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SCIENTIFIC SERIES NO. 110
(Résumé en français)

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Abstract

A new analysis of hypolimnetic oxygen in central Lake Erie indicates that historic increases in the apparent depletion were not as great as formerly believed. The differences that did occur were mostly related to variations in hypolimnion thickness. Changes, if any, in the oxygen depletion rate due to eutrophication are as yet too small to be recognized. Present-day oxygen depletion rates, when corrected for the relatively high temperatures in Lake Erie, are within the range thought to be indicative of mesotrophy in small lakes. The general level of oxygen depletion observed in the Central Basin of Lake Erie is expected on the basis of morphology alone.

Résumé

D'après une nouvelle analyse de l'hypolimnion de la cuvette centrale de lac Érié, l'accélération de sa désoxygénation n'aurait pas été aussi importante que les données antérieures le montraient. Les différences relevées par le passé s'expliqueraient surtout par les variations de l'épaisseur de cette couche. L'influence de l'eutrophisation serait, si elle existe, encore trop faible pour être decelée. La désoxygénation actuelle, quand on tient compte des températures relativement élevées du lac, correspond à ce qu'on observe dans les petits lacs arrivés au stade mésotrophe. Dans le centre du bassin du lac Érié, elle serait uniquement attribuable à la morphologie de la cuvette lacustre.

Hypolimnetic Oxygen Depletion in Central Lake Erie: Has There Been Any Change?

Murray N. Charlton

INTRODUCTION

Increases in the rate of depletion of hypolimnetic oxygen in Lake Erie have been attributed to cultural eutrophication occurring since the 1920's (Dobson and Gilbertson 1971). While it is recognized that the depletion rate might indicate some difference in trophic status between lakes, very few lakes have been studied long enough to determine their variability (and its causes). Thus, in most lakes, if two measurements were obtained some years apart, it would be difficult to test whether a difference was caused by an external factor, e.g., nutrient loading, or whether a difference was significant at all. If one is interested in relating trends in oxygen depletion and cultural eutrophication, it may be necessary to compensate for coincidental changes in physical factors. As an example, consider a lake which has become subjected to heating, sewage disposal, and damming. Although net effects may be determined by an extended before-after study, it would be difficult to assign a proportion of change to any one use without actual measurements of changes in temperature, nutrient concentration and water depth. In addition, one would hope for comparable weather patterns during the two parts of the study.

Hypolimnetic oxygen depletion is caused by decreased downward transport of oxygen across the thermocline and the presence of oxidizable material and associated processes. Many small temperate lakes, completely unaffected by human activity, have anoxic hypolimnia by the end of summer stratification; they serve to illustrate that some degree of deoxygenation is normal and not necessarily a sign of pollution. As a consequence, before a lake is enriched, there will have been a background average depletion rate with year-to-year, or perhaps decade-to-decade, variation. It may be difficult, but necessary, to determine whether one year's or five consecutive years' measurements represent noise "spikes" on an average signal, peaks of long-term oscillations, or stable averages. By determining and measuring factors that cause variation in oxygen depletion rates, an assessment of these effects on apparent trends may be made. The purpose of this paper is to determine the scope for interpretation in historic Lake Erie oxygen data and examine the effects of factors which may cause variation.

OXYGEN DEPLETION RATES

The apparent trend to increasing depletion rates in Lake Erie in the period 1929-1970 has been discussed by Dobson and Gilbertson (1971), who stated that some selection of data was necessary in the analysis. Carr (1962) and Beeton (1963) indicated that early studies, in 1929 and 1948-1953, might have included inappropriate data owing to sampling problems and less than representative station patterns. It should be noted that oxygen concentrations of less than 4.8 mg/L were found in each of the early studies. Because of the importance of early rates in the determination of the trend, the author decided to re-examine the data to determine whether a variety of interpretations were possible.

A preliminary look at the data showed that there are great differences in the quantity and quality of the data available. Oxygen depletion rates calculated from early data (1929 and 1948-1953) are typically based on one to four stations, whereas the later rates (1959-1963 and 1967-1970) are based on 15 to 33 stations. On the other hand, sampling was more frequent in 1948-1953 than in other years.

DATA FOR 1929

In 1929, depths recorded on repeat visits to the same station often differed by several metres and some part of the metalimnion may have been included in hypolimnion samples. The few temperature profiles available in 1929 (Fish 1960) indicate that the lake was weakly stratified in June, but strongly stratified in July and August, with hypolimnion temperatures below 12°C and 14°C, respectively. Table 1 shows the pertinent data and some possible interpretations. From the combination of temperature profiles and isopleth maps of near-bottom temperature (Fish 1960), it can be seen that the usable data in July are within the 12°C isotherm. There was no thermocline in June, and in August only half (6) of the July stations were within the 14°C isotherm, which marked the upper boundary of the hypolimnion. Of these six data, three are similar to surface oxygen concentrations and indicate that

Table 1. Central Lake Erie Hypolimnion Oxygen Concentration and Calculated Depletion Rates for 1929 (mg/L/mo)

Station	June 17 (weakly stratified)	July 12 (within 12°C isotherm)	August 17 (within 14°C isotherm)
30	8.5		7.9*
35	9.5	9.3*	8.3*
40	8.9	7.5	7.1*
41	8.7	6.8	4.8
42	9.5	7.0	5.6
45	9.3	8.0	4.4
33	10.0	7.1	
34	10.1	9.3*	
39	9.3	7.2	
46	8.1		
44	9.2	7.0	
43	8.7	7.0	
Mean	9.2 mg/L	7.6 mg/L	6.4 mg/L
Rate:	1.9 mg/L/mo	1.0 mg/L/mo	
Mean of values not similar to surface:		7.2 mg/L	4.9 mg/L
Rate:		1.9 mg/L/mo	
Mean of values above but also within 14°C isotherm:		7.3 mg/L	4.9 mg/L
Rate:		2.0 mg/L/mo	

*Denotes values which are the same as or within 1.1 mg/L of near-surface oxygen.

these samples do not represent hypolimnion oxygen. Of the hypolimnion oxygen depletion rates in Table 1, the June-July calculations should be rejected because there was no hypolimnion in June. The first two July-August calculations are based on inappropriate data and, therefore, also rejected. The most reasonable depletion rate, based on the 1929 data, appears to be 2.0 mg/L/mo; this is 25% higher than that reported by Dobson and Gilbertson (1971). Because of the small number of sampling dates and stations, little confidence can be attached to any estimate of the oxygen depletion rate in 1929. Also, assuming that half of the important August values were for metalimnion waters, it is possible that the three data used to calculate the rate represent a mix of hypolimnion and metalimnion water (Carr 1962) and the actual depletion rate was higher than I have calculated.

DATA FOR 1948-1953

Oxygen data for 1948-1953 were collected by the University of Western Ontario and published by Powers *et al.* (1960). Most of these data were collected at stations (Nos. 1 to 6) beginning near Erieau and extending midway on a line to Cleveland. Other, less frequent, data were from stations (Nos. 14 to 23) on a line from Point Pelee to Long Point. Oxygen values used here were reported as "bottom" at stations that were obviously stratified. Oxygen data reported from the hypolimnion at arbitrary depths above the "bottom" were not used, as these were often intermediate between surface and "bottom" values..

The data for 1948-1953 and calculated regression lines are shown in graphical form on Figure 1. In general, oxygen concentrations declined in a regular, linear fashion during the summer with two notable exceptions. The 1948 data are sporadic and scattered; as the regression is not significant at the 5% level, I do not consider the data to be useful. The 1952 data are complicated by a very low value in June, four inexplicably high values in August, and a sort of discontinuity of concentration and, to some degree, rate of decline in mid-July. If all these data are used, a low slope and poor correlation are found, which probably misrepresent the depletion rate. Such a discontinuity in slope and oxygen concentration at a small number of stations (2) may be caused by a weather event and/or water mass movement. If this was the case, data before and after the discontinuity need not be treated as points in the same trend, but may be used to calculate two slopes. Figure 1 (1952) shows that a clear trend developed in June and another developed in July-August; even the slope of the four high August data is similar to that developed by the main data. Consequently, two slopes are reported that are both somewhat higher than the slope derived from a regression of all but the odd data. While the approach is somewhat speculative, it seems preferable to lumping the data or discarding them.

For the years 1949, 1950, 1951, and 1953, station 1 or 2 was sampled frequently and several other stations were sporadically represented. Regression values calculated for both the single station alone and including all data are shown in Figure 1. Slightly better correlations were obtained with data from the single stations.

Some of the oxygen depletion rates calculated from the University of Western Ontario data for 1948-1953 differ from those reported previously by Dobson and Gilbertson (1971). The 1948 data do not appear suitable for the calculation of a depletion rate, but my analysis of the 1951 data yields a depletion rate similar to the findings of Dobson and Gilbertson (1971). The other oxygen depletion rates are all higher than previously reported; some are equivalent to 3 mg/L/mo, which may be the critical rate for the occurrence of anoxia, given sufficient duration of stratification. The reasons for the discrepancies between analyses here and those of Dobson and Gilbertson (1971) are given in Appendix A.

