depletion rate.

Hutchinson put forward a classification scheme, as follows:

	oligotrophic	<0.5 mg/cm^2/month
	mesotrophic	0.5 to 1.0 mg/cm^2/month
and	eutrophic	>1.0 mg/cm^2/month

Future work on the Great Lakes data may possibly be used to define classes of oxygen depletion rate consistent with the trophic classes of surface parameters in this paper.

The areal oxygen depletion rate allows oxygen regimes to be compared among lakes with different morphometry, for the purpose of trophic classification. However it should not be forgotten that the oxygen concentration in mg/litre is the fundamental water quality aspect of dissolved oxygen, and this latter property is linked to hypolimnetic thickness in a way that plankton stocks are not: thus lakes with thin hypolimnions are susceptible to oxygen problems even when surface waters are sparsely populated with phytoplankton. Oxygen concentrations (mg/litre) cannot be correlated with surface-water trophic classification in a series of lakes. I do not try to fit oxygen into my trophic system, but only emphasize that oxygen in lakes must be studied for its own sake, and only incidentally be used for trophic classification.

Train (1972) asked the question: "How important is dissolved oxygen compared to turbidity...?" Here a partial answer has been attempted for the case of seasonally-stratified lakes: both aspects are vitally important and they both deserve to be assessed separately.

Propects for recovery: Lake Washington.

The eutrophication and recovery of Lake Washington at Seattle, U.S.A., have been well described in a series of papers by W.T. Edmondson and others (Edmondson, Anderson and Peterson, 1956; Anderson, 1961; Edmondson, 1961, 1966, 1968, 1970, 1972a, 1972b, 1973). Intensive study of the lake began in 1957. Increasing sewage diversion to ocean waters occurred from 1963 to 1968. The lake responded quickly with lower wintertime phosphorus concentrations, lower summertime chlorophyll and increased transparency in summer. The lake's surface water conditions in summer (Edmondson, 1972a), using the trophic system of the present paper, changed from mesotrophic in 1950 to slightly hypereutrophic in the years 1963 to 1965, and back to slightly eutrophic by 1969. The rapid response of Lake Washington to remedial measures suggests that other lakes may also be responsive.

The "ELA" experiments.

Schindler and Fee (1974) and Schindler (1974) summarized the results of experiments with small lakes in the "Experimental Lakes Area" in northwestern Ontario. The lakes responded to fertilization with phosphate and nitrate. Additional carbon was not needed for eutrophication response. Also, recovery swiftly followed when phosphate additions alone were stopped. Schindler (1974) thought his results indicated that the lower Great Lakes also would respond quickly to reduced phosphorus loadings.

The mean residence time of total phosphorus in Lakes Erie and Ontario.

The mean residence time of phosphorus in a lake is defined as the (annual mean) mass of particulate and dissolved phosphorus in the lake waters, divided by the annual flux of phosphorus in or out of the lake waters.

From the graph of total phosphorus seasonal cycles (Figure 5, this paper) we can take as an approximate mean concentration of total phosphorus in recent years:

Lake Erie	19. μg P/litre
Lake Ontario	24. μg P/litre

Taking as volumes Lake Erie 492 km^3; Lake Ontario 1636 km^3, we get the following mass of phosphorus in each lake:

Lake Erie	9.3×10^6 kg.
Lake Ontario	39.3×10^6 kg.

The external loading of total phosphorus into each lake has been reported for 1967 by the International Joint Commission (1970), and for 1971 by the Great Lakes Water Quality Board (1973), as follows:

Lake Erie -	
1967:	27.3×10^6 kg/year
1971:	28.3×10^6 kg/year
mean:	27.8×10^6 kg/year
Lake Ontario-	
1967:	12.4×10^6 kg/year
1971:	16.3×10^6 kg/year
mean:	14.4×10^6 kg/year

Then the phosphorus residence times are as follows:

$$\frac{\text{mass in Lake Erie}}{\text{flux into Lake Erie}}$$

$$= \frac{9.3 \times 10^6 \text{ kg}}{27.8 \times 10^6 \text{ kg/year}} = 0.33 \text{ years}$$

and

$$\frac{\text{mass in Lake Ontario}}{\text{flux into Lake Ontario}}$$

$$= \frac{39.3 \times 10^6 \text{ kg}}{14.4 \times 10^6 \text{ kg/year}} = 2.7 \text{ years}$$

These phosphorus residence times are remarkably shorter than those of chloride which are 2.6 years for Lake Erie and 7.8 years for Lake Ontario (Rainey, 1967). Apparently the phosphorus residence times are shortened by sedimentation of organic particles. This evidence contradicts Curl (1967) who thought that recycling of phosphorus between lake-water and sediments must cause the phosphorus residence time to be even longer than that of chloride.

Lakes Erie and Ontario will probably respond quickly to changes in the external phosphorus loading.

CONCLUSION

The present work suggests the use of four related parameters which are fairly practical for actual measurements and which together confirm each other in lakes for which turbidity is planktonic, or qualify each other in lakes for which turbidity is partly due to stirred-up sediment or humic substances.

Dissolved oxygen should be included in any complete assessment of water quality.

To end with a little environmental philosophy: a new eutrophication management attitude is now needed, to which the present work is thought to contribute. We need to elevate our management efforts with lakes to the category of caretaking rather than merely manipulating. With a new attitude, there need to be value-judgements applied to trophic conditions, including aesthetic value judgements for water-clarity but also judgements related to an understanding of the range of ideal trophic conditions for lakes and their living populations. This concept of ideal conditions is only clear at the present time for one parameter: dissolved oxygen should be greater than 50% saturation for the sake of fish and zooplankton. Eventually a consensus may develop for an ideal range of plankton abundance. The quantitative value judgements contained in this present paper are thought to be a useful suggestion along the above lines for this common water-quality problem of the eutrophication of surface waters.

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REFERENCES

Anderson, G.C. 1961. Recent changes in the trophic nature of Lake Washington - a review. p. 27-33 in "Algae and Metropolitan Wastes", Robert A. Taft Sanit. Engr. Center, Cincinnati, Ohio, Tech. Rept. W61-3.

Beeton, A.M. 1961. Environmental changes in Lake Erie. Trans. Am. Fish. Soc., 90 (2): p. 153-159.

Beeton, A.M. 1965. Eutrophication of the St. Lawrence Great Lakes. Limnol. Oceanogr., 10 (2): p.240-254.

Beeton, A.M. 1966. Indices of Great Lakes eutrophication. Univ. Michigan, Great Lakes Res. Div., Publ. No. 15, (Proc. 9th Conf. Great Lakes Res.), p. 1-8.

Beeton, A.M. 1969. Changes in the environment and biota of the Great Lakes. p. 150-187 in "Eutrophication: Causes, Consequences, Correctives." National Academy of Sciences, Washington.

Braarud, T. 1958. Counting methods for determination of the standing crop of phytoplankton. Rapp. et. Proc. -Verb. des Réun., (Cons. Perm. Int. p. l'Expl. de la Mer.), 144: p. 17-19.

Carew, T.J., and D.J. Williams. 1975. Surveillance methodology - 1974. Environment Canada, Inland Waters Directorate, Canada Centre for Inland Waters, Tech. Bull. No. 92. 28 p.

Carlson, R.E. 1976. A trophic state index for lakes. Contribution No. 141, Limnological Research Center, University of Minnesota. In press, Limnol. Oceanogr.

Carr, J.F. 1962. Dissolved oxygen in Lake Erie, past and present. Univ. Michigan, Great Lakes Res. Div., Publ. No. 9 (Proc. 5th Conf. Great Lakes Res.), p. 1-14.

Curl, H.C. 1967. "Sluggish process of purification." letter in Science, 156 (3779), p. 1179.

Davis, C.C. 1964. Evidence for the eutrophication of Lake Erie from phytoplankton records. Limnol. Oceanogr., 9 (3): p. 275 -283.

Dillon, P.J. and F.H. Rigler. 1974. The phosphorus -chlorophyll relationship in lakes. Limnol. Oceanogr. 19 (5): p. 767-773.

Dobson, H.H. 1967. Principal ions and dissolved oxygen in Lake Ontario. Proc. 10th Conf. Great Lakes Res. (Internat. Assoc. Great Lakes Res.), p. 337-356.

Dobson, H.H., and M. Gilbertson. 1971. Oxygen depletion in the hypolimnion of the central basin of Lake Erie, 1929 to 1970. Proc. 14th Conf. Great Lakes Res. (Internat. Assoc. Great Lakes Res.), p. 743 -748.

Dobson, H.F.H., M. Gilbertson, and P.G. Sly. 1974. A summary and comparison of nutrients and related water quality in Lakes Erie, Ontario, Huron and Superior. J. Fish. Res. Board Can., 31 (5): p. 731 -738.

Edmondson, W.T. 1961. Changes in Lake Washington following an increase in the nutrient income. Verh. Internat. Verein. Limnol., 14: p. 167-175.

Edmondson, W.T. 1966. Changes in the oxygen deficit of Lake Washington. Verh. Internat. Verein. Limnol., 16: p. 153-158.

Edmondson, W.T. 1968. Water quality management and lake eutrophication: the Lake Washington case. p. 139-178 in T.H. Campbell and R.O. Sylvester (editors), "Water Resources Management and Public Policy", Univ. of Washington Press, Seattle.

Edmondson, W.T. 1970. Phosphorus, nitrogen, and algae in Lake Washington after diversion of sewage. Science, 169: p. 690-691.

Edmondson, W.T. 1972a. Nutrients and phytoplankton in Lake Washington. p. 172 -193 in: Likens, G.E. (editor), "Nutrients and Eutrophication: the limiting nutrient controversy. Amer. Soc. Limnol. Oceanogr. Special Symposia, Vol. I.

Edmondson, W.T. 1972b. The present condition of Lake Washington. Verh. Internat. Verein. Limnol., 18: p. 284-291.

Edmondson, W.T. 1973. Lake Washington. p. 281-298 in "Environmental Quality and Water Development", edited by C.R. Goldman, J. McEvoy, and P.J. Richerson, published by W.H. Freeman & Co.

Edmondson, W.T. G.C. Anderson and D.R. Peterson. 1956. Artificial eutrophication of Lake Washington. Limnol. Oceanogr., 1 (1): p. 47 - 53.

Elster, H. - J. 1958. Das limnologische seetypensystem, Rückblick und Ausblick. [The limnological system of lake types; survey and perspectives.] Verh. Internat. Verein. Limnol., 13: p. 101 - 120.

Findenegg, I. 1955. Trophiezustand und Seetypen. [The trophic condition and lake types.] Schweiz. Z. Hydrol., 17 (1): p. 87-97.

Gächter, R., R.A. Vollenweider, and W.A. Glooschenko. 1974. Seasonal variations of temperature and nutrients in the surface waters of Lakes Ontario and Erie. J. Fish. Res. Board Can. 31 (3): p. 275 -290.

Glooschenko, W.A., J.E. Moore and R.A. Vollenweider. 1972. The seasonal cycle of pheo-pigments in Lake Ontario with particular emphasis on the role of zooplankton grazing. Limnol. Oceanogr., 17 (4): p. 597-605.

Glooschenko, W.A., J.E. Moore and R.A. Vollenweider. 1973. Chlorophyll *a* distribution in Lake Huron and its relationship to primary productivity. Proc. 16th Conf. Great Lakes Res. (Internat. Assoc. Great Lakes Res.), p. 40-49.

Glooschenko, W.A., J.E. Moore, and R.A. Vollenweider. 1974. Spatial and temporal distribution of chlorophyll *a* and pheopigments in surface waters of Lake Erie. J. Fish. Res. Board Can., 31 (3): p. 265-274.

Governments of Canada and the United States. 1972. Agreement between Canada and the United States of America on Great Lakes water quality. Ottawa, April 15, 1972.

Great Lakes Water Quality Board. 1973. "Great Lakes Water Quality Annual Report to the International Joint Commission." 315 p.

Hansen, K. 1962. The dystrophic lake type. Hydrobiologia, 19 (2): p. 183-191.

Hasler, A.D. 1947. Eutrophication of lakes by domestic drainage. Ecology, 28: p. 383-395.

Hutchinson, G.E . 1938. On the relation between the oxygen deficit and the productivity and typology of lakes. Int. Rev. Gesamten Hydrobiol. Hydrogr., 36: p. 336-355.

Hutchinson, G.E. 1973. Eutrophication: the scientific background of a contemporary practical problem. Amer. Scientist, 61 (3): p. 269-279.

International Joint Commission, Canada and United States. 1970. "Pollution of Lake Erie, Lake Ontario and the International Section of the St. Lawrence River." 105p.

Järnefelt, H. 1958. On the typology of the northern lakes. Verh. Internat. Verein. Limnol., 13: p. 228-235.

Moyle, J.B. 1949. Some indices of lake productivity. Trans. Amer. Fish. Soc., 76: p. 322-334.

Munawar, M. and I.F. Munawar. 1975. The abundance and significance of phytoflagellates and nannoplankton in the St. Lawrence Great Lakes. I. Phytoflagellates. Verh. Internat. Verein. Limnol., 19: p.705-723.

Munawar, M., and A. Nauwerck. 1971. The composition and horizontal distribution of phytoplankton in Lake Ontario during the year 1970. Proc. 14th Conf. Great Lakes Res. (Internat. Assoc. Great Lakes Res.), p.69 -78.

Munawar, M., P. Stadelmann, and I.F. Munawar. 1974. Phytoplankton biomass, species composition and primary production at a nearshore and a midlake station of Lake Ontario during IFYGL. Proc. 17th Conf. Great Lakes Res. (Internat. Assoc. Great Lakes Res.), p. 629-652.

Norvell, W.A., and C.R. Frink. 1975. Water chemistry and fertility of twenty-three Connecticut lakes. Connecticut Agricultural Experiment Station, New Haven, Bulletin 759. 45p.

Philbert, F.J., and W.J. Traversy. 1973. Methods of sample treatment and analysis of Great Lakes water and precipitation samples. Proc. 16th Conf. Great Lakes Res., (Internat. Assoc. Great Lakes Res.), p. 294-308.

Phillips, D.W. 1974. IFYGL weather highlights. Proc. 17th Conf. Great Lakes Res. (Internat. Assoc. Great Lakes Res.), p. 296-320.

Postma, H. 1961. Suspended matter and Secchi disc visibility in coastal waters. Neth. J. of Sea Res., 1 (3): p. 359-390.

Rainey, R.H. 1967. Natural displacement of pollution from the Great Lakes. Science, 155 (3767): p. 1242-1243.

Rodgers, G.K. 1965. The thermal bar in the Laurentian Great Lakes. Proc. 8th Conf. Great Lakes Res., Publ. No. 13, Great Lakes Res. Div., Univ. Michigan, p. 358 -363.

Rodhe, W. 1969. Crystallization of eutrophication concepts in northern Europe. p. 50-64 _in_ "Eutrophication: Causes, Consequences, Correctives", Proceedings of a symposium, National Academy of Sciences, Washington, D.C.

Schelske, C.L., and E.F. Stoermer. 1971. Eutrophication, silica depletion, and predicted changes in algal quality in Lake Michigan. Science, 173: p. 423-424.

Schindler, D.W. 1974. Eutrophication and recovery in experimental lakes: implications for lake management. Science, 184 (4139): p. 897 -899.

Schindler, D.W., and E.J. Fee. 1974. Experimental Lakes Area: whole-lake experiments in eutrophication. J. Fish. Res. Board Can., 31 (5): p. 937-953.

Shannon, E.E., and P.L. Brezonik. 1972. Eutrophication analysis: a multivariate approach. J. San. Eng. Div. ASCE, 98 (SA 1): p. 37-57.

Shapiro, J. 1975. The current status of lake trophic indices, a review. Interim Rept. No. 15, Limnological Research Center, University of Minnesota. 49p.

Shapiro, J., J.B. Lundquist, and R.E. Carlson. 1975. Involving the public in limnology — an approach to communication. Verh. Internat. Verein. Limnol., 19 (2): p. 866 -874.

Shiomi, M.T., and V.K. Chawla. 1970. Nutrients in Lake Ontario. Proc. 13th Conf. Great Lakes Res. (Internat. Assoc. Great Lakes Res.), p. 715 -732.

Stadelmann, P., and A. Fraser. 1974. Phosphorus and nitrogen cycle on a transect in Lake Ontario during the International Field Year 1972-1973. Proc. 17th Conf. Great Lakes Res. (Internat. Assoc. Great Lakes Res.) p. 92 -108.

Stadelmann, P., and M. Munawar. 1974. Biomass parameters and primary production at a nearshore and a midlake station of Lake Ontario during IFYGL. Proc. 17th Conf. Great Lakes Res. (Internat. Assoc. Great Lakes Res.), p. 109-119.

Stewart, K.M., and G.A. Rohlich. 1967. Eutrophication — A Review. Calif. St. Wat. Qual. Control Bd., Publ. No. 34. 188p.

Train, R.E. 1972. Editorial: "The quest for environmental indices." Science, 178 (4057): p. 121.

Utermöhl, H. 1931. Neue Wege in der quantitativen Erfassung des Planktons. Verh. Internat. Verein. Limnol., 5: p. 567-596.

Vallentyne, J.R., J. Shapiro, and 8 others. 1969. The process of eutrophication and criteria for trophic state determination· p. 57-67 _in_ "Modelling the Eutrophication Process", proceedings of a workshop at St. Petersburg, Florida, Nov. 19-21, 1969.

? Vollenweider, R.A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Report for the Organization for Economic Co-operation and Development (OECD). 159 p.+ 34 figures.

Vollenweider, R.A., M. Munawar, and P. Stadelmann. 1974. A comparative review of phytoplankton and primary production in the Laurentian Great Lakes. J. Fish. Res. Board Can., 31 (5): p. 739-762.

Watson, N.H.F. 1974. Zooplankton of the St. Lawrence Great Lakes — species composition, distribution, and abundance. J. Fish. Res. Board Can., 31 (5): p. 783-794.

Watson, N.H.F., G.F. Carpenter, and M. Munawar. 1975. Problems in the monitoring of biomass. p. 311-319 in "Water Quality Parameters", ASTM STP 573, American Society for Testing and and Materials.

Watson, N.H.F., K.P.B. Thomson, and F.C. Elder 1975. Sub-thermocline biomass concentration detected by transmissometer in Lake Superior. Verh. Internal. Verein. Limnol., 19: p. 682-688.

1969. Eutrophication: Causes, Consequences, Correctives. Proceedings of a symposium. National Academy of Sciences, Washington, D.C. 661p.

ADDITIONAL REFERENCES

Lorenzen, C.J. 1966. A method for the continuous measurement of *in vivo* chlorophyll concentration. Deep-Sea Res., 13:223-227.

Parsons, T.R. and J.D.H. Strickland. 1963. Discussion of spectrophotometric determination of marine-plant pigments, with revised equations for ascertaining chlorophylls and carotenoids. J. Mar. Res., 21(3): p. 155-163.

Strickland, J.D.H., and T.R. Parsons. 1968. A Practical Handbook of Seawater Analysis. Fish. Res. Board Can., Bull. 167. 309p.

1966. Determination of photosynthetic pigments in sea-water. Unesco Monographs in Oceanographic Methodology, No. 1.69p.

Table A-1 Summary of Secchi reciprocal values (m^{-} x 30) in the offshore part (sounding > 100 metres) of Lake Superior.

Mean date	Vessel	Minimum Secchi reciprocal (m^{-1}x30)	Mean Secchi reciprocal (m^{-1}x30)	Maximum Secchi reciprocal (m^{-1}x30)	Number of Observations
Aug. 17, 1967	Porte Dauphine	2.2	2.6	4.5	36
Aug. 23, 1968	Theron	2.5	3.5	6.0	22
Nov. 5, 1968	Porte Dauphine	[2.1]	[2.4]	[2.5]	3 only
Sept. 9, 1969	Porte Dauphine	2.1	2.6	3.3	15
Nov. 19, 1969	Martin Karlsen	2.5	3.3	4.3	22
Apr. 18, 1970	Martin Karlsen	1.7	2.6	3.8	25
Sept. 16, 1970	Porte Dauphine	2.3	3.0	3.5	10
Nov. 1, 1970	Martin Karlsen	1.9	3.3	6.1	24
May 29, 1971	Martin Karlsen	1.9	3.1	6.0	19
July 3, 1971	Martin Karlsen	2.1	3.2	6.0	26
Oct. 9, 1971	Martin Karlsen	2.5	3.8	6.0	19
May 17, 1973	Martin Karlsen	1.9	3.6	7.5	38
June 21, 1973	Martin Karlsen	1.4	3.1	6.0	77
Aug. 1, 1973	Martin Karlsen	2.0	3.6	7.5	68
Sept. 12, 1973	Martin Karlsen	1.8	4.0	6.0	44
Oct. 21, 1973	Martin Karlsen	2.5	3.2	4.0	27
Nov. 23, 1973	Martin Karlsen	2.1	2.7	3.3	19

Table A-2 Summary of Secchi reciprocal values (m^{-1}x30) in the offshore part (sounding >50m) of Lake Huron.