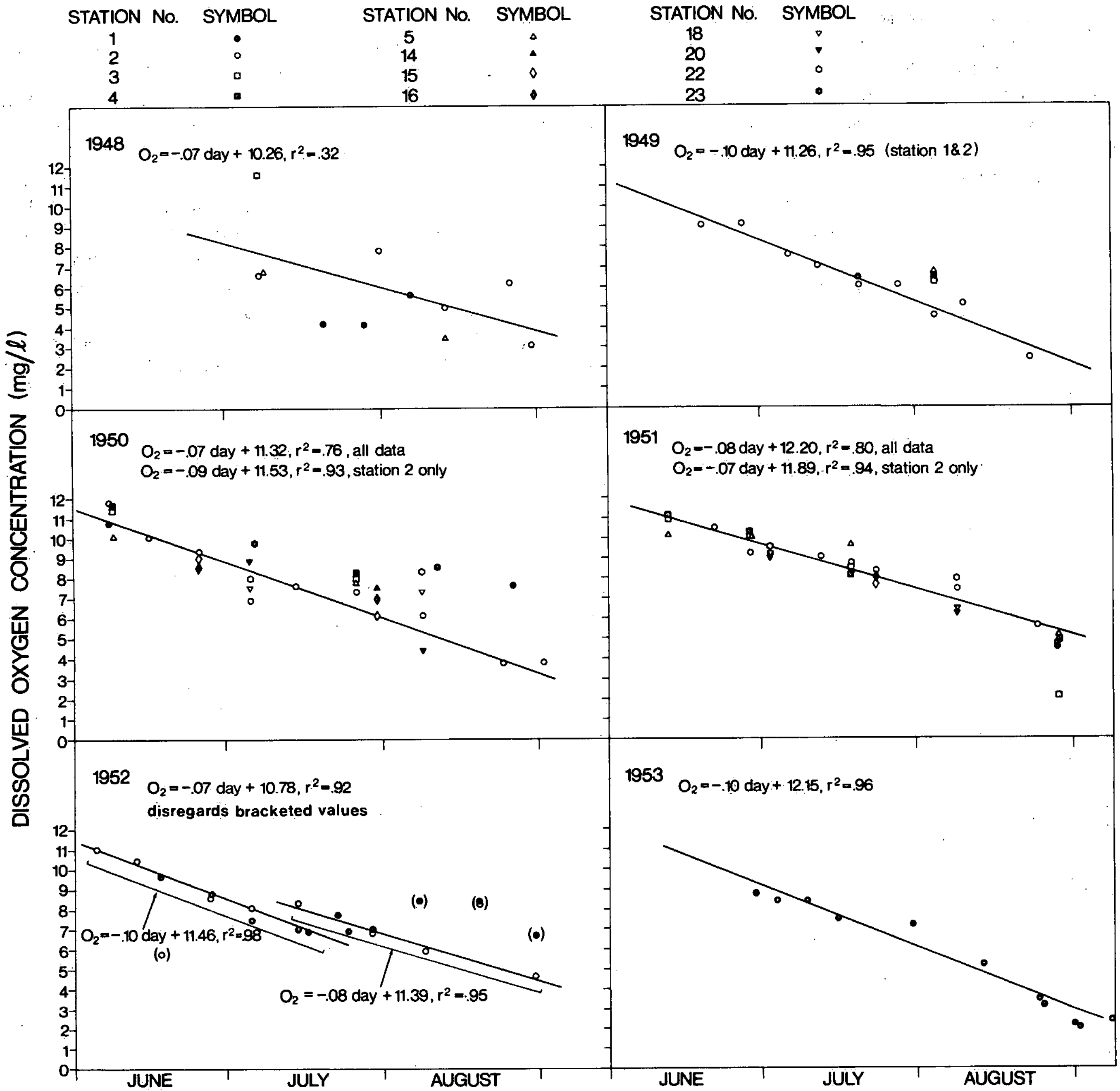

Figure 1. Oxygen depletion in the hypolimnion of central Lake Erie, 1948-1953. Points represent individual observations. Data are from Powers *et al.* (1960).

DATA FOR 1960–1963 AND 1967–1970

After 1953, oxygen data were collected in 1960-1963 by the Great Lakes Institute (G.L.I.) and in 1967-1970 by the Canada Centre for Inland Waters. In general, these data were collected at a greater number of stations more evenly distributed in the lake than before, and are supported by a large number of reversing thermometer and bathythermograph recordings. Because of better sampling, features such as incursion of colder East Basin hypolimnion water and lack of stratification at very shallow stations were revealed. Only rarely were station patterns repeated exactly, and on some cruises there was a high concentration of stations close to Cleveland.

For the purpose of oxygen depletion rate calculation, some data selection was again necessary. Owing to the great variety of station location and distribution, each datum was checked for peculiarities which cannot be foreseen unless one is familiar with the data. Near-bottom oxygen data were selected at stations that were over 15 m deep, were stratified, and showed no evidence of incursion of East Basin water. In addition, to avoid a bias in the calculations, one station was arbitrarily chosen from the many that were close to Cleveland on some cruises.

The mean (±1 SD) hypolimnion oxygen concentrations for each cruise were plotted at the mid-point of each cruise and the best straight line found by linear regression. Results are shown in Figures 2 and 3. The 1960 cruises were augmented by data from a station near Wheatley (Beeton 1963). The oxygen depletion rate of 0.10 mg/L/day in 1970 is slightly lower than that of 0.11 mg/L/day reported by Burns (1976) because no correction was made for oxygen transferred from the mesolimnion to the hypolimnion. This type of calculation was omitted because it depends on the determination of whole basin quantities and is, therefore, inconsistent with the limitations of the earlier data.

Since some of the earlier data were from stations in the west end of the Central Basin, the means for stations west of Erieau in addition to the cruise means for 1970 have been plotted in Figure 3. Apparently, the westerly stations may begin stratification at a slightly lower than average oxygen concentration, but the rate of decline is similar to the whole lake rate. In addition, oxygen depletion rates were calculated with data from only two to three stations near Erieau and then compared with rates calculated from cruise means. There were no consistent differences between the pairs of results and the means of the two groups were not different (t test, 1% level). Providing sampling was done properly, the early depletion rates in 1929 and 1949-1953 are probably comparable with those derived from cruise means of extensive but less frequent surveys after 1960.

There are moderate differences between the oxygen depletion rates published earlier (Dobson and Gilbertson 1971) and those calculated here. My depletion rates for 1960 and 1961 are higher than reported previously, while those for 1967, 1968, 1969 and 1970 are lower. Some of the reasons for these differences are given in Appendix A.

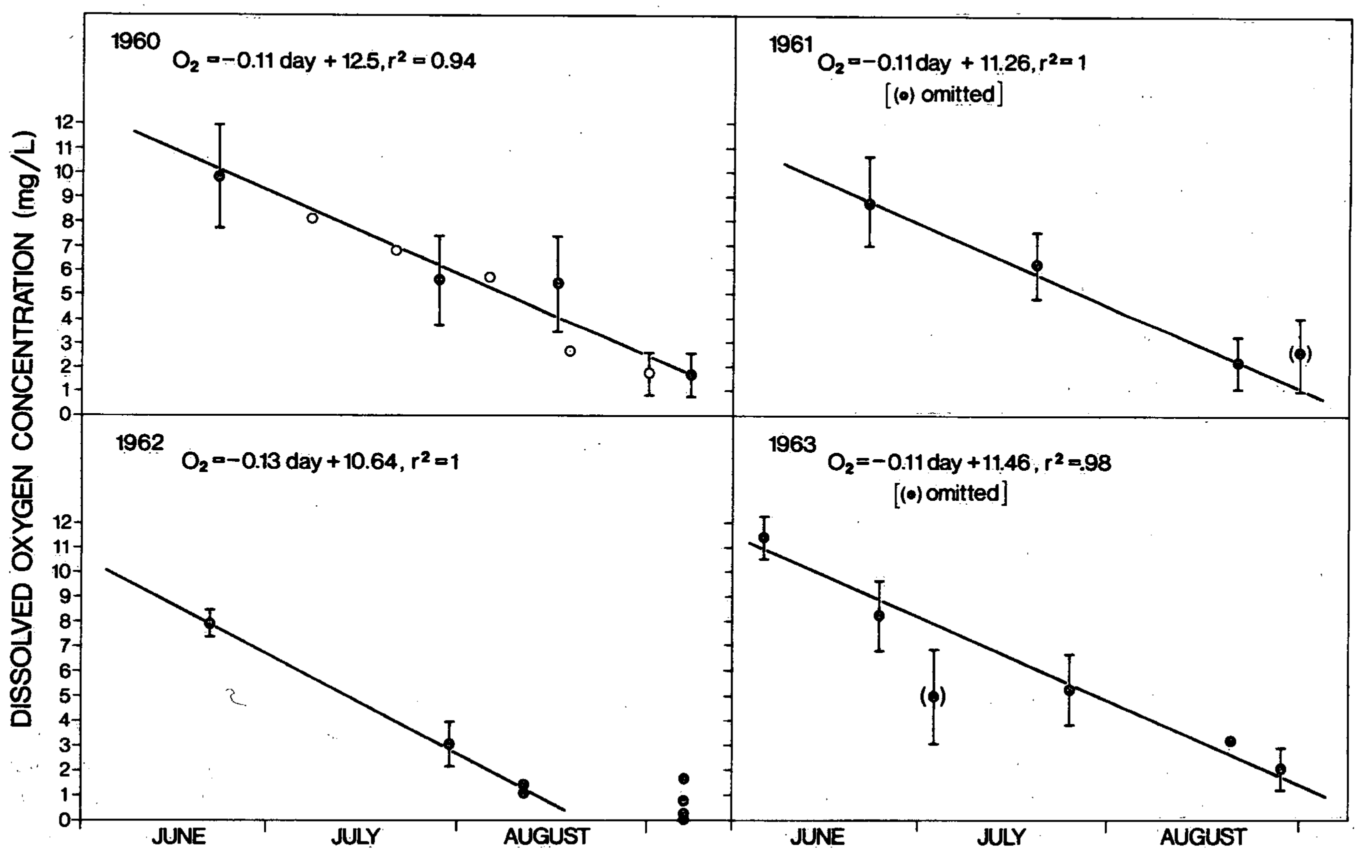

Figure 2. Oxygen depletion in the hypolimnion of central Lake Erie, 1960-1963. Points and regression represent cruise means ±1 SD. Data are from the Great Lakes Institute (1964, 1965) and Rodgers (1962, 1963). Additional data in 1960 are from Beeton (1963).