Mean date	Vessel	Minimum Secchi reciprocal (m^{-1}x30)	Mean Secchi reciprocal (m^{-1}x30)	Maximum Secchi reciprocal (m^{-1}x30)	Number of Observations
Sept.11, 1966	Porte Dauphine	2.2	2.8	4.3	21
Aug. 9, 1968	Theron	2.7	3.7	6.0	31
Sept.27, 1968	Porte Dauphine	[3.3]	[3.7]	[3.8]	4 only
Oct. 13, 1968	Porte Dauphine	2.5	3.2	4.3	13
Sept.26, 1969	Martin Karlsen	3.3	4.7	10.0	25
Oct. 29, 1969	Porte Dauphine	2.3	2.9	3.5	14
Nov. 29, 1969	Limnos	3.8	8.2	15.0	14
May 15, 1970	Martin Karlsen	3.3	4.8	7.5	26
Aug.20, 1970	Porte Dauphine	2.5	3.0	3.8	6
Oct. 3, 1970	Martin Karlsen	3.3	4.0	5.5	16
Apr. 24, 1971	Martin Karlsen	3.0	4.8	6.0	29
May 22, 1971	Martin Karlsen	2.7	4.9	7.5	16
June 25, 1971	Martin Karlsen	3.3	4.8	6.0	24
July 23, 1971	Martin Karlsen	2.5	4.0	6.0	20
Aug.27, 1971	Martin Karlsen	2.5	3.7	7.5	17
Oct. 1, 1971	Martin Karlsen	3.3	4.8	7.5	14
Oct. 31, 1971	Martin Karlsen	3.3	4.3	6.0	11
Dec. 3, 1971	Martin Karlsen	2.3	4.2	6.0	16
May 6, 1972	Martin Karlsen	2.3	4.5	7.5	24
Aug. 13, 1972	Martin Karlsen	2.5	3.9	6.0	22
Nov. 5, 1972	Martin Karlsen	3.0	3.9	6.0	14
May 10, 1973	Martin Karlsen	5.0	6.4	7.5	5
Sept. 20, 1973	Martin Karlsen	[3.8]	[3.8]	[3.8]	2 only

Cont'd.....

Table A-2, continued (Secchi reciprocals in Lake Huron)

Mean date	Vessel	Minimum Secchi reciprocal (m^{-1}x30)	Mean Secchi reciprocal (m^{-1}x30)	Maximum Secchi reciprocal (m^{-1}x30)	Number of Observations
Apr. 26, 1974	Martin Karlsen	[3.3]	[3.6]	[4.0]	2 only
May 15, 1974	Martin Karlsen	[3.3]	[3.9]	[4.3]	4 only
June 25, 1974	Martin Karlsen	4.0	4.5	5.5	6
July 24, 1974	Martin Karlsen	2.7	3.4	4.3	7
Aug. 28, 1974	Martin Karlsen	2.7	3.2	4.0	7
Oct. 2, 1974	Martin Karlsen	[2.7]	[4.2]	[6.0]	3 only

Table A-3 Summary of Secchi reciprocal values ($m^{-1}x30$) in the offshore part (sounding >20 metres) of central Lake Erie.

Mean date	Vessel	Minimum Secchi reciprocal ($m^{-1}x30$)	Mean Secchi reciprocal ($m^{-1}x30$)	Maximum Secchi reciprocal ($m^{-1}x30$)	Number of Observations
Apr. 13, 1966	Porte Dauphine	6.0	7.9	10.0	7
May 25, 1966	Porte Dauphine	5.5	9.2	20.0	11
July 6, 1966	Porte Dauphine	2.5	3.8	6.0	7
Aug. 10, 1966	Brandal	3.8	5.2	7.5	5
Aug. 23, 1966	Porte Dauphine	5.0	6.5	10.0	11
Nov. 16, 1966	Porte Dauphine	12.0	14.9	20.0	10
Apr. 6, 1967	Porte Dauphine	5.0	6.3	7.5	11
May 3, 1967	Porte Dauphine	6.7	9.6	12.0	10
June 5, 1967	Brandal	5.0	7.4	12.0	9
June 24, 1967	Brandal	3.0	4.2	9.4	13
July 5, 1967	Porte Dauphine	3.0	3.3	4.0	12
July 14, 1967	Brandal	3.0	3.9	7.5	18
Aug. 4, 1967	Brandal	[4.3]	[5.8]	[10.0]	4 only
Aug. 25, 1967	Brandal	4.3	5.1	6.0	5
Aug. 30, 1967	Porte Dauphine	3.9	4.8	6.0	5
Sept.6, 1967	Porte Dauphine	6.0	6.6	7.1	7
Sept.14, 1967	Brandal	[5.0]	[6.8]	[10.0]	4 only
Oct. 6, 1967	Brandal	[6.0]	[7.1]	[7.5]	4 only
Oct. 27, 1967	Brandal	[15.0]	[25.0]	[30.0]	3 only
Nov. 9, 1967	Porte Dauphine	8.6	16.5	25.0	6
Dec. 1, 1967	Porte Dauphine	8.6	15.0	20.0	7
Apr. 24, 1968	Porte Dauphine	5.0	7.7	15.0	8
May 20, 1968	Theron	5.0	10.1	20.0	14
June 17, 1968	Theron	[5.0]	[6.9]	[10.0]	4 only
Aug. 1, 1968	Theron	4.3	8.0	15.0	7
Sept.1, 1968	Theron	5.5	9.5	15.0	5
Sept.30, 1968	Theron	[10.0]	[13.3]	[15.0]	3 only
Nov. 7, 1968	Theron	10.0	17.0	30.0	5
Nov. 28, 1968	Porte Dauphine	[18.8]	[29.1]	[42.9]	4 only

Cont'd...

Table A-3, continued (Secchi reciprocals in central Lake Erie)

Mean date	Vessel	Minimum Secchi reciprocal (m^{-1}x30)	Mean Secchi reciprocal (m^{-1}x30)	Maximum Secchi reciprocal (m^{-1}x30)	Number of Observations
Apr. 15, 1969	Porte Dauphine	4.6	6.6	8.3	13
June 2, 1969	Martin Karlsen	8.6	11.0	15.0	8
July 4, 1969	Martin Karlsen	3.8	6.4	7.5	10
July 31, 1969	Martin Karlsen	3.8	6.5	8.6	10
Aug. 27, 1969	Martin Karlsen	6.0	6.8	7.5	9
Sept. 16, 1969	Martin Karlsen	7.5	8.8	10.0	6
Oct. 18, 1969	Martin Karlsen	[15.0]	[21.7]	[30.0]	3 only
Dec. 10, 1969	Limnos	10.0	12.0	15.0	6
Apr. 9, 1970	Martin Karlsen	[8.6]	[12.9]	[15.0]	3 only
May 8, 1970	Martin Karlsen	8.6	9.0	10.0	5
June 4, 1970	Martin Karlsen	7.5	8.2	10.0	5
July 5, 1970	Martin Karlsen	3.3	4.8	7.5	7
July 30, 1970	Martin Karlsen	5.5	6.5	9.1	5
Aug. 27, 1970	Martin Karlsen	4.3	5.9	8.8	6
Sept. 25, 1970	Martin Karlsen	6.0	8.0	10.0	6
Oct. 23, 1970	Martin Karlsen	[7.5]	[9.8]	[12.0]	3 only
Nov. 28, 1970	Martin Karlsen	[20.0]	[36.7]	[60.0]	3 only
Dec. 16, 1970	Martin Karlsen	[20.0]	[21.7]	[25.0]	3 only
Feb. 8, 1971	N.B. McLean	[8.6]	[10.2]	[12.0]	3 only
Apr. 15, 1971	Martin Karlsen	7.5	12.7	30.0	7
July 7, 1971	Porte Dauphine	4.3	6.1	10.0	5
Aug. 19, 1971	Martin Karlsen	5.0	6.7	10.0	6
Nov. 25, 1971	Martin Karlsen	[12.0]	[15.5]	[20.0]	4 only

Cont'd......

Table A-3, continued (Secchi reciprocals in central Lake Erie)

Mean date	Vessel	Minimum Secchi reciprocal (m^{-1}x30)	Mean Secchi reciprocal (m^{-1}x30)	Maximum Secchi reciprocal (m^{-1}x30)	Number of Observations
April 26, 1972	Martin Karlsen	6.7	7.8	10.0	5
June 8, 1972	Martin Karlsen	6.7	8.2	10.0	6
June 28, 1972	Porte Dauphine	[7.5]	[7.5]	[7.5]	2 only
Aug. 3, 1972	Martin Karlsen	5.0	5.9	7.5	5
Aug. 30, 1972	Porte Dauphine	5.0	6.2	7.5	7
Sept. 30, 1972	Martin Karlsen	[7.5]	[10.6]	[15.0]	4 only
Nov. 12, 1972	Martin Karlsen	[7.5]	[9.2]	[10.0]	3 only
Apr. 14, 1973	Limnos	15.0	33.1	60.0	9
July 27, 1973	Limnos	5.0	7.0	10.0	13
Aug. 30, 1973	Martin Karlsen	6.0	9.2	15.0	7
Nov. 10, 1973	Limnos	10.0	21.4	30.0	7
Apr. 26, 1974	Porte Dauphine	[6.0]	[12.0]	[15.0]	3 only
Aug. 23, 1974	Martin Karlsen	3.8	4.2	6.0	6
Apr. 9, 1975	Limnos	15.0	35.8	60.0	9
May 16, 1975	Northern Seal	6.2	13.0	20.0	9
June 27, 1975	Northern Seal	2.5	4.1	6.7	15
Aug. 8, 1975	Northern Seal	4.0	5.0	6.2	13
Oct. 9, 1975	Northern Seal	7.5	8.8	10.0	10
Oct. 29, 1975	Northern Seal	7.5	14.8	30.0	9
Nov. 27, 1975	Limnos	12.0	20.0	37.5	9