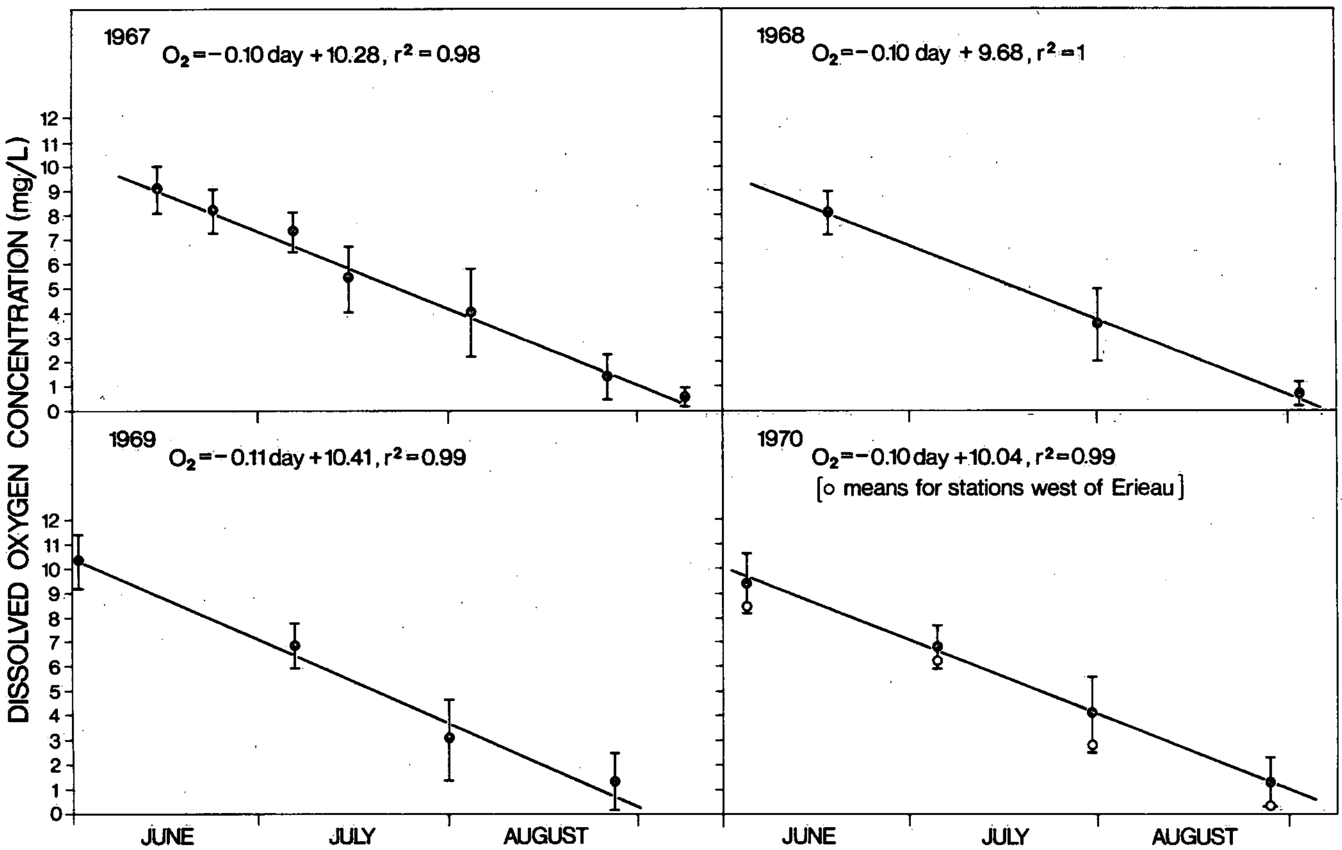

Figure 3. Oxygen depletion in the hypolimnion of central Lake Erie, 1967-1970. Points and regression represent cruise means ±1 SD. Open circles in 1970 are for stations west of Erieau. Data are from C.C.I.W. reports (1970a,b,c) and unpublished C.C.I.W. data for 1970.

ADDITIONAL DATA

A limited number of cruises in 1972, 1973, 1975 and 1977 (CCIW and CLEAR unpublished data) allowed provisional depletion rates to be calculated. These results span the range of most of the available data as far back as 1949.

Provisional Depletion Rates

Date	Source	No. of cruises	No. of stations	O_2 depletion rate (mg/L/day)
1972	CCIW	3	16-22	0.10
1973	CCIW	2	24	0.07
1974	CLEAR	4	32	0.11
1975	CCIW/CLEAR	5	25	0.08
1977	CCIW	5	38	0.10

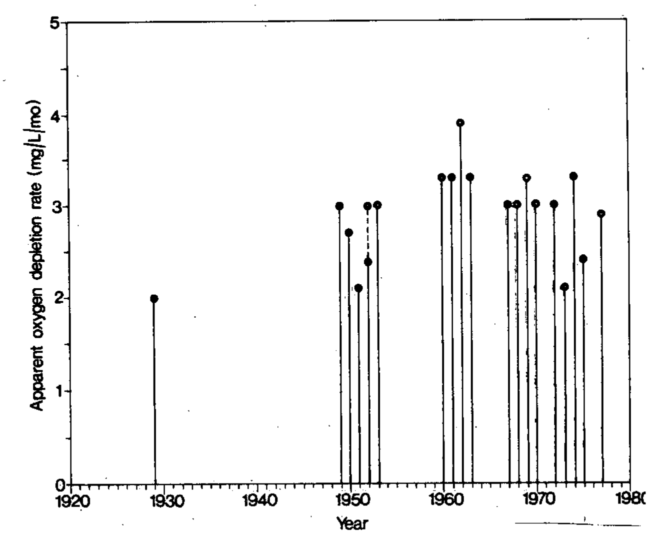

Figure 4. Apparent historic oxygen depletion rates in the hypolimnion of central Lake Erie.

HISTORICAL TRENDS

A summary of the calculated rates of oxygen depletion is shown in Table 2 and graphically in Figure 4. The data have been converted to mg/L/month in order to be comparable to other presentations. Figure 4 indicates that the historic trend is ambiguous. One interpretation could be that the depletion rate increased by 50% from 1929 to 1970; another might be that there was a 30% decrease in the rate from 1949 to 1973. Alternatively, if the extreme years of 1962 and 1973 are taken as some measure of variability, it may be cavalier to suggest that any trend existed. This is in contrast with the analysis of Dobson and Gilbertson (1971), who concluded that there was a clear historic trend which resulted in the rate of oxygen depletion more than doubling from 1929 to 1970.

Table 2. Historical Rates of Oxygen Depletion in Central Basin of Lake Erie

Year	O_2 depletion rate mg/L/mo	No. of stations	Regression N	R^2
1929	2.0	3	2	
1949	3.0	1	11	0.95
1950	2.7	1	9	0.93
1951	2.1	1	9	0.94
1952	2.4-3.0	2	4	0.98
1953	3.0	1	11	0.96
1960	3.3	15-33	8	0.94
1961	3.3	20-30	3	1.0
1962	3.9	2-16	3	1.0
1963	3.3	20	4	0.98
1967	3.0	18-40	6	0.96
1968	3.0	15-30	3	1.0
1969	3.3	24-34	4	0.99
1970	3.0	21-24	4	0.99

EFFECTS OF CLIMATIC VARIATION

The degree of oxygen depletion that occurs in the hypolimnion of lakes is dependent on variables such as hypolimnion volume and the supply of organic matter or trophic state (Hutchinson 1938). The effect of hypolimnion volume or thickness is that the oxygen demand of sediments and falling seston is exerted on larger or smaller quantities of oxygen. Thus, the rate of change of oxygen concentration varies inversely with hypolimnion thickness. Also, as with any metabolic measurement, the rate of oxygen depletion is probably affected by temperature. In Lake Erie, changes in the rate of oxygen depletion have been assumed to indicate changes only in the general level of metabolism (trophic state). The purpose of this section is to examine the potential effects on the oxygen depletion rate of variations in climate, hypolimnion thickness and hypolimnion temperature.

There were important climatic differences between the years in which oxygen depletion rates were estimated in Lake Erie. One of the symptoms of these climatic differences, which may confuse analyses of a long-term trend, is shown in Figure 5. The mean of the annual monthly mean outflow in Figure 5 is 202 x 10^3 cfs ± 10% (SD). Mean monthly outflow for 1924-1975 was 204 x 10^3 cfs with a range of ±20%. Since the flow or flushing rate of a lake helps determine the effect of phosphorus loading on chlorophyll concentration (Vollenweider 1976), there may be fluctuations in trophic state (e.g., chlorophyll) in the absence of any change in phosphorus loading. In years of low flow, the effects of phosphorus loading should be accentuated and vice versa. The effects of flow variations may be damped in the other Great Lakes by their great volumes. Also, given the same relative change in phosphorus loading characteristics, the absolute change in chlorophyll, for example, is dependent on the original chlorophyll concentration. Thus, changes in trophic status may occur more rapidly and may be more noticeable in Lake Erie than in the other Great Lakes.

Figure 5 shows that there were long-term oscillations, which culminated in extreme high and low flows in 1929, 1952, 1973, and 1926, 1934, 1964, respectively. These flow variations were associated with fluctuations in annual rainfall (Powers *et al.* 1960). Also, as might be expected, peak lake levels in June are highly correlated with outflow. During the years of historic oxygen depletion measurements, the range of lake levels was about 1 m; this may be important as the average hypolimnion thickness is only about 4 m. It is unfortunate that, as shown in Figure 5, the early depletion rates were measured in years with high flows, whereas the later rates tended to be in years with lower flows. The average flow for the years 1929 and 1948-1953 was 221 x 10^3 cfs, but for 1959-1963 and 1967-1970 average flows were 195 x 10^3, and 215 x 10^3 cfs, respectively. Of the 7 early years, 6 had above average flow, but of the 9 later years, only 5 were above average.

It is not the purpose here to discuss whether climate cycles existed or the effects of sunspots, etc. The main

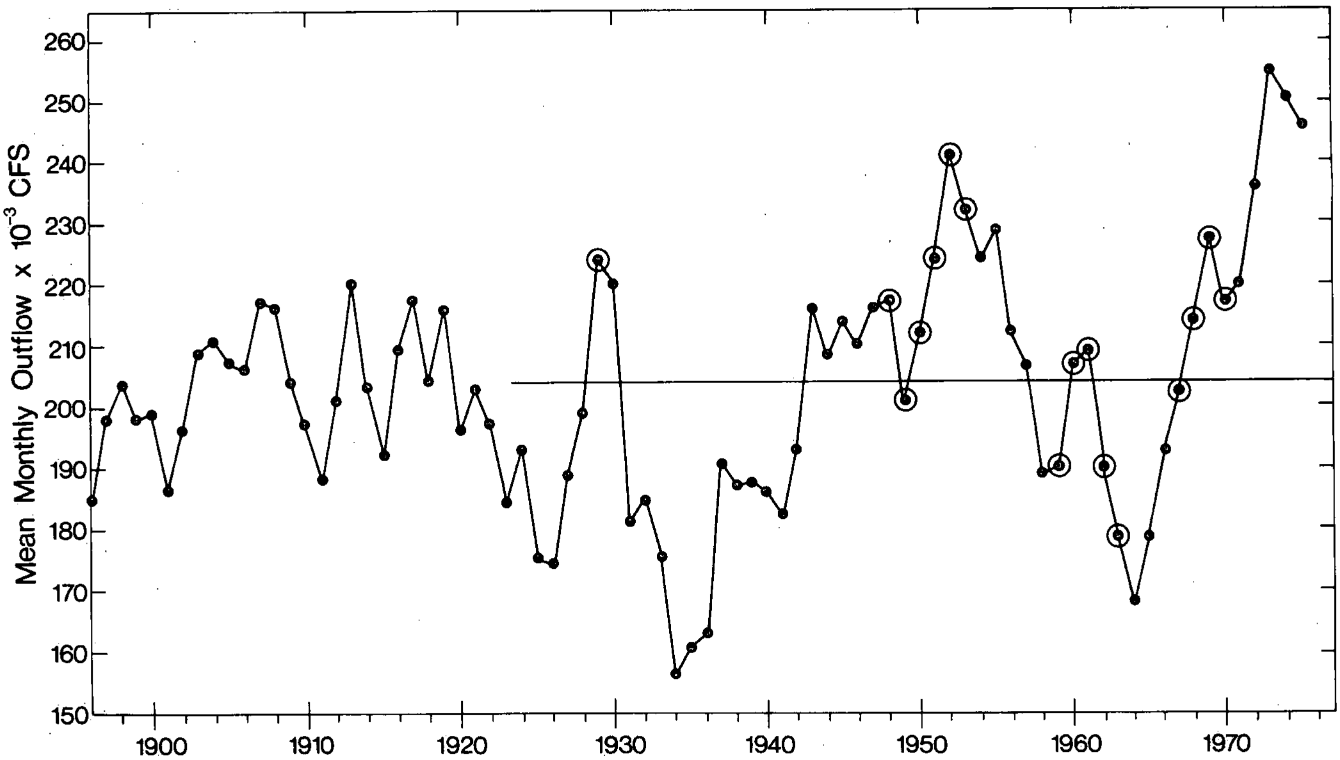

Figure 5. Historic mean monthly outflow from Lake Erie. Circled points are years when oxygen concentration was measured in the hypolimnion. Horizontal line represents average flow after 1920. Data are from the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (1976).

Table 3. Hypolimnion Temperature and Thickness in Central Lake Erie

	June		July		August		Mean	
Year	T (°C)	H_t (m)	T (°C)	H_t (m)	T (°C)	H_t (m)	T (°C)	H_t (m)
1929	9.4		10.4	4.5	12.0		10.6	
1948			11.1		13.3		12.2	
1949	10.5		12.4		11.7		11.5	
1950	7.6		9.5		12.3		9.8	
1951	7.8		9.1		10.6		9.2	
1952	10.4		11.1		11.7		11.1	
1953	11.8		11.3		13.1		12.1	
1960	7.8	5.7	9.9	4.6	13.5	1.9	10.4	4.1
1961	11.6	2.3	12.9	3.1	14.4	3.6	13.0	3.0
1962	10.2	3.7	12.1	1.6	15.6	1.7	12.6	2.3
1963	9.5	5.7	10.2	3.2	14.7	1.7	11.4	3.9
			11.3	5.0				
1967	10.3	7.9*	10.6	4.7	11.5	3.4	10.9	4.1
	10.4	4.3	10.6	4.7	11.6	3.2		
1968	10.0	4.0	13.8	3.3	13.8	2.2	12.5	3.2
1969	8.5	2.6*	10.9	2.9	13.6	2.8	11.5	2.6
			12.9	2.2				
1970	9.4	3.4	9.3	3.5	13.1	2.7	10.8	3.2
			11.3	3.1				
1973			10.3	5.0	11.9	4.4	11.1	4.7
1974	8.8	6.2	11.8	4.6	13.5	4.3	11.4	5.0
1975	6.5	7.7	7.7	6.7	10.2	6.8	8.1	7.1
1976	9.4	6.6	13.7	3.0			11.6	4.8

*Not included in regression.

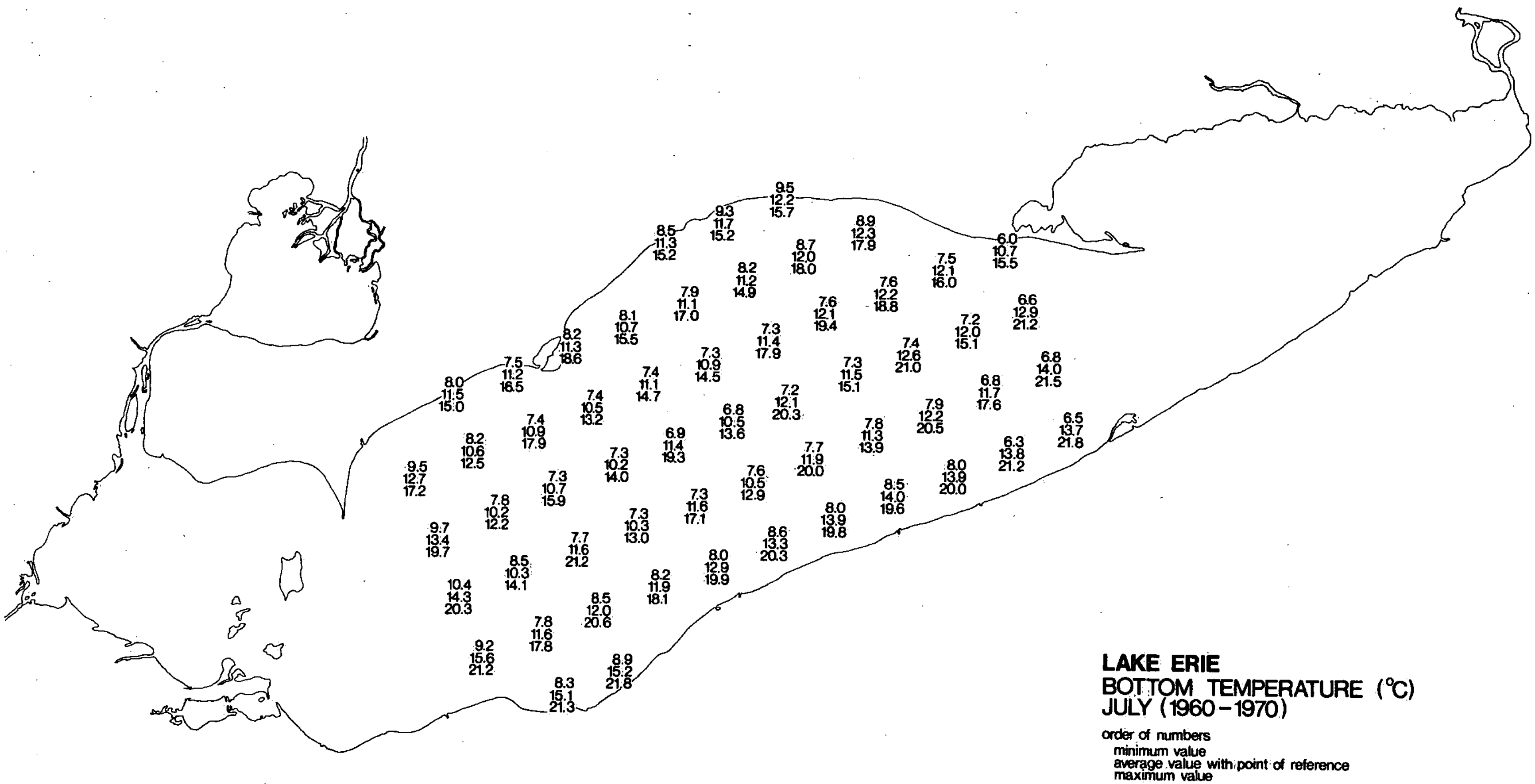

Figure 6. Temperature (°C) means and extremes during July in the hypolimnion of central Lake Erie, 1960-1970. After C.C.I.W. Paper No. 10 (1973).

points are that important hydrologic conditions were not stable during the years in which oxygen depletion measurements were made, and the early (low?) rates tended to be during high water periods whereas the later (higher ?) rates tended to be in low water periods. These factors may be insignificant in larger, deeper lakes but important in Lake Erie.

Concurrent with changes in water level and flow, there were changes in both the thickness and temperature of Lake Erie's hypolimnion; these three factors exert synergistic effects on the oxygen depletion rate. Figure 6 shows that, in July, the difference between hypolimnion temperature extremes can be over 10°C between years at some localities. This illustrates that hypolimnion temperature is not consistent and a comprehensive sampling is required to establish a basin-wide mean. Cruise mean temperature differences shown in Table 3 are not so extreme but are still significant. In July, for example, there is a difference of 4.7°C between 1951 and 1968. Assuming that hypolimnion metabolism would double due to a temperature change of 10°C, the difference in temperature between 1951 and 1968 could cause a 37% difference in the oxygen depletion rate.

Hypolimnion thickness (H_t) was estimated from EBT recordings or calculated from the combination of sounding depth, water sample temperature and depth at the top of the hypolimnion. Cruise mean H_t (arithmetic) for the summer months and the arithmetic mean of the monthly means are shown in Table 3. The thickness of the hypolimnion ranged from 1.7 m to 7.7 m with a grand mean of 4 m. Under the assumption of a simple inverse proportionality, these thickness differences could alter the oxygen depletion rate. Also, Figure 7 shows that hypolimnion thickness is inversely related to temperature. Thus, for years in which the oxygen depletion rate is increased by a thin hypolimnion, the rate may be even greater due to the higher temperature.

By means of Figure 7 the hypolimnion thickness can be estimated for years in which only bottom temperature was measured. This now permits a test of whether oxygen depletion is related to hypolimnion thickness.