Table A-4 Summary of Secchi reciprocal values ($m^{-1}x30$) in the offshore part (sounding >50 metres) of Lake Ontario

Mean date	Vessel	Minimum Secchi reciprocal ($m^{-1}x30$)	Mean Secchi reciprocal ($m^{-1}x30$)	Maximum Secchi reciprocal ($m^{-1}x30$)	Number of Observations
June 8, 1966	Brandal	3.0	5.5	10.0	11
June 22, 1966	Brandal	5.5	9.3	12.0	20
July 7, 1966	Brandal	5.0	9.3	15.0	28
July 22, 1966	Brandal	6.0	8.7	11.5	8
Aug. 5, 1966	Brandal	6.0	10.9	15.8	13
Aug. 17, 1966	Brandal	6.7	9.6	15.0	14
Aug. 31, 1966	Brandal	7.9	11.5	20.0	11
Sept. 15, 1966	Brandal	7.5	8.3	10.0	9
Sept. 28, 1966	Brandal	3.8	6.4	8.1	7
June 14, 1967	Theron	5.0	8.6	12.0	20
June 26, 1967	Theron	5.2	8.6	12.0	22
July 11, 1967	Theron	6.0	9.3	15.0	21
July 26, 1967	Theron	7.5	12.0	15.0	23
Aug. 7, 1967	Theron	7.5	10.6	15.0	22
Aug. 23, 1967	Theron	6.0	10.5	15.0	22
Sept. 6, 1967	Theron	5.5	8.3	10.0	21
Sept. 18, 1967	Theron	6.0	7.4	10.0	20
Oct. 2, 1967	Theron	4.6	6.7	8.6	14
Oct. 19, 1967	Theron	5.0	7.0	8.6	13
Oct. 30, 1967	Theron	3.3	4.9	7.5	17
April 30, 1968	Theron	2.7	4.6	10.0	23
May 28, 1968	Theron	3.5	6.5	15.0	25
July 4, 1968	Theron	8.6	13.0	20.0	20
July 24, 1968	Limnos	6.0	8.4	12.0	16
Aug. 21, 1968	Limnos	6.0	10.4	20.0	16
Sept. 10, 1968	Limnos	5.5	7.8	10.0	15
Oct. 6, 1968	Theron	5.0	9.1	15.0	14
Oct. 29, 1968	Theron	2.1	6.8	10.0	19
Nov. 19, 1968	Theron	4.3	6.3	10.0	5

cont'd....

Table A-4, continued (Secchi reciprocals in Lake Ontario.)

Mean date	Vessel	Minimum Secchi reciprocal (m^{-1}x30)	Mean Secchi reciprocal (m^{-1}x30)	Maximum Secchi reciprocal (m^{-1}x30)	Number of Observations
April 14, 1969	Limnos	2.7	4.9	12.0	32
May 15, 1969	Martin Karlsen	2.5	4.8	10.0	37
June 10, 1969	Martin Karlsen	2.3	8.1	15.0	36
July 10, 1969	Martin Karlsen	7.5	11.7	15.0	29
Aug. 7, 1969	Martin Karlsen	7.5	11.1	15.0	23
Sept. 7, 1969	Martin Karlsen	7.5	10.5	15.0	32
Oct. 4, 1969	Martin Karlsen	6.0	9.7	15.0	21
Nov. 2, 1969	Martin Karlsen	4.3	6.7	10.0	14
Dec. 3, 1969	Martin Karlsen	3.8	6.2	10.0	15
Jan. 9, 1970	Martin Karlsen	3.8	5.3	7.5	13
Feb. 6, 1970	Martin Karlsen	3.3	5.2	7.5	16
Mar. 6, 1970	Martin Karlsen	4.3	7.2	12.0	19
Apr. 2, 1970	Martin Karlsen	3.8	6.7	15.0	10
Apr. 30, 1970	Martin Karlsen	3.3	5.8	10.0	25
May 27, 1970	Martin Karlsen	3.8	5.3	10.0	22
June 25, 1970	Martin Karlsen	6.0	9.6	15.0	27
July 18, 1970	Martin Karlsen	5.9	11.0	15.0	22
Aug. 19, 1970	Martin Karlsen	8.6	16.3	33.3	23
Sept. 16, 1970	Martin Karlsen	4.3	8.1	10.3	20
Oct. 15, 1970	Martin Karlsen	5.0	7.7	12.0	16
Nov. 17, 1970	Martin Karlsen	4.3	6.5	10.0	12
Dec. 9, 1970	Martin Karlsen	3.8	5.3	7.5	13
Mar. 31, 1971	Martin Karlsen	3.3	5.0	7.5	10
Aug. 11, 1971	Martin Karlsen	15.0	22.2	30.0	16
Nov. 17, 1971	Martin Karlsen	3.8	5.7	12.0	11
Apr. 5, 1972	Porte Dauphine & Limnos	3.3	6.0	15.0	18
Apr. 11, 1972	Porte Dauphine & Limnos & Martin Karlsen	3.0	4.4	12.0	38
April 18, 1972	Porte Dauphine & Limnos	2.7	5.0	10.0	27
April 25, 1972	Porte Dauphine & Limnos	2.7	4.3	7.5	25

cont'd....

Table A-4, continued (Secchi reciprocals in Lake Ontario)

Mean date	Vessel	Minimum Secchi reciprocal (m^{-1}x30)	Mean Secchi reciprocal (m^{-1}x30)	Maximum Secchi reciprocal (m^{-1}x30)	Number of Observations
May 2, 1972	Porte Dauphine & Limnos	2.5	4.3	7.5	28
May 9, 1972	Porte Dauphine & Limnos	3.0	4.5	10.0	27
May 25, 1972	Martin Karlsen	2.7	4.1	6.0	12
June 6, 1972	Limnos & Porte Dauphine	2.3	8.0	30.0	30
June 20, 1972	Martin Karlsen	3.3	9.4	12.0	11
July 18, 1972	Martin Karlsen	6.0	8.8	15.0	10
Sept. 6, 1972	Martin Karlsen	10.0	14.5	20.0	12
Sept. 21, 1972	Martin Karlsen	7.5	12.3	15.0	27
Oct. 4, 1972	Porte Dauphine & Martin Karlsen	6.0	8.1	10.0	17
Oct. 19, 1972	Martin Karlsen	4.3	6.3	8.6	7
Nov. 22, 1972	Martin Karlsen	3.8	5.1	6.7	9
Dec. 7, 1972	Porte Dauphine & Limnos	5.0	7.2	10.0	11
Dec. 12, 1972	Porte Dauphine & Limnos	3.0	5.0	12.0	10
Dec. 19, 1972	Limnos	[7.5]	[7.5]	[7.5]	2 only
Jan. 4, 1973	Porte Dauphine & Martin Karlsen	6.0	7.8	12.0	10
Jan. 9, 1973	Martin Karlsen	[5.0]	[6.7]	[7.5]	3 only
Jan. 16, 1973	Limnos	3.3	5.3	6.0	7
Jan. 30, 1973	Limnos	[4.3]	[5.5]	[7.5]	4 only
Feb. 13, 1973	Limnos	3.8	5.5	10.0	11
Feb. 27, 1973	Limnos	3.0	5.6	10.0	10
Mar. 7, 1973	Martin Karlsen	3.8	6.2	10.0	12
Mar. 13, 1973	Porte Dauphine & Limnos	2.5	4.8	7.5	19
Mar. 21, 1973	Martin Karlsen	3.3	8.9	20.0	20
Mar. 27, 1973	Limnos	3.8	6.5	15.0	13
Apr. 3, 1973	Porte Dauphine	3.8	5.2	12.0	14
Apr. 26, 1973	Martin Karlsen	3.3	6.6	10.0	12

cont'd....

Table A-4, continued (Secchi reciprocals in Lake Ontario)

Mean date	Vessel	Minimum Secchi reciprocal (m^{-1}x30)	Mean Secchi reciprocal (m^{-1}x30)	Maximum Secchi reciprocal (m^{-1}x30)	Number of Observations
May 1, 1973	Porte Dauphine	3.8	5.3	6.7	11
June 5, 1973	Limnos	3.8	9.7	15.0	22
June 13, 1973	Limnos	8.6	12.4	15.0	11
June 27, 1973	Limnos	7.5	10.9	15.0	22
Oct. 31, 1973	Martin Karlsen	3.3	5.2	7.5	10
Dec. 5, 1973	Martin Karlsen	3.0	3.9	5.5	7
Apr. 2, 1974	Martin Karlsen	3.3	4.6	6.0	10
Apr. 17, 1974	Porte Dauphine	2.5	5.6	10.0	21
Apr. 31, 1974	Porte Dauphine	3.3	5.7	12.0	15
May 14, 1974	Porte Dauphine	3.0	6.5	20.0	25
June 4, 1974	Porte Dauphine	2.5	7.0	15.0	22
June 18, 1974	Porte Dauphine	5.0	10.5	30.0	30
July 25, 1974	Advent	6.0	10.6	15.0	34
Aug. 7, 1974	Martin Karlsen	8.6	14.8	30.0	26
Aug. 14, 1974	Martin Karlsen	7.5	14.4	30.0	20
Aug. 20, 1974	Limnos	12.0	23.1	30.0	27
Sept. 4, 1974	Porte Dauphine	6.7	10.1	15.0	17
Sept. 17, 1974	Porte Dauphine	4.6	9.6	13.6	28
Oct. 2, 1974	Porte Dauphine	5.0	6.2	8.6	16
Oct. 17, 1974	Limnos	5.2	7.2	13.6	25
Nov. 27, 1974	Porte Dauphine	4.6	7.5	15.0	17
Apr. 12, 1975	Limnos	2.5	6.7	30.0	22
May 25, 1975	Northern Seal	2.3	7.5	17.6	32
June 5, 1975	Northern Seal	2.5	7.6	13.6	23

cont'd....