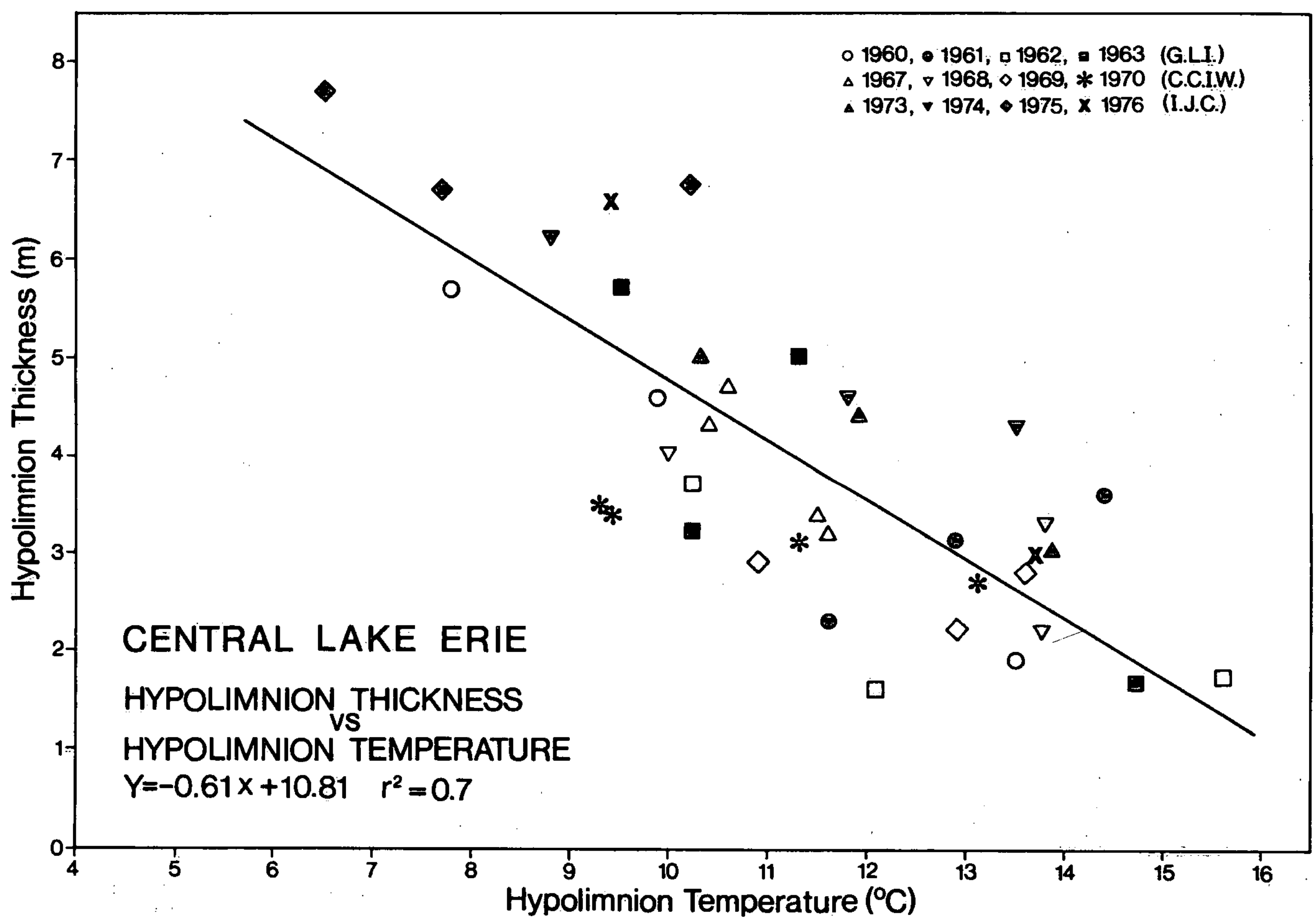

Figure 7. Relationship between hypolimnion thickness and temperature in the hypolimnion of central Lake Erie.

Figure 8 shows that there is an inverse relationship between oxygen depletion and hypolimnion thickness. A least-squares regression of the form $Y = aX^b$ is significant at the 1% level. For the early years, 1929 and 1949-1953, in which only a few temperature measurements were available, the hypolimnion thickness was estimated from the relationship in Figure 7. The lower oxygen depletion rates in the "early" years tended to be associated with thick hypolimnia, whereas the higher rates in later years were associated with thin hypolimnia.

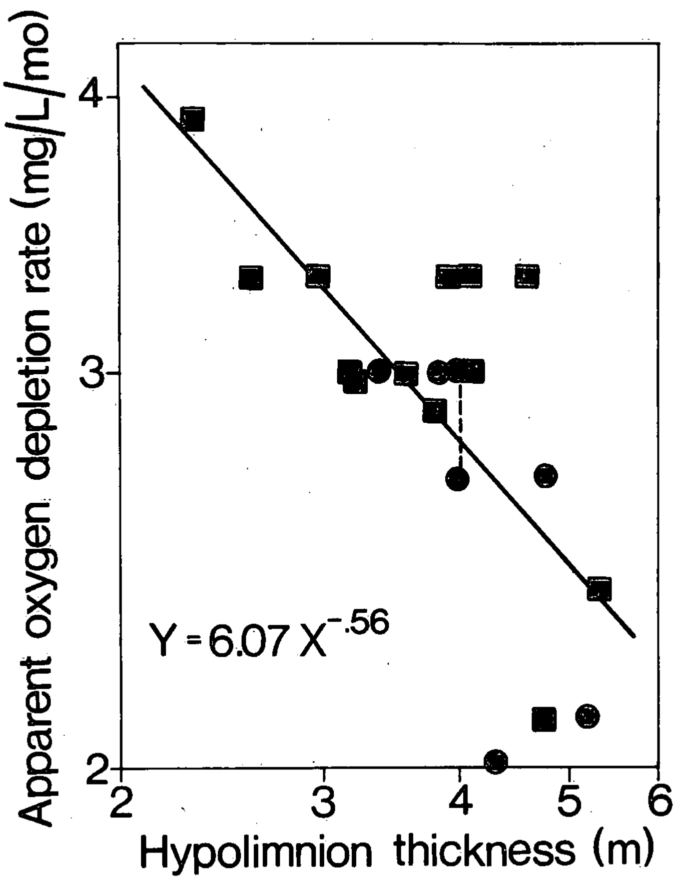

Figure 8. Relationship between oxygen depletion rate and hypolimnion thickness in central Lake Erie. Circles are for years in which thickness was estimated from temperature (1929-1953).

When lake levels are high, as in 1929 and 1949-1953, there is a greater chance that the hypolimnion will be thick. Since the oxygen depletion rates were unintentionally measured at biased intervals with respect to hydrologic fluctuations, any apparent trends in the depletion rate alone are not sufficient to indicate whether a real change occurred.

In order to elucidate long-term trends in oxygen depletion data now available, the confusing effects of variations in hypolimnion thickness and temperature should be removed. This may be done by standardizing or back-correcting each year's depletion rate to the thickness and temperature conditions of a standard year. Under the assumptions that a temperature rise of 10°C will cause a doubling of the metabolic rate ($Q_{10} = 2$) and the depletion rate is inversely proportional to the thickness, then

Standardized Depletion Rate =

$$\frac{\text{Apparent depletion rate of test year}}{\frac{Kt}{Ks} \cdot \frac{\text{Standard year thickness}}{\text{Test year thickness}}} \qquad (1)$$

where $Q_{10} = 2 = \left(\frac{Kt}{Ks}\right)^{\left(\frac{10}{T_t - T_s}\right)}$ and $\frac{Kt}{Ks}$ is the ratio of metabolic rates in the test and standard year.

Similarly, for each year, if the divisor in Equation 1 is multiplied by the depletion rate of a standard year, then a series of depletion rates can be predicted. These calculations depend only on the assumptions above, not on the actual depletion-thickness-temperature relationship.

Predicted oxygen depletion rates based on the year 1970 are compared to the measured apparent depletion rates in Figure 9. Many of the depletion rates are predicted

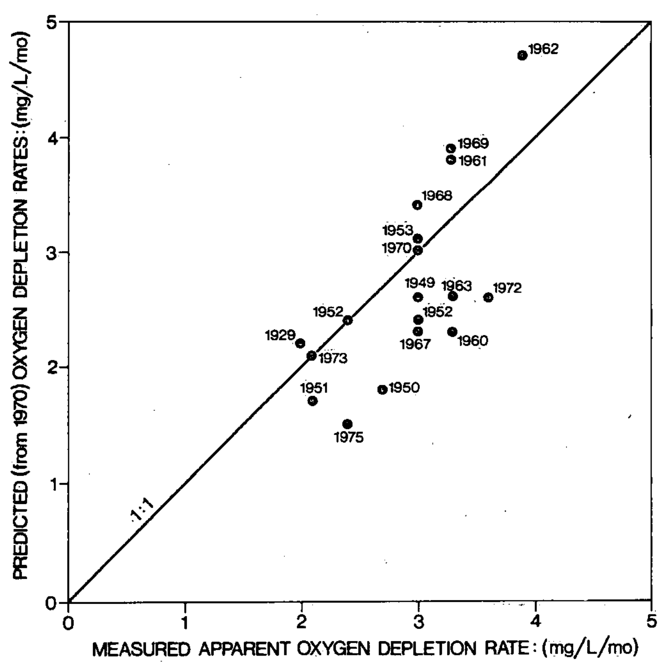

Figure 9. Predicted vs. measured oxygen depletion rates in the hypolimnion of central Lake Erie. Predicted rates are from 1970 as modified by later changes in hypolimnion thickness and temperature.

quite well from only the most rudimentary data. The simple assumptions about the effects of temperature and thickness differences alone are probably responsible for poor predictions. More understanding is needed of the development of the temperature response in relation to different stratification temperatures, and the mechanisms of the thickness effect.

Figure 10 shows that although there is some variation, the standardized oxygen depletion rates show no consistent long-term trend. When the same standardization procedure was applied to the graph of Dobson and Gilbertson (1971), their obvious upward trend in depletion rates disappeared. Thus, the conclusion here that the data do not indicate an increase in the oxygen depletion rate is not affected by slight differences of methodology between analysts.