Table A-4, continued (Secchi reciprocals in Lake Ontario)

Mean date	Vessel	Minimum Secchi reciprocal (m^{-1}x30)	Mean Secchi reciprocal (m^{-1}x30)	Maximum Secchi reciprocal (m^{-1}x30)	Number of Observations
July 4, 1975	Northern Seal	4.3	8.4	20.0	28
July 22, 1975	Northern Seal	5.7	18.9	30.0	31
Aug. 14, 1975	Northern Seal	8.6	16.2	30.0	33
Sept. 4, 1975	Northern Seal	6.7	10.2	16.7	24
Sept. 25, 1975	Northern Seal	4.3	6.6	10.0	31
Oct. 18, 1975	Northern Seal	4.6	7.1	12.0	19
Nov. 5, 1975	Northern Seal	4.3	5.0	6.0	17
Dec. 7, 1975	Limnos	3.8	5.5	10.0	17

Table A-5 Summary of total chlorophyll *a* values (micrograms per litre) in near-surface waters of the offshore part (sounding > 100 metres) of Lake Superior.

Mean date	Vessel	Sample depths (metres)	Minimum TCa (μg/litre)	Mean TCa (μg/litre)	Maximum TCa (μg/litre)	Number of Observations
Aug. 22, 1968	Theron	1m	0.4	0.7	1.0	47
Nov. 19, 1969	Martin Karlsen	1m	0.0	0.8	2.3	51
Apr. 18, 1970	Martin Karlsen	1m	0.2	0.3	0.6	42
Nov. 1, 1970	Martin Karlsen	1m	1.4	2.2	3.1	50
May 29, 1971	Martin Karlsen	1m	0.1	0.7	1.1	32
July 3, 1971	Martin Karlsen	1m	0.5	0.6	0.8	40
Oct. 9, 1971	Martin Karlsen	1m	0.9	1.4	2.3	39
May 18, 1973	Martin Karlsen	0 to 50m	0.6	0.9	1.2	69
June 21, 1973	Martin Karlsen	0 to 20m	0.7	0.9	1.5	79
Aug. 1, 1973	Martin Karlsen	0 to 20m	0.7	1.3	2.4	81
Sept.11, 1973	Martin Karlsen	0 to 20m	0.5	1.3	2.8	82
Oct. 20, 1973	Martin Karlsen	0 to 15m	0.7	1.6	3.0	70
Nov. 23, 1973	Martin Karlsen	0 to 20m	0.6	1.0	1.5	72

Table A-6 Summary of total chlorophyll *a* values (micrograms per litre) in near-surface waters of the offshore part (sounding > 50 metres) of Lake Huron

Mean date	Vessel	Sample depths (metres)	Minimum TCa (µg/litre)	Mean TCa (µg/litre)	Maximum TCa (µg/litre)	Number of Observations
Aug. 10, 1968	Theron	1m	0.2	1.1	2.9	37
Nov. 29, 1969	Limnos	1m	0.9	2.5?	3.7	44
May 15, 1970	Martin Karlsen	1m	1.8	3.2?	4.3	42
Oct. 3, 1970	Martin Karlsen	1m	2.2	2.9?	3.4	46
Apr. 24, 1971	Martin Karlsen	1m	1.0	1.6	2.8	50
May 22, 1971	Martin Karlsen	1m	1.9	2.2	2.5	32
June 25, 1971	Martin Karlsen	1m	0.8	1.2	2.0	35
July 23, 1971	Martin Karlsen	1m	0.0	1.5	4.0	32
Aug. 27, 1971	Martin Karlsen	1m	0.4	1.1	2.1	31
Oct. 2, 1971	Martin Karlsen	1m	0.7	1.6	3.9	30
Oct. 31, 1971	Martin Karlsen	1m	0.8	1.4	2.0	29
Dec. 3, 1971	Martin Karlsen	1m	0.9	1.4	2.0	32
May 4, 1972	Martin Karlsen	1m	1.1	1.3	1.6	10
Aug. 13, 1972	Martin Karlsen	1m	0.4	0.7	1.1	9
Nov. 5, 1972	Martin Karlsen	1m	1.1	1.3	1.5	10
May 11, 1973	Martin Karlsen	0 to 20m	1.0	1.6	2.0	7
Sept. 20, 1973	Martin Karlsen	0 to 20m	1.5	1.8	2.5	8
Apr. 26, 1974	Martin Karlsen	0 to 20m	1.8	2.0	2.3	9
May 16, 1974	Martin Karlsen	0 to 20m	2.2	2.4	2.9	8
June 25, 1974	Martin Karlsen	0 to 20m	1.4	1.7	2.0	11
July 25, 1974	Martin Karlsen	0 to 20m	0.6	1.0	1.4	10
Aug. 29, 1974	Martin Karlsen	0 to 20m	0.6	1.0	1.4	10
Oct. 4, 1974	Martin Karlsen	0 to 20m	1.2	1.5	1.8	10

Table A-7 Summary of total chlorophyll a values (micrograms per litre) in near-surface waters of the offshore part (sounding > 20 metres) of central Lake Erie.

Mean date	Vessel	Sample depths (metres)	Minimum TCa (µg/litre)	Mean TCa (µg/litre)	Maximum TCa (µg/litre)	Number of Observations
May 20, 1968	Theron	1m	3.0	4.4	8.0	18
June 18, 1968	Theron	1m	1.2	4.3	11.4	10
Aug. 1, 1968	Theron	1m	1.0	3.7	6.1	18
Sept.2, 1968	Theron	1m	0.7	6.5	16.5	6
Oct. 1, 1968	Theron	1m	2.1	5.6	9.0	18
Nov. 8, 1968	Theron	1m	1.3	2.2	6.9	19
June 2, 1969	Martin Karlsen	1m	6.4	11.3	16.0	16
Sept. 16, 1969	Martin Karlsen	1m	3.5	8.2	13.3	13
Dec. 10, 1969	Limnos	1m	6.3	7.3	8.4	18
Apr. 9, 1970	Martin Karlsen	1m	3.6	5.0	5.8	5
May 8, 1970	Martin Karlsen	1m	3.7	5.0	6.4	7
June 4, 1970	Martin Karlsen	1m	2.5	4.3	6.8	10
July 5, 1970	Martin Karlsen	1m	0.8	2.0	4.3	10
July 30, 1970	Martin Karlsen	1m	3.9	4.5	5.2	10
Aug. 27, 1970	Martin Karlsen	1m	3.2	4.9	10.1	10
Sept. 25, 1970	Martin Karlsen	1m	7.4	10.6	13.6	10
Oct. 23, 1970	Martin Karlsen	1m	4.9	8.0	14.6	11
Nov. 28, 1970	Martin Karlsen	1m	3.4	4.7	6.9	9
Dec. 16, 1970	Martin Karlsen	1m	2.1	3.4	5.3	5
Apr. 16, 1971	Martin Karlsen	1m	5.6	8.0	11.8	10
Apr. 19, 1971	Martin Karlsen	1m	1.2	2.4	6.2	10
Nov. 25, 1971	Martin Karlsen	1m	6.6	10.0	14.5	8
Apr. 27, 1972	Martin Karlsen	1m	2.0	3.3	6.6	8
June 8, 1972	Martin Karlsen	1m	1.8	2.8	4.9	11
June 28, 1972	Porte Dauphine	1m	1.2	2.2	3.2	6
Aug. 4, 1972	Martin Karlsen	1m	[3.9]	[4.1]	[4.2]	3 only
Aug. 30, 1972	Porte Dauphine	1m	3.0	6.3	20.5	10
Nov. 12, 1972	Martin Karlsen	1m	[2.5]	[3.7]	[5.0]	4 only

Cont'd.....

Table A-7, continued Summary of total chlorophyll a values (micrograms per litre) in near-surface waters of the offshore part (sounding > 20 metres) of central Lake Erie

Mean date	Vessel	Sample depths (metres)	Minimum TCa (µg/litre)	Mean TCa (µg/litre)	Maximum TCa (µg/litre)	Number of Observations
Apr. 14, 1973	Limnos	0 to 15m	3.9	9.7	18.2	19
July 27, 1973	Limnos	0 to 20m	2.6	4.4	8.7	19
Aug. 30, 1973	Martin Karlsen	0 to 10m	3.4	5.8	7.9	11
Nov. 11, 1973	Limnos	0 to 19m	4.2	8.0	18.5	13
Apr. 26, 1974	Porte Dauphine	0 to 20m	3.1	4.1	5.0	15
Aug. 23, 1974	Martin Karlsen	0 to 20m	2.0	3.4	6.3	16
Apr. 8, 1975	Limnos	0 to 20m	1.9	4.3	6.1	18
May 16, 1975	Northern Seal	0 to 20m	2.9	4.1	5.5	20
June 27, 1975	Northern Seal	0 to 20m	1.1	2.0	3.4	22
Aug. 9, 1975	Northern Seal	0 to 20m	2.4	4.0	7.9	21
Oct. 9, 1975	Northern Seal	0 to 20m	7.0	9.3	11.0	21
Oct. 30, 1975	Northern Seal	0 to 20m	5.7	7.5	12.0	18
Nov. 27, 1975	Limnos	0 to 20m	5.7	7.0	8.2	18

Table A-8 Summary of total chlorophyll a values (micrograms per litre) in near-surface waters of the offshore part (sounding >50 metres) of Lake Ontario.

Mean date	Vessel	Sample depths (metres)	Minimum TCa (µg/litre)	Mean TCa (µg/litre)	Maximum TCa (µg/litre)	Number of Observations
June 15, 1967	Theron	1m	7.6	19.0?	30.3	11
June 27, 1967	Theron	1m	13.2	21.3?	32.8	36
July 12, 1967	Theron	1m	0.7	3.2	8.3	36
July 27, 1967	Theron	1m	0.0	5.5	13.8	37
Aug. 7, 1967	Theron	1m	1.8	3.2	5.6	36
Aug. 23, 1967	Theron	1m	3.0	4.8	10.6	36
Sept. 7, 1967	Theron	1m	4.0	5.6	8.3	36
Sept. 18, 1967	Theron	1m	5.9	8.4	12.4	36
Oct. 3, 1967	Theron	1m	3.4	5.3	7.5	38
Oct. 19, 1967	Theron	1m	4.9	8.1	14.1	27
Oct. 30, 1967	Theron	1m	1.8	3.6	5.7	37
May 1, 1968	Theron	1m	2.3	4.0	6.8	42
May 28, 1968	Theron	1m	2.6	4.1	6.9	29
July 4, 1968	Theron	1m	4.0	9.0	18.1	42
Oct. 7, 1968	Theron	1m	1.4	2.3	4.9	27
Oct. 29, 1968	Theron	1m	1.1	1.8	2.6	40
Nov. 20, 1968	Theron	1m	0.8	1.3	1.8	23
Apr. 14, 1969	Limnos	1m	0.4	2.0	3.7	27
May 15, 1969	Martin Karlsen	1m	0.2	6.5	22.0	53
June 11, 1969	Martin Karlsen	1m	1.9	8.4	20.0	53
July 10, 1969	Martin Karlsen	1m	2.7	5.5	10.1	53
Aug. 7, 1969	Martin Karlsen	1m	2.1	3.9	7.8	53
Sept.7, 1969	Martin Karlsen	1m	0.0	3.5	12.3	53
Oct. 4, 1969	Martin Karlsen	1m	3.4	7.6	16.8	51
Nov. 2, 1969	Martin Karlsen	1m	1.9	4.5	7.7	53
Dec. 3, 1969	Martin Karlsen	1m	0.8	2.5	5.6	51
Jan. 10, 1970	Martin Karlsen	1m	0.3	0.9	1.4	12
Feb. 6, 1970	Martin Karlsen	1m	1.2	2.2	3.6	50
Mar. 6, 1970	Martin Karlsen	1m	0.1	2.6	5.3	43

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Table A-8, continued Summary of total chlorophyll a values (micrograms per litre) in near-surface waters of the offshore part (sounding > 50 metres) of Lake Ontario.

Mean date	Vessel	Sample depths (metres)	Minimum TCa (µg/litre)	Mean TCa (µg/litre)	Maximum TCa (µg/litre)	Number of Observations
Apr. 2, 1970	Martin Karlsen	1m	2.5	3.6	5.8	26
Apr. 30, 1970	Martin Karlsen	1m	2.8	4.7	10.9	25
May 27, 1970	Martin Karlsen	1m	3.5	4.8	7.8	24
June 25, 1970	Martin Karlsen	1m	2.2	9.6	17.2	27
July 18, 1970	Martin Karlsen	1m	2.9	5.8	9.6	37
Aug. 19, 1970	Martin Karlsen	1m	2.5	3.9	7.5	38
Sept. 17, 1970	Martin Karlsen	1m	3.8	7.4	12.5	38
Oct. 15, 1970	Martin Karlsen	1m	3.5	6.7	17.8	41
Nov. 18, 1970	Martin Karlsen	1m	2.5	3.7	4.6	27
Dec. 9, 1970	Martin Karlsen	1m	1.1	2.1	3.3	40
Apr. 1, 1971	Martin Karlsen	1m	1.3	2.0	3.6	28
Aug. 11, 1971	Martin Karlsen	1m	3.5	4.8	8.1	30
Nov. 17, 1971	Martin Karlsen	1m	1.6	3.6	4.8	30
Apr. 6, 1972	Porte Dauphine & Limnos	1m	1.7	2.6	5.4	54
Apr. 11, 1972	Porte Dauphine & Limnos	1m	1.0	1.9	5.8	54
Apr. 12, 1972	Martin Karlsen	1,5,&10m	1.6	2.6	6.4	62
Apr. 18, 1972	Porte Dauphine & Limnos	1m	0.9	2.0	6.1	53
Apr. 25, 1972	Porte Dauphine & Limnos	1m	1.3	2.3	6.4	55
May 2, 1972	Porte Dauphine & Limnos	1m	1.2	2.4	5.8	55
May 9, 1972	Porte Dauphine & Limnos	1m	1.1	2.7	12.2	56
May 25, 1972	Martin Karlsen	1,5,&10m	1.5	3.3	8.5	66
June 21, 1972	Martin Karlsen	1,5,&10m	1.0	6.9	14.0	65
July 19, 1972	Martin Karlsen	1,5,&10m	1.4	8.1	20.4	62
Sept. 7, 1972	Martin Karlsen	1,5,&10m	1.2	6.5	16.2	63

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Table A-8, continued Summary of total chlorophyll a values (micrograms per litre) in near-surface waters of the offshore part (sounding > 50 metres) of Lake Ontario.

Mean date	Vessel	Sample depths (metres)	Minimum TCa (µg/litre)	Mean TCa (µg/litre)	Maximum TCa (µg/litre)	Number of Observations
Oct. 4, 1972	Porte Dauphine & Martin Karlsen	1m	5.0	8.2	13.1	57
Oct. 19, 1972	Martin Karlsen	1,5,&10m	0.6	3.4	6.2	66
Nov. 22, 1972	Martin Karlsen	1,5,&10m	0.9	1.9	2.8	66
Dec. 6, 1972	Porte Dauphine & Limnos	1m	1.0	1.7	5.4	55
Dec. 12, 1972	Porte Dauphine & Limnos	1m	1.1	1.4	2.1	52
Dec. 19, 1972	Porte Dauphine & Limnos	1m	1.0	1.5	2.9	32
Jan. 4, 1973	Porte Dauphine & Martin Karlsen	1m	0.8	1.5	3.2	31
Jan. 10, 1973	Martin Karlsen	1,5,&9m	0.7	1.1	3.2	39
Jan. 17, 1973	Porte Dauphine & Limnos	1m	0.7	1.2	2.7	47
Jan. 30, 1973	Porte Dauphine & Limnos	1m	0.7	1.2	2.2	24
Feb. 13, 1973	Limnos	1m	0.8	1.3	2.2	33
Feb. 27, 1973	Limnos	1m	0.9	1.8	2.5	30
Mar. 7, 1973	Martin Karlsen	1,5,&10m	1.0	1.6	2.0	66
Mar. 13, 1973	Porte Dauphine & Limnos	1m	0.9	1.7	2.8	55
Mar. 27, 1973	Porte Dauphine & Limnos	1m	0.7	1.7	5.4	56
Nov. 1, 1973	Martin Karlsen	1m	0.4	3.0	6.6	35
Apr. 18, 1974	Porte Dauphine	0 to 20m	1.3	3.2	12.2	48
May 1, 1974	Porte Dauphine	0 to 20m	1.5	3.5	7.6	45
May 14, 1974	Porte Dauphine	0 to 20m	1.5	4.9	15.1	50
June 5, 1974	Porte Dauphine	0 to 20m	1.2	4.4	10.1	47
June 18, 1974	Porte Dauphine	0 to 20m	2.4	5.5	8.3	47

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Table A-8, continued Summary of total chlorophyll a values (micrograms per litre) in near-surface waters of the offshore part (sounding > 50 metres) of Lake Ontario.

Mean date	Vessel	Sample depths (metres)	Minimum TCa (µg/litre)	Mean TCa (µg/litre)	Maximum TCa (µg/litre)	Number of Observations
July 25, 1974	Advent	0 to 20m	1.9	4.1	9.4	34
Aug. 8, 1974	Martin Karlsen	0 to 20m	2.0	4.0	8.0	50
Aug. 14, 1974	Martin Karlsen	0 to 20m	1.3	4.4	8.5	38
Aug. 20, 1974	Limnos	0 to 20m	1.9	3.3	5.6	47
Sept. 5, 1974	Porte Dauphine	0 to 20m	2.8	4.8	9.7	46
Sept. 18, 1974	Porte Dauphine	0 to 20m	0.7	6.8	15.3	47
Oct. 3, 1974	Porte Dauphine	0 to 20m	3.3	5.3	9.3	37
Oct. 17, 1974	Limnos	0 to 20m	4.5	8.4	11.5	42
Nov. 27, 1974	Porte Dauphine	0 to 20m	2.8	5.5	9.2	45
Apr. 12, 1975	Limnos	0 to 20m	0.6	1.4	5.3	48
May 25, 1975	Northern Seal	0 to 20m	0.6	3.9	9.9	48
June 5, 1975	Northern Seal	0 to 20m	1.3	5.4	9.8	47
July 4, 1975	Northern Seal	0 to 20m	3.8	5.5	8.8	47
July 23, 1975	Northern Seal	0 to 20m	1.7	2.9	7.9	51
Aug. 14, 1975	Northern Seal	0 to 20m	1.7	4.5	7.4	48
Sept. 5, 1975	Northern Seal	0 to 20m	3.2	6.0	10.0	48
Sept.25, 1975	Northern Seal	0 to 20m	2.0	5.6	8.5	48
Oct. 18, 1975	Northern Seal	0 to 20m	1.0	4.7	7.3	48
Nov. 5, 1975	Northern Seal	0 to 20m	3.1	4.6	6.0	47
Dec. 7, 1975	Limnos	0 to 20m	1.3	1.9	3.3	45

Table A-9 Summary of particulate organic carbon values (micrograms carbon per litre) in near-surface waters of the offshore part (sounding > 100 metres) of Lake Superior.

Mean date	Vessel	Sample depths (metres)	Minimum POC (μgC/litre)	Mean POC (μgC/litre)	Maximum POC (μgC/litre)	Number of Observations
May 18, 1973	Martin Karlsen	1,5,&10m	55.	82.	181.	57
June 21, 1973	Martin Karlsen	1,5,&10m	55.	84.	131.	52
Aug. 1, 1973	Martin Karlsen	1,5,&10m	70.	140.	249.	52
Sept.11, 1973	Martin Karlsen	1,5,&10m	41.	149.	262.	54
Oct. 21, 1973	Martin Karlsen	1 & 5m	71.	157.	246.	33
Nov. 23, 1973	Martin Karlsen	1,5,&10m	47.	80.	129.	57

Table A-10 Summary of particulate organic carbon values (micrograms carbon per litre) in near-surface waters of the offshore part (sounding > 50 metres) of Lake Huron.

Mean date	Vessel	Sample depths (metres)	Minimum POC (μgC/litre)	Mean POC (μgC/litre)	Maximum POC (μgC/litre)	Number of Observations
May 11, 1973	Martin Karlsen	1 & 10m	43.	68.	98.	15
Apr. 25, 1974	Martin Karlsen	1m	113.	142.	183.	11
May 15, 1974	Martin Karlsen	1m	165.	196.	248.	11
June 26, 1974	Martin Karlsen	1m	130.	197.	269.	17
July 25, 1974	Martin Karlsen	1m	117.	157.	268.	15
Aug. 28, 1974	Martin Karlsen	1m	128.	198.	274.	14
Oct. 3, 1974	Martin Karlsen	1m	165.	219.	303.	13

Table A-11 Summary of particulate organic carbon values (micrograms carbon per litre) in near-surface waters of the offshore part (sounding > 20 metres) of central Lake Erie.