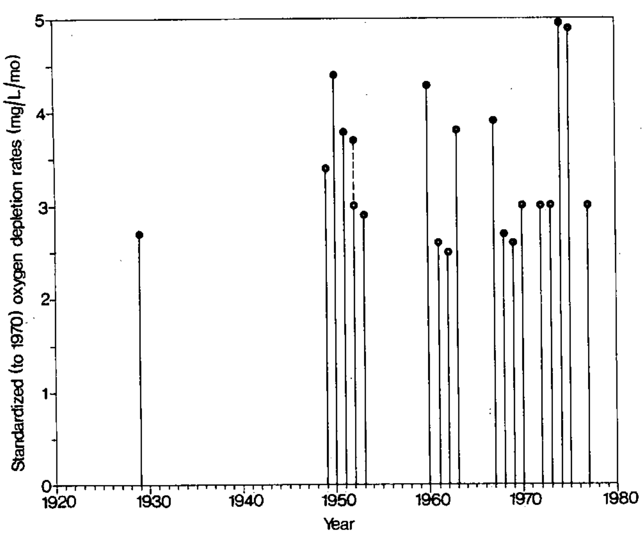

Figure 10. **Historic oxygen depletion rates in the hypolimnion of central Lake Erie standardized to thickness and temperature conditions of 1970.**

The theoretical response of oxygen depletion to hypolimnion thickness and temperature assumed in the correction procedure above may not be realized in nature. For example, oxygen supplied to the hypolimnion would have a relatively greater effect on diminishing apparent oxygen depletion when the hypolimnion is thin. This supply effect may be one reason why the exponent in Figure 8 is only -.56 instead of the -1 expected from thickness effects alone. The relationship in Figure 8 embodies all of the various thickness and temperature effects on the oxygen depletion rate in the Central Basin.

Extrapolation of Figure 8 to a representative thickness of the deeper East Basin hypolimnion predicts almost exactly the oxygen depletion rate there. Since oxygen depletion is proportional to thickness raised to -.56, a "normalized" oxygen depletion rate can be calculated:

$$\frac{\text{Normalized (to 1970) oxygen depletion rate}}{(\text{1970 hypo thickness})^{-.56}} = \frac{\text{Apparent oxygen depletion rate}}{(\text{hypo thickness})^{-.56}}$$

The procedure normalizes each oxygen depletion rate to represent the depletion rate which would have prevailed if hypolimnion thickness and temperature were always as in 1970. Any year can be used as the "normal" year.

Figure 11 shows that, again, removing the interference caused by physical factors failed to elucidate a large long-term trend to higher oxygen depletion rates. The 1929 rate may be too low (Carr 1962), and since it stands alone it may give the appearance of a slight upward trend.

Some variability occurs in lakes with more consistent hypolimnion than Lake Erie (Thienemann 1928; Stewart 1976) and can be expected in Figure 11. Thickness and temperature are only two of the important factors involved; others may be the relative importance of vertical oxygen transport to thick and thin hypolimnia, summer weather and resuspension of oxygen-consuming sediments, incorporation of oxygen from East Basin incursions, mixing depth, and actual changes in trophic state. Nevertheless, hypolimnion thickness and temperature have a profound effect on hypolimnetic oxygen depletion in the Central Basin of Lake Erie. An apparent trend to higher depletion rates was caused by the chance occurrence of early studies at times of high water, thick hypolimnia, and low temperatures.

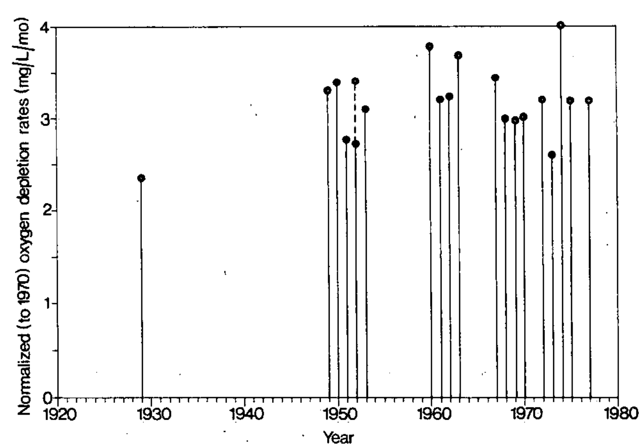

Figure 11. **Historic oxygen depletion rates in the hypolimnion of central Lake Erie normalized to thickness conditions of 1970 (see text).**

DISCUSSION

The present calculations show that changes in the oxygen depletion rate in central Lake Erie can be explained by changes in physical factors. The present analysis does not support the hypothesis that there was a long-term trend to increasing oxygen depletion. If such a trend existed, it was so small as to be undetectable.

To assess this, it is necessary to ask what oxygen depletion trend could have been expected given trends in other data. The problem is the paucity of historic data for central Lake Erie on which to form a judgment. A review by Beeton (1965) showed that concentrations of sulphate and chloride have approximately doubled since 1930. An often-cited paper by Davis (1964) seems to show a three-fold increase in the concentration of phytoplankton cells from the 1930's to the 1960's. These data are from a water treatment plant at Cleveland and represent water drawn from a depth of 13 m, 5.2 km offshore. Unfortunately, currents may cause these data to be more representative of West Basin conditions (Powers *et al.* 1960), and at times of low water there may have been a greater chance of sampling only from the epilimnion. In addition, the Cleveland area is known to have elevated nutrient and plankton levels compared with the open lake.

The net result is that although there are many references to changes in West Basin benthos, species of algae, timing of algal abundance, and *Cladophora* growth, there is no actual documentation of a long-term change in a supply variable, such as POC or chlorophyll, in the Central Basin that would relate directly to the oxygen depletion rate. Lack of documentation does not preclude the possibility that organic supplies to the hypolimnion increased before the lake was studied.

One factor that may potentially effect a change in oxygen conditions is the increase in phosphorus loading due to increased population, sewage facilities, and detergent usage. Present P loadings are about seven times greater than in precolonial times and have approximately doubled since the 1930's (Chapra 1977). Most of the phosphorus loading, however, is into the shallow West Basin which, relative to the rest of the lake, may function as a gigantic wastewater treatment plant. It is impossible to speculate on what fraction of the available P loaded to the West Basin may actually be available in the Central Basin. The mechanism by which P loading may affect oxygen depletion is the stimulation of algal carbon fixation and maintenance of a higher average standing crop, which may export more carbon to be oxidized in the hypolimnion. This fixed carbon is subject to losses by respiration, zooplankton grazing and sedimentation. By incorporation into particles, some organic P and C is continually lost through sedimentation and burial, but the supply of C is essentially limitless. In contrast, the supply of P is limited by the loading rate and recycling characteristics. In addition, the annual rate of carbon fixation appears to be related to P loading in an asymptotic fashion (Vollenweider *et al.* 1974). Thus, changes in P loadings that are already high may have a relatively minor effect on the primary production of organic carbon, which may eventually contribute to the oxygen deficit. As expected from global correlations of oxygen deficits and P concentration (Rast and Lee 1978), changes in P loading should not result in exactly proportionate changes in oxygen depletion in the Central Basin. Dobson and Gilbertson (1971) suggested that the oxygen depletion rate increased by a factor only slightly more than two; the present analysis does not suggest an increase. Because of the peculiarities of Lake Erie, it is difficult to decide whether there should be expectations (of P loading effects) consistent with either analysis. This is especially difficult when it is recognized that the linkage between P loading, organic material fluxes, and oxygen depletion have not been fully examined in Lake Erie. For example, phytoplankton are most concentrated close to nutrient sources (inshore) in Lake Erie. The Central Basin hypolimnion receives organic matter from inshore and offshore areas, rivers, and the West Basin outflow. Storage of oxidizable material in sediments may cause oxygen depletion responses to lag behind changes in phosphorus loading. It is now as impossible to describe how all of these processes are integrated to produce a depletion rate as it is to predict how hypolimnion conditions will react to changing epilimnion conditions. Clearly, modelling the oxygen depletion rate is a lengthy proposition.

Finally, a large change in Secchi depth might lead to expectations of change in the oxygen depletion rate, but even this has not materialized in the Central Basin. Summer Secchi depths averaged 4.2 m in 1929, 7.3 m in 1948-1953, 5.2 m in 1962, and 2.9 m in 1968. In 1969-1971, summer Secchi depths averaged between 4 and 5 m (Dobson *et al.* 1974). Although the seasonal nature of this measurement makes comparison of years somewhat tenuous, there does not seem to have been a large long-term trend which would support expectations of changes in the oxygen depletion rate.

The oxygen depletion rates of lakes can be used as an index of trophic state. Hutchinson (1938, 1957) suggested upper limits that, for a 4-m hypolimnion in Lake Erie, are 1.25 mg/L/mo for oligotrophy and 2.50 mg/L/mo for mesotrophy. Unfortunately, this has led to the conclusion that the Central Basin of Lake Erie is eutrophic because the depletion rate is 3 mg/L/mo. This conclusion is misguided because the depletion rate limits are for small deep lakes with hypolimnion temperatures close to 4°C, whereas the average temperature for the Central Basin is 11.2°C. This means that, relative to Hutchinson's lakes, the Central Basin depletion rate is 1.66 times too high for comparative purposes. A depletion rate of 3 mg/L/mo at 11.2°C is equivalent to 1.8 mg/L/mo at 4°C and falls within the limits of mesotrophy. Further, as pointed out by Hutchinson (1938) and Thienemann (1928), lakes with a low ratio of hypolimnion to epilimnion volume such as Erie are bound to have a relatively high oxygen depletion rate as a result of their morphology alone. Other physical effects, such as downward oxygen transport, may also be significant to a thin hypolimnion. In 1970, this supply was equivalent to 12% of the oxygen consumed (Burns 1976).

The hypolimnetic oxygen depletion rate in lakes is an intrinsic feature of each lake which is dependent on geology, geography, climate, water chemistry and trophic state. In lakes for which all the other factors are sufficiently similar, differences in the depletion rate may indicate differences in trophic state. It is probably futile then to consider whether Lake Erie's oxygen depletion rate is similar to that of, say, Lake Mendota. Instead, it may be more profitable to focus research on specific areas such as the effect of nutrient loading on the movement of toxic chemicals in relation to oxygen depletion; the effect of materials exported from the West Basin; what ambient oxygen concentration is necessary to release P from sediments; which fish stocks might be improved by better oxygen conditions; and what might be the effects of maintaining high summer water levels.

Predictions of the exact response to nutrient loading changes in all areas of a large heterogenous lake are difficult. There is, however, little doubt that where water quality has been most degraded by excessive nutrients, control of nutrient loading will be beneficial (Vollenweider 1976). Models constructed under various assumptions about Lake Erie's oxygen response calculate that while there may be some changes, significant oxygen depletion would still remain after annual P loadings are reduced by 9000 metric tons from current levels of 20 000 metric tons (Vallentyne and Thomas, 1978). Previously, when P loadings increased by 6000 to 7000 metric tons (1950-1970; Chapra 1977), no real change in oxygen depletion occurred. There seems to be little reason at present either to expect immediate large changes in Lake Erie's oxygen depletion or to use oxygen depletion as an overall trophic indicator. The available data indicate that hypolimnion oxygen depletion rates in the Central Basin of Lake Erie have been basically similar for at least 20 years, probably for 30 years, and that considerable depletion occurred 50 years ago. Fluctuations in the available oxygen data do not indicate a clear correlation with trophic changes which have occurred elsewhere in the lake. The background level of oxygen depletion is mainly related to Lake Erie's morphology; physical variations will continue to cause high and low oxygen conditions in the hypolimnion.

SUMMARY AND CONCLUSIONS

1. A new analysis of historic trends in central Lake Erie's oxygen depletion is provided. The trend towards increasing apparent depletion rates was less than formerly believed.

2. Climate-induced changes in water level, flow rate, hypolimnion thickness and hypolimnion temperature probably caused most of the apparent trend to increasing depletion rates.

3. Apparent oxygen depletion rates, when standardized with respect to hypolimnion thickness and temperature, show no obvious trend since 1929.

4. There is little evidence to support expectations of trends to lower or higher oxygen depletion rates.

5. Temperature-corrected, present-day oxygen depletion rates in central Lake Erie are within the arbitrary limits indicative of mesotrophy in smaller lakes, but this comparison is largely unjustified.

6. The large year-to-year variability in the extent of oxygen depletion and the variability in associated oxygen depletion rates that have been reported to the International Joint Commission in the reports of the Surveillance Committee of the Water Quality Board are, in large measure, explained by the physical factors described in the report.

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REFERENCES

Beeton, A.M. 1963. Limnological survey of Lake Erie, 1959-1960. Great Lakes Fishery Commission, Technical Report No. 6, 32 pp.

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

Burns, N.M. 1976. Oxygen depletion in the Central and Eastern Basins of Lake Erie, 1970. J. Fish Res. Board Can. 33: 512-519.

Canada Centre for Inland Waters. 1970a. Limnological Data Report: Lake Erie, 1969, Nos. 1 and 2.

Canada Centre for Inland Waters. 1970b. Limnological Data Report: Lake Erie, 1968, Nos. 1 and 2.

Canada Centre for Inland Waters. 1970c. Limnological Data Report: Lake Erie, 1967, Nos. 1, 2 and 3.

Canada Centre for Inland Waters. 1973. Summary Data Atlas of Lake Ontario and Lake Erie. C.C.I.W. Paper No. 10.

Carr, J.F. 1962. Dissolved oxygen in Lake Erie, past and present. Pub. No. 9, Great Lakes Res. Div., Univ. of Michigan, pp. 1-14.

Chapra, S.C. 1977. Total phosphorus model for the Great Lakes. J. Environ. Eng. Div., ASCE 103 (EE2): 147-161.

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. Chicago, Illinois, and Cornwall, Ontario. 1976. Lake Erie outflow 1860-1964 with addendum 1965-1975.

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

Dobson, H.H., and M. Gilbertson. 1971. Oxygen depletion in the hypolimnion of the Central Basin of Lake Erie, 1929-1970. Proc. Conf. Great Lakes Res. 14: 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: 731-738.

Fish, C.J. 1960. Limnological survey of eastern and central Lake Erie, 1928-1929. U.S. Fish and Wildlife Service, Special Scientific Report — Fisheries No. 334, 198 pp.

Great Lakes Institute, University of Toronto. 1964. Great Lakes Institute data record, 1962 surveys, Part I, Lake Ontario and Lake Erie. Report PR 16, 97 pp.

Great Lakes Institute, University of Toronto. 1965. Great Lakes Institute data record, 1963 surveys, Part I, Lake Ontario, Lake Erie, and Lake St. Clair. Report PR 23, 195 pp.

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

Hutchinson, G.E. 1957. A Treatise on Limnology, Vol. 1. J. Wiley and Sons, Inc., New York, 1015 pp.

Powers, C.F., D.L. Jones, P.C. Mundinger and J.C. Ayers. 1960. Applications of data collected along shore to conditions in Lake Erie. Publ. No. 5, Great Lakes Res. Div., Univ. of Michigan, 78 pp.

Rast, W., and G.F. Lee. 1978. Summary analysis of the North American (U.S. Portion) OECD Eutrophication Project: Nutrient loading — lake response relationships and trophic state indices. EPA-600/3-78-008, 455 pp.

Rodgers, G.K. 1962. Lake Erie data report, 1961. Great Lakes Institute, University of Toronto, Preliminary Rept. No. 3, 141 pp.

Rodgers, G.K. 1963. Lake Erie data report, 1960. Great Lakes Institute, University of Toronto, Preliminary Rept. No. 11, 138 pp.

Stewart, K.M. 1976. Oxygen deficits, clarity, and eutrophication in some Madison lakes. Int. Rev. Gesamten Hydrobiol. 61: 563-579.

Thienemann, A. 1928. Der saverstoff im eutrophen und ilogotrophen seen. Die Binnengewässer, 4. Stuttgart, Schweizerbartsche Verlagsbuchhandlung, 175 pp.

Vallentyne, J.R., and N.A. Thomas. 1978. "Fifth year review of Canada-United States Great Lakes water quality agreement". Report of Task Group III; a technical group to review phosphorus loadings (Windsor, Ontario). Feb. 1978, 86 pp.

Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist. Ital. Idrobiol. 33: 58-83.

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: 739-762.

Appendix A

An Explanation of the Differences Between Oxygen Depletion Rates in Dobson and Gilbertson (1971) and This Paper

An Explanation of the Differences Between Oxygen Depletion Rates in Dobson and Gilbertson (1971) and This Paper

In other fields of limnology, two investigators might be gratified if their estimates of a rate process fell within 20% of each other as do the estimates of Lake Erie oxygen depletion shown in Table A-1. Because the historic depletion rate proposed by Dobson and Gilbertson (1971) was little more than doubled, small differences in the calculations are important and should be explained. The most sensitive data are from 1929-1953 because the calculations are based on as few as nine data from only one to three stations.

Table A-1. A Comparison of Central Lake Erie Oxygen Depletion Rates (mg/L/mo)

Year	Dobson & Gilbertson (1971)	Charlton (this paper)
1929	1.6	2.0
1948	2.5	–
1949	2.5	3.0
1950	2.1	2.7
1951	2.3	2.1
1952	2.2	2.4-3.0
1953	2.5	3.0
1959	2.6	–
1960	2.8	3.3
1961	3.1	3.3
1962	3.9	3.9
1963	3.3	3.3
1967	3.9	3.0
1968	3.6	3.0
1969	3.8	3.3
1970	3.3	3.0

Explanations of the different calculations appear in chronological order in this appendix. Some years are omitted owing to lack of significant difference between results or because the cause of the difference was not apparent.

The author wishes to thank H.H. Dobson, who made his original notes available for comparison.

1929: Dobson and Gilbertson (1971) generally used data for samples that were taken at a temperature within 3°C of the minimum hypolimnion temperature. This procedure resulted in the inclusion of three data for the August cruise in addition to those used for calculation in this paper.

Station	Oxygen, mg/L – Data used by This paper	Oxygen, mg/L – Data used by Dobson and Gilbertson 1971
31		6.4
35		8.3
40		7.1
41	4.8	4.8
42	5.6	5.6
45	4.4	4.4

Stations 41, 42 and 45 were close together in the centre of the basin and had the lowest oxygen values. Station 31 was not used because it was a great distance from the central stations. Data from stations 35 and 40 were not used because the oxygen values were very close to recorded surface values, and hence some sampling difficulties may have occurred. While still a matter of opinion, it seemed preferable to refrain from combining the consistently low values with other higher, but doubtful, values. Also, the June-July depletion rate in Table 1, which relies on few assumptions, is consistent with the July-August rate. As a result of the differences in analysis, Dobson and Gilbertson (1971) calculated a depletion rate of 1.6 mg/L/mo, whereas this paper reports 2.0 mg/L/mo.

1948: None of the sporadically sampled stations had a consistent oxygen depletion and the correlation coefficient of oxygen with time was only 0.6. Because of the poor correlation coefficient, this paper does not report a slope; Dobson and Gilbertson (1971) reported 2.5 mg/L/mo.

1949: This paper reports the slope of a trend line through data from one regularly sampled station. Dobson and Gilbertson (1971) included data from three unusual stations sampled once on the same day, early in August. Unfortunately, these data were all higher than that of the regular station and they caused a rotation of the trend line, so that a slope of 2.5 mg/L/mo (Dobson and Gilbertson

1971) instead of the 3.0 mg/L/mo in this paper was indicated by regression.

1950: Dobson and Gilbertson (1971) used up to three data (depths) per station, and sometimes one of these had a higher oxygen value than the other two. This may have biased their results, but the major difference between the two analyses is that this paper reports the slope through the one station which was sampled regularly and exhibited a consistent oxygen decline. Dobson and Gilbertson (1971) reported a slope for a regression on all of the inconsistent and irregular data available. Thus, their depletion rate was 2.1 mg/L/mo, whereas this paper reports 2.7 mg/L/mo.

1952: Essentially, similar results were obtained from analyses of all data for the duration of stratification. Analyses of shorter term slopes in this paper show that the real depletion rate was 2.4-3.0 mg/L/mo in contrast with the 2.2 mg/L/mo reported by Dobson and Gilbertson (1971).

1953: Only one station was sampled, but a strong oxygen decline trend was evident. Early in June, the station was sampled when the lake was only weakly stratified. Since these data did not seem to represent stratified conditions and were lower than the trend established once the lake was strongly stratified, they were ignored in this paper. Dobson and Gilbertson (1971) included these data in their analyses and the resultant downward "pull" on the regression line caused their slope to be 2.5 mg/L/mo instead of the 3.0 mg/L/mo reported in this paper.

Compared to information available since 1960, the data collections from 1949-1953 are unique in their high sampling frequency and low number of stations. Oxygen depletion rates calculated with recent data from two to three stations near those of 1949-1953 are similar to rates calculated from basin-wide data. Thus, the 1949-1953 rates are probably comparable to the subsequent data derived from extensive surveys.

1959: Dobson and Gilbertson (1971) used some measured late summer O_2 values and an estimated initial concentration and stratification date to calculate a depletion rate; their procedure was inadequate for the purposes of this paper and no rate is reported here.