Mean date	Vessel	Sample depths (metres)	Minimum POC (μgC/litre)	Mean POC (μgC/litre)	Maximum POC (μgC/litre)	Number of Observations
Apr. 27, 1972	Martin Karlsen	1 - 8m	146.	204.	292.	17
Aug. 3, 1972	Martin Karlsen	1 -10m	215.	337.	466.	26
Aug. 30, 1972	Porte Dauphine	1 & 10m	357.	564.	849.	24
Nov. 12, 1972	Martin Karlsen	1m	178.	287.	480.	10
Apr. 14, 1973	Limnos	1 & 5m	128.	255.	676.	28
July 27, 1973	Limnos	1 -10m	79.	510.	1007.	42
Aug. 30, 1973	Martin Karlsen	1m	332.	540.	950.	13
Nov. 11, 1973	Limnos	1 & 5m	204.	384.	583.	28
Apr. 26, 1974	Porte Dauphine	0 to 20m	248.	361.	450.	15
Aug. 23, 1974	Martin Karlsen	0 to 20m	309.	400.	471.	7
Apr. 8, 1975	Limnos	0 to 19m	501.	757.	936.	11
May 16, 1975	Northern Seal	0 to 20m	441.	538.	612.	8
June 27, 1975	Northern Seal	0 to 20m	285.	416.	741.	9
Aug. 9, 1975	Northern Seal	0 to 20m	425.	545.	695.	13
Oct. 9, 1975	Northern Seal	0 to 20m	475.	596.	713.	10
Oct. 30, 1975	Northern Seal	0 to 20m	411.	531.	628.	9
Nov. 27, 1975	Limnos	0 to 20m	320.	577.	1,686	11

Table A-12 Summary of particulate organic carbon values (micrograms carbon per litre) in near-surface waters of the offshore part (sounding > 50 metres) of Lake Ontario.

Mean date	Vessel	Sample depths (metres)	Minimum POC (μgC/litre)	Mean POC (μgC/litre)	Maximum POC (μgC/litre)	Number of Observations
Apr. 13, 1972	Martin Karlsen	1,5,&10m	80.	179.	352.	51
May 25, 1972	Martin Karlsen	1,5,&10m	75.	184.	465.	66
June 21, 1972	Martin Karlsen	1,5,&10m	84.	551.	1,060.	65
July 19, 1972	Martin Karlsen	1,5,&10m	190.	733.	1,287.	65
Sept.7, 1972	Martin Karlsen	1,5,&10m	276.	708.	1,203.	66
Sept.21, 1972	Martin Karlsen	1,5,&10m	135.	552.	941.	63
Oct. 19, 1972	Martin Karlsen	1,5,&10m	123.	338.	549.	64
Nov. 22, 1972	Martin Karlsen	1,5,&10m	81.	171.	286.	66
Jan. 10, 1973	Martin Karlsen	1,5,&9m	106.	164.	331.	36
Mar. 7, 1973	Martin Karlsen	1,5,&10m	86.	129.	258.	66
Mar. 21, 1973	Martin Karlsen	1 & 10m	80.	157.	253.	49
Apr. 26, 1973	Martin Karlsen	1,5,&10m	2.	76.	239.	72
Nov. 1, 1973	Martin Karlsen	1,5,&10m	92.	225.	486.	104
Dec. 5, 1973	Martin Karlsen	1 & 5m	92.	131.	311.	44
Apr. 18, 1974	Porte Dauphine	0 to 20m	96.	162.	251.	24
May 1, 1974	Porte Dauphine	0 to 20m	107.	189.	436.	21
May 14, 1974	Porte Dauphine	0 to 20m	97.	200.	366.	27
June 5, 1974	Porte Dauphine	0 to 20m	102.	326.	630.	26
June 18, 1974	Porte Dauphine	0 to 20m	270.	508.	797.	26
July 25, 1974	Advent	0 to 20m	286.	518.	717.	18
Aug. 8, 1974	Martin Karlsen	0 to 20m	218.	432.	844.	28
Aug. 14, 1974	Martin Karlsen	0 to 20m	184.	385.	744.	25
Aug. 20, 1974	Limnos	0 to 20m	272.	374.	539.	25
Sept. 4, 1974	Porte Dauphine	0 to 20m	227.	415.	567.	22
Sept. 18, 1974	Porte Dauphine	0 to 20m	115.	376.	574.	24
Oct. 3, 1974	Porte Dauphine	0 to 20m	234.	348.	432.	26
Oct. 17, 1974	Limnos	0 to 20m	287.	404.	592.	23
Nov. 27, 1974	Porte Dauphine	0 to 20m	199.	263.	331.	27
Apr. 12, 1975	Limnos	0 to 20m	119.	178.	358.	21
May 25, 1975	Northern Seal	0 to 20m	99.	474.	888.	28
June 5, 1975	Northern Seal	0 to 20m	202.	564.	829.	20

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Table A-12, continued Summary of particulate organic carbon values (micrograms carbon per litre) in near-surface waters of the offshore part (sounding > 50 metres) of Lake Ontario.

Mean date	Vessel	Sample depths (metres)	Minimum POC (μgC/litre)	Mean POC (μgC/litre)	Maximum POC (μgC/litre)	Number of Observations
July 4, 1975	Northern Seal	0 to 20m	383.	614.	1,160.	37
July 23, 1975	Northern Seal	0 to 20m	207.	336.	577.	22
Aug. 14, 1975	Northern Seal	0 to 20m	348.	474.	694.	21
Sept. 5, 1975	Northern Seal	0 to 20m	355.	516.	671.	28
Sept. 25, 1975	Northern Seal	0 to 20m	192.	412.	593.	33
Oct. 18, 1975	Northern Seal	0 to 20m	222.	362.	535.	25
Nov. 5, 1975	Northern Seal	0 to 20m	266.	328.	413.	20
Dec. 7, 1975	Limnos	0 to 20m	136.	190.	374.	27

Table A-13. Summary of total phosphorus values (micrograms phosphorus per litre) in near-surface waters of the offshore part (sounding > 100 metres) of Lake Superior.

Mean date	Vessel	Sample depths (metres)	Minimum total phosphorus (μgP/litre)	Mean total phosphorus (μgP/litre)	Maximum total phosphorus (μgP/litre)	Number of Observations
Aug. 23, 1968	Theron	1m	[1.0]	[3.1]	[5.9]	8 only
Apr. 17, 1970	Martin Karlsen	1m	[2.9]	[3.3]	[3.6]	6 only
Nov. 1, 1970	Martin Karlsen	1m	[2.0]	[2.6]	[3.3]	8 only
May 29, 1971	Martin Karlsen	1,5,&10m	2.0	3.0	4.6	77
July 3, 1971	Martin Karlsen	1,5,&10m	2.0	3.4	6.2	91
Oct. 9, 1971	Martin Karlsen	1,5,&10m	0.7	2.9	4.6	95
May 18, 1973	Martin Karlsen	1 & 10m	2.8	7.6	15.0	149
June 21, 1973	Martin Karlsen	1 & 10m	3.1	5.3	12.7	170
Aug. 1, 1973	Martin Karlsen	1 & 10m	2.4	4.7	11.0	180
Sept. 11, 1973	Martin Karlsen	1 & 10m	1.0	6.9	15.0	154
Oct. 20, 1973	Martin Karlsen	1 & 5m	2.8	5.3	13.8	87
Nov. 23, 1973	Martin Karlsen	1,5,&10m	0.9	4.7	11.0	163

Table A-14 Summary of total phosphorus values (micrograms phosphorus per litre) in near-surface waters of the offshore part (sounding (> 50 metres) of Lake Huron.

Mean date	Vessel	Sample depths (metres)	Minimum total phosphorus (μgP/litre)	Mean total phosphorus (μgP/litre)	Maximum total phosphorus (μgP/litre)	Number of Observations
Aug. 9, 1968	Theron	1m	[3.3]	[4.3]	[5.9]	9 only
Sept. 26, 1969	Martin Karlsen	1,5,&10m	3.9	6.3	9.5	19
May 14, 1970	Martin Karlsen	1m	[4.2]	[5.3]	[6.5]	6 only
Apr. 24, 1971	Martin Karlsen	1,5,&10m	2.3	3.8	6.2	86
May 22, 1971	Martin Karlsen	1,5,&10m	2.3	4.1	7.5	69
June 25, 1971	Martin Karlsen	1,5,&10m	2.9	6.9	13.4	80
July 23, 1971	Martin Karlsen	1,5,&10m	2.0	3.3	5.2	78
Aug. 27, 1971	Martin Karlsen	1,5,&10m	2.0	3.6	6.8	75
Oct. 2, 1971	Martin Karlsen	1,5,&10m	2.3	4.1	11.7	72
Oct. 31, 1971	Martin Karlsen	1,5,&10m	1.0	2.7	6.5	70
Dec. 3, 1971	Martin Karlsen	1,5,&10m	2.6	4.5	9.8	74
May 5, 1972	Martin Karlsen	1 & 10m	3.1	4.4	6.8	64
Aug. 12, 1972	Martin Karlsen	1 to 10m	2.9	5.0	15.3	62
Nov. 5, 1972	Martin Karlsen	1 & 10m	3.7	5.0	9.1	49
May 11, 1973	Martin Karlsen	1 to 10m	6.4	9.7	16.0	14
Sept. 20, 1973	Martin Karlsen	1 to 10m	7.1	8.2	11.0	14
Apr. 25, 1974	Martin Karlsen	1m	5.9	8.2	13.3	12
May 16, 1974	Martin Karlsen	1m	3.1	4.4	5.6	10
June 26, 1974	Martin Karlsen	1m	3.5	4.7	5.5	18
July 25, 1974	Martin Karlsen	1 & 10m	2.7	4.3	6.8	15
Aug. 28, 1974	Martin Karlsen	1m	2.8	4.7	7.2	12
Oct. 3, 1974	Martin Karlsen	1m	4.6	5.3	7.3	13

Table A-15 Summary of total phosphorus values (micrograms phosphorus per litre) in near-surface waters of the offshore part (sounding >20 metres) of central Lake Erie.

Mean date	Vessel	Sample depths (metres)	Minimum total phosphorus (µg P/litre)	Mean total phosphorus (µg P/litre)	Minimum total phosphorus (µg P/litre)	Number of Observations
June 18, 1968	Theron	1m	[6.8]]	[8.5]	[9.8]	3 only
Aug. 1, 1968	Theron	1 & 10m	[8.8]	[11.7]	[14.3]	4 only
Oct. 1, 1968	Theron	1 & 10m	[5.5]	[15.6]	[22.5]	6 only
Nov. 8, 1968	Theron	1 & 10m	[12.7]	[22.1]	[26.4]	6 only
June 2, 1969	Martin Karlsen	1, 5 & 10m	[7.8]	[11.6]	[19.6]	9 only
Sept. 16, 1969	Martin Karlsen	1, 5 & 10m	[18.3]	[20.3]	[21.5]	6 only
Apr. 9, 1970	Martin Karlsen	1, 5 & 10m	9.5	13.8	19.2	18
May 8, 1970	Martin Karlsen	1, 5 & 10m	12.1	18.7	27.4	21
June 4, 1960	Martin Karlsen	1, 5 & 10m	9.8	18.0	31.3	33
July 5, 1970	Martin Karlsen	1, 5 & 10m	7.2	10.2	15.0	30
July 30, 1970	Martin Karlsen	1, 5 & 10m	6.5	10.9	20.5	30
Aug. 27, 1970	Martin Karlsen	1, 5 & 10m	5.5	10.4	19.6	30
Sept. 25, 1970	Martin Karlsen	1, 5 & 10m	8.2	14.3	28.0	30
Oct. 23, 1970	Martin Karlsen	1, 5 & 10m	10.8	16.0	23.8	33
Nov. 28, 1970	Martin Karlsen	1, 5 & 10m	21.2	28.7	35.5	27
Dec. 16, 1970	Martin Karlsen	1, 5 & 10m	25.8	29.6	34.6	15
Feb. 8, 1971	N.B. McLean	1 & 5m	[17.3]	[21.6]	[24.5]	6 only
Mar. 3, 1971	N.B. McLean	1 & 5m	[22.8]	[25.2]	[29.7]	6 only
Apr. 16, 1971	Martin Karlsen	1, 5 & 10m	13.4	18.8	29.3	30
July 7, 1971	Porte Dauphine	1m	[11.7]	[19.7]	[27.7]	8 only
Aug. 19, 1971	Martin Karlsen	1, 5 & 10m	7.5	11.2	19.6	30
Nov. 25, 1971	Martin Karlsen	1, 5 & 10m	8.8	16.1	19.9	24
Apr. 27, 1972	Martin Karlsen	1 to 8m	9.8	14.6	23.4	17
June 8, 1972	Martin Karlsen	1 to 8m	7.1	11.4	18.4	22
June 29, 1972	Porte Dauphine	1 to 10m	8.2	16.4	38.5	18

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Table A-15, continued. Total phosphorus in central Lake Erie

Mean date	Vessel	Sample depths (metres)	Minimum total phosphorus (µg P/litre)	Mean total phosphorus (µg P/litre)	Minimum total phosphorus (µg P/litre)	Number of Observations
Aug. 3, 1972	Martin Karlsen	1 to 10m	10.0	13.7	18.1	26
Aug. 30, 1972	Porte Dauphine	1 to 10m	8.4	15.2	29.3	24
Sept. 30, 1972	Martin Karlsen	1 to 12m	11.2	19.7	30.7	20
Nov. 12, 1972	Martin Karlsen	1 & 7m	15.0	18.9	23.0	13
Apr. 14, 1973	Limnos	1 & 5m	16.0	25.0	39.0	35
Nov. 11, 1973	Limnos	1 & 5m	18.0	26.9	40.0	28
Apr. 26, 1974	Porte Dauphine	0 to 20m	14.0	18.5	26.0	13
Aug. 23, 1974	Martin Karlsen	0 to 20m	9.6	14.3	24.2	15
Apr. 8, 1975	Limnos	1m, & 0-20m	17.0	32.9	74.0	36
June 27, 1975	Northern Seal	0 to 20m	[10.5]	[18.9]	[33.6]	7 only
Aug. 9, 1975	Northern Seal	0 to 20m	[9.4]	[11.9]	[16.1]	7 only
Oct. 9, 1975	Northern Seal	1m, & 0-20m	12.0	17.4	27.0	42

Table A-16. Summary of total phosphorus values (micrograms phosphorus per litre) in near-surface waters of the offshore part (sounding > 50 metres) of Lake Ontario.

Mean date	Vessel	Sample depths (metres)	Minimum total phosphorus (µgP/litre)	Mean total phosphorus (µgP/litre)	Maximum total phosphorus (µP/litre)	Number of Observations
Sept. 17, 1967	Theron	1m	[7.]	[12.]	[20.]	7 only
Oct. 2, 1967	Theron	1m	7.	16.	33.	10
Oct. 19, 1967	Theron	1m	[10.]	[13.]	[23.]	8 only
Oct. 30, 1967	Theron	1m	[10.]	[13.]	[15.]	5 only
May 28, 1968	Theron	1m	7.	24.	52.	19
July 3, 1968	Theron	1m	13.	21.	33.	19
Oct. 6, 1968	Theron	1m	9.	16.	23.	17
Oct. 29, 1968	Theron	1m	10.	16.	29.	19
Nov. 20, 1968	Theron	1m	[3.?]	[4.?]	[5.?]	9 only
May 15, 1969	Martin Karlsen	1 & 10m	8.2	22.2	32.6	55
June 11, 1969	Martin Karlsen	1 & 10m	11.7	24.5	39.8	60
July 11, 1969	Martin Karlsen	1 & 10m	12.1	19.8	32.6	52
Aug. 7, 1969	Martin Karlsen	1,5,&10m	7.8	17.0	29.7	71
Sept. 7, 1969	Martin Karlsen	1,5,&10m	11.4	16.1	27.7	72
Oct. 5, 1969	Martin Karlsen	1,5,&10m	9.8	16.1	34.9	70
Nov. 2, 1969	Martin Karlsen	1 & 10m	14.3	19.3	29.3	51
Dec. 4, 1969	Martin Karlsen	1 & 10m	15.0	20.8	28.0	53
Jan. 10, 1970	Martin Karlsen	1,5,&10m	16.3	21.6	27.7	53
Feb. 6, 1970	Martin Karlsen	1,5,&10m	16.0	23.9	32.0	76
Mar. 6, 1970	Martin Karlsen	1,5,&10m	14.0	22.2	29.0	62
May 26, 1970	Martin Karlsen	1 & 5m mixed	20.2	24.5	35.2	12
June 25, 1970	Martin Karlsen	1 & 5m mixed	17.3	27.1	40.8	18
July 18, 1970	Martin Karlsen	1 & 5m mixed	20.2	28.4	40.1	17
Aug. 19, 1970	Martin Karlsen	1 & 5m mixed	17.3	20.4	24.5	16
Sept. 17, 1970	Martin Karlsen	1 & 5m mixed	5.9	14.4	20.2	16
Oct. 15, 1970	Martin Karlsen	1 & 5m mixed	11.7	15.4	19.6	17
Nov. 18, 1970	Martin Karlsen	1 & 5m mixed	14.3	18.3	20.9	19
Dec. 9, 1970	Martin Karlsen	1 & 5m mixed	19.2	22.3	26.1	19
Apr. 1, 1971	Martin Karlsen	1,5,&10m	20.5	23.7	32.6	81
Aug. 11, 1971	Martin Karlsen	1,5,&10m	15.3	22.2	33.3	87
Nov.17, 1971	Martin Karlsen	1,5,&10m	6.2	13.0	39.5	88

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Table A-16, continued Summary of total phosphorus values (micrograms phosphorus per litre) in near-surface waters of the offshore part (sounding > 50 metres) of Lake Ontario.

Mean date	Vessel	Sample depths (metres)	Minimum total phosphorus (μgP/litre)	Mean total phosphorus (μgP/litre)	Maximum total phosphorus (μgP/litre)	Number of Observations
Feb. 8, 1972	Porte Dauphine	1m	20.2	23.7	32.0	29
Apr. 12, 1972	Martin Karlsen	1,5,&10m	20.4	22.4	27.4	55
May 25, 1972	Martin Karlsen	1,5,&10m	17.0	21.2	24.2	66
June 21, 1972	Martin Karlsen	1,5,&10m	14.2	22.1	31.1	66
July 19, 1972	Martin Karlsen	1,5,&10m	10.0	20.3	33.6	66
Sept. 7, 1972	Martin Karlsen	1,5,&10m	8.1	17.8	25.9	63
Sept. 21, 1972	Martin Karlsen	1,5,&10m	13.2	17.0	21.8	61
Oct. 19, 1972	Martin Karlsen	1,5,&10m	8.3	14.5	23.0	65
Nov. 22, 1972	Martin Karlsen	1,5,&10m	16.0	17.9	23.0	66
Jan. 10, 1973	Martin Karlsen	1,5,&9m	21.0	25.3	39.0	42
Mar. 7, 1973	Martin Karlsen	1,5,&10m	21.0	23.8	33.0	66
Mar. 21, 1973	Martin Karlsen	1 & 10m	17.0	24.2	33.0	49
Apr. 26, 1973	Martin Karlsen	1,5,&10m	18.6	26.0	44.4	78
Nov. 1, 1973	Martin Karlsen	1,5,&10m	12.0	20.3	35.0	102
Dec. 5, 1973	Martin Karlsen	1 & 5m	16.0	17.9	25.0	
Apr. 3, 1974	Martin Karlsen	1m	20.0	24.5	46.0	22
May 14, 1974	Porte Dauphine	0 to 20m	19.0	24.1	36.0	48
Sept. 5, 1974	Porte Dauphine	0 to 20m	14.0	18.5	38.0	40
Nov. 27, 1974	Porte Dauphine	0 to 20m	13.0	17.3	34.0	46
Apr. 12, 1975	Limnos	1m &0 to 20m	18.0	21.1	32.0	96
June 5, 1975	Northern Seal	0 to 20m	13.0	20.2	27.0	32
July 5, 1975	Northern Seal	0 to 20m	13.9	20.4	28.2	18
Sept. 5, 1975	Northern Seal	0 to 20m	12.0	16.2	23.0	48
Sept. 25, 1975	Northern Seal	0 to 20m	11.5	15.9	21.0	19