1960: Some caution and imagination are required to analyze the 1960 Great Lakes Institute data. The main problem is that the surface oxygen values were consistently low by about 20%, but in other studies, values close to saturation were obtained. Also, the effect was systematic, as the same percentage deviation from saturation occurred independent of the actual O_2 concentration changes from spring to late summer. Such a systematic error might result from confusion in the strength of sodium thiosulphate used to titrate the 100-mL aliquots for the Winkler's oxygen method. Although it is reported that 0.01 *N* thiosulphate was used (Rodgers 1972), substitution of the more convenient (buret reads directly in mg/L) 0.0125 *N* would result in the observed systematic error.

While several hypotheses may be proposed about the cause of the error, a systematic correction may be applied in order to utilize the data. All Great Lakes Institute (G.L.I.) data for 1960 were multiplied by 1.25 and plotted on Figure 2. It can be seen that there is general agreement between the modified G.L.I. data and those of Beeton (1963). The calculated depletion rate from all the data combined is 3.3 mg/L/mo. Dobson and Gilbertson (1971) obtained a rate of 2.8 mg/L/mo from the difference between the first unmodified (low) G.L.I. cruise mean and the last (correct) Beeton data set.

1961: The first of the four cruises seemed to have the same error as in 1960 and the same correction was applied; subsequent cruise data appear normal. Dobson and Gilbertson (1971) used both bottom and upper hypolimnion oxygen data where possible; this resulted in somewhat higher cruise means than in this paper. Their calculation, based on the second and third cruises only, yielded a depletion rate of 3.1 mg/L/mo. The slope between the first (modified), second and third cruise means in this report is 3.3 mg/L/mo. The fourth cruise was not used because the mean O_2 concentration had increased, probably owing to advection. Both calculations are uncertain, but the real depletion rate must have been between 3 and 4 mg/L/mo.

1967: Dobson and Gilbertson (1971) used four of the eight cruises in 1967; their first cruise mean in early June was much too high to be consistent with the depletion trend established by the seven other cruises. Consequently, their depletion rate appeared to be 3.96 mg/L/mo. A regression through the seven later cruise means yields the slope of 3.0 mg/L/mo reported in this paper.

1968: When the hypolimnion was thick enough, Dobson and Gilbertson (1971) used two hypolimnion O_2 values per station, which resulted in slightly higher cruise means than used here. Also, they did not use the third cruise in 1968 (see text, Fig. 3). These minor differences in approach cause the difference between their rate of 3.6 mg/L/mo and the rate of 3.0 mg/L/mo presented here.

1969: The data comprise four cruises. There was a consistent trend line between Nos. 1, 2 and 4, but the third cruise mean was below the line. Dobson and Gilbertson (1971) based their regression on the first three cruises and obtained 3.8 mg/L/mo. The slope through all four cruises is 3.3 mg/L/mo as reported here.

It must be stressed that both analyses utilized exactly the same data set but differed slightly in which data were used. The problem of how to estimate the mean concentration of oxygen in the hypolimnion has not been attacked here for two reasons. First, the definition of a hypolimnion depends on arbitrary temperature-density specifications which limnologists are loath to agree upon. Secondly, near-bottom oxygen only was used here because it was most often the only oxygen measurement available. The formidable problem of sampling more than one depth in the thin hypolimnion of central Lake Erie meant that these data, when available, were of questionable meaning; they were not then combined with the easily defined and understood near-bottom measurements.

REFERENCES

Beeton, A.M. 1963. Limnological survey of Lake Erie, 1959-1960. Great Lakes Fishery Commission Technical Report No. 6, 32 pp.

Dobson, H.H., and M. Gilbertson. 1971. Oxygen depletion in the hypolimnion of the Central Basin of Lake Erie, 1929-1970. Proc. Conf. Great Lakes Res. 14: 743-748.

Rodgers, G.K. 1972. Great Lakes Institute Data Catalogue and Methods for 1960 and 1970. Publ. EG-7. Institute of Environmental Sciences and Engineering, University of Toronto.

Appendix B

A Hypothesis to Explain Hypolimnion Oxygen Depletion Rates in the Central and Eastern Basins of Lake Erie

A Hypothesis to Explain Hypolimnion Oxygen Depletion Rates in the Central and Eastern Basins of Lake Erie

On a volumetric basis, oxygen depletion rates in the Eastern Basin of Lake Erie are about one half of those in the Central Basin, but in absolute or areal terms, more oxygen is apparently consumed in the Eastern Basin hypolimnion (Burns 1976). The question then arises: "In order to compare the trophic status of the two basins, which measure of oxygen depletion is applicable?" The answer is that probably neither measure is useful without an analysis of physical controlling factors.

The oxygen depletion-thickness relationship shown in Figure 8 is the result of regular physical/biological processes. Extrapolating the relationship to a representative basin hypolimnion thickness of 13.4 m in 1970 (Burns 1976) yields a volumetric depletion rate of 1.3 mg/L/mo. This is close to the measured 1.4 mg/L/mo for 1970 (Burns 1976) and the 1.2 mg/L/mo for 1973-1975 reported by the International Joint Commission (1977). On the other end of the scale, a very thin hypolimnion of 0.1-0.2 would be expected to have an oxygen depletion rate of 15-22 mg/L/mo. It is interesting that actual measurements of sediment oxygen demand (S.O.D.) by Blanton and Winklhofer (1972) averaged 14.3 mg/L/mo in a rectangular box 0.67 m high. From Figure 8, a hypolimnion 0.67 m thick would have a depletion rate of 7.6 mg/L/mo. The difference between the ratios of rate to thickness may be due to a supply of oxygen to the hypolimnion which would not be available to the experimental chamber or it may be just an example of unwarranted extrapolation. On the other hand, if the depletion rate is assumed to be in simple inverse proportionality to hypolimnion thickness, then the 1970 depletion rate of 3.0 mg/L/mo at a thickness of 3.2 m becomes $3 \times \frac{3.2}{0.67} = 14.3$ mg/L/mo at a thickness equivalent to the depth of water in the S.O.D. chamber. The latter calculation may be the more comparable, as depletion rates extrapolated from the rate-thickness relationship comprise the net effect of oxygen sinks and sources, such as advection, which would be more important the thinner the hypolimnion.

The hypothesis then is that the proportion of total oxygen demand owing to sediments decreases as the thickness of the hypolimnion increases. This means that the proportion due to water oxygen demand increases with thickness. Because there is at most a 25% difference in fertility (as chlorophyll or primary production), the result is the differing volumetric and areal depletion rates of the Central and Eastern Basins of Lake Erie.

Although it will require much experimentation to test the hypothesis, some support already exists in the various measurements of oxygen demand in Lake Erie. In order to combine these measurements, some assumptions are necessary:

1. The oxygen concentration measured at any one time and place is a result of the difference between supply and demand.

2. The difference between O_2 demand extrapolated from Figure 8, and that observed in S.O.D. chambers is due to the net effect of all sources of oxygen to the hypolimnion.

3. Oxygen sources in (2) apply equally to the Central and Eastern Basins of Lake Erie.

4. Given apparent total demand as well as supply and sediment demand, the demand of the water alone can be calculated from the Central Basin. This water demand can be applied to the Eastern Basin after correction for lower temperature there.

5. Sediment oxygen demand measured in the Central Basin can be applied to the Eastern Basin with a temperature correction.

Table B-1 shows that the calculation of oxygen depletion rates of 0.65 $g/m^2/d$ and 0.049 $g/m^3/d$ are remarkably similar to the representative measurements of 0.61 $g/m^2/d$ and 0.046 $g/m^3/d$ by Burns (1976). Replacement of the Eastern Basin supply term by an amount equivalent to 5% estimated by Burns (1976) yields expected depletion rates of 0.71 $g/m^2/d$ and 0.052 $g/m^3/d$. Again, these are remarkably similar to the actual observed rates. In addition, the Central Basin supply term is equivalent to 33% of the total demand, whereas Burns' (1976) estimated supplies were 37% of an almost identical observed total demand.

Table B-1. Calculation of East Basin Oxygen Depletion by Extrapolation from Central Basin Measurements

Oxygen consumed in 0.67 m high S.O.D. chamber (Blanton and Winklhofer 1972)	0.31 g/m²/day	−0.31 g/m²/day
Expected oxygen depletion rate in a hypolimnion 0.67 m thick	0.17 g/m²/day	
Supplied to hypolimnion	0.14 g/m²/day	0.14 g/m²/day
Apparent total depletion of hypolimnion in 1970 is 0.1 gm/m³/day x 3.2 m =	0.32 g/m²/day	0.32 g/m²/day
Actual demand of 3.2 − 0.67 = 2.5 m of Central Basin water is		0.15 g/m²/day
A representative East Basin hypolimnion thickness in 1970 was 13.4 m (see Burns 1976). East Basin temperature is 5°C cooler than Central Basin (hypolimnia); temperature correction factor is 1.4		
Oxygen demand of 13.4 m of East Basin hypolimnion water is $\frac{13.4}{2.5} \times \frac{0.15}{1.4} =$		0.57 g/m²/day
S.O.D. is $\frac{0.310}{1.4} =$		0.22 g/m²/day
Supplied to the hypolimnion		−0.14 g/m²/day
Apparent depletion in the Eastern Basin rate should be		0.65 g/m²/day
		or
		0.049 g/m³/day

The point of these comparisons is to illustrate that the processes involved probably form an orderly continuum on a moderately short term (months) basis. In relatively shallow waters which have an appreciable S.O.D., such as Lake Erie, differences in volumetric depletion rates are caused mainly by differences in hypolimnion thickness. As Figure 8 suggests, this effect diminishes with increasing depth or thickness. Concurrently, the areal depletion rate can increase with depth because the standing stock of oxygen-consuming material per square metre increases. It is obvious then that as Hutchinson (1938) pointed out, lakes or basins with widely differing depths or hypolimnion thickness cannot be compared on the basis of oxygen depletion alone as a means of differentiating trophic status.

REFERENCES

Blanton, J.O., and A.R.W. Winklhofer. 1972. Physical processes affecting the hypolimnion of the Central Basin of Lake Erie, pp. 9–38. *In* Project Hypo. Edited by N.M. Burns and C. Ross, Canada Centre for Inland Waters Paper No. 6.

Burns, N.M. 1976. Oxygen depletion in the Central and Eastern Basins of Lake Erie, 1970. J. Fish. Res. Board Can. 33: 512–519.

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

International Joint Commission. 1977. Great Lakes Water Quality, Annual Report of the Surveillance Subcommittee, Appendix B.