LAKE ERIE CENTRAL BASIN

OXYGEN DEPLETION CHANGES

FROM 1929-1980

by

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ABSTRACT

The hypolimnetic oxygen depletion rates of the Lake Erie Central Basin have been reassessed using a new approach. In the past, the Central Basin rates have been calculated using the available data, excluding some areas based on either temperature and/or depth definition. The high spatial variability in the data caused uncertainties in the mean value which were sufficiently large to prevent a statistically meaningful interval oxygen depletion rate time-trend analysis. The new approach reduces the effect of spatial variability (80%) on the calculation of the interval oxygen depletion rates and hence permits the identification of a time-trend with more precision, particularly when the data is corrected for the effects of vertical mixing, temperature effects on metabolic rates by using Q_{10} coefficient, variable hypolimnion thicknesses, and seasonal variability. A linear regression analysis of the final corrected depletion rates with time shows a significant increase in the yearly average hypolimnetic oxygen depletion rate of 0.030 $gm \cdot m^{-3} mo.^{-1} yr.^{-1}$ between 1929 and 1980. This increase in the rate accounts for a loss of 4 to 5 $gm.m^{-3}$ of oxygen from the Central Basin hypolimnion since the earliest oxygen records in 1929. This increase may be directly related to an increase in the trophic level of the Central Basin, since most of the major limnological variables which affect the depletion rate have been accounted for.

RÉSUMÉ

On s'est servi d'une nouvelle approche pour réévaluer les taux d'appauvrissement en oxygène de l'hypolimnion du bassin central du lac Érié. Par le passé, on a calculé ces taux pour le basin central en se servant des données existantes, en excluant certaines régions pour les raisons de température et/ou de profondeur. La grande variabilité des données dans l'espaces causait certaines incertitudes sur la valeur moyenne qui étaient suffisamment importantes pour empêcher une analyse statistique significative de la tendance du taux d'appauvrissement en oxygène en fonction du temps. La nouvelle approche diminue l'effet de la variabilité dans l'espace (80%) sur le calcul des taux d'appauvrissement en oxygène; elle permet donc d'identifier avec plus de précision les tendances temporelles surtout si les données sont corrigées en fonction des effets du mélange vertical, des effets de la température sur le taux métabolique en fonction de la loi de Van't Hoff-Arrhénius, de l'épaisseur variable de l'hypolimnion et de la variabilité saisonnière. Une analyse par régression linéaire des taux d'appauvrissement corrigés en fonction du temps montre un accroissement important de 0,030 $g.m^{-3}mo.^{-1}a^{-1}$ du taux annuel moyen d'appauvrissement de l'hypolimnion en oxygène de 4 à

5 $g.m^{-3}$ dans l'hypolimnion du bassin central depuis les premiers enregistrements des teneurs en oxygène en 1929. Cet accroissement peut être lié directement à une augmentation du niveau trophique du bassin central, car on a tenu compte des principales variables limnologiques affectant le taux d'appauvrissement.

EXECUTIVE SUMMARY

"Lake Erie Central Basin Oxygen Depletion Changes from 1929-1980"

The Lake Erie Central basin hypolimnetic oxygen depletion rates have been reassessed using a new approach. A semi-objective method using oxygen depletion rates and chemical data was used to determine the trend study area, where the high spatial variability that exists in the Central Basin, was reduced by 80 to 90%, thus allowing any time-trend to be identified with more precision.

The oxygen depletion rates using only data in the trend study area for the years 1929 to 1980 are calculated and corrected for effects of vertical mixing, temperature, thickness, and seasonal variability. A linear regression analysis of the final corrected depletion rates with time shows a significant increase in the yearly average hypolimnetic oxygen depletion rate of 0.030 $gm.m.^{-3}mo.^{-1}yr.^{-1}$ between 1929 and 1980. This increase in the rate accounts for an oxygen loss of 4 to 5 $gm.m^{-3}$, and can be attributed to an increase in biological production, due to increasing phosphorus loadings, since most of the major limnological variables which affect the depletion rate have been accounted for. Conversely, allowing time for the lake to respond, the oxygen conditions in the hypolimnion can be improved by reducing the phosphorus loadings, which proves the validity of the GLWQA.

RÉSUMÉ À L'INTENTION DE LA DIRECTION

"Appauvrissement en oxygène du bassin central du lac Érié entre 1929 et 1980"

On s'est servi d'une nouvelle approche pour réévaluer le taux d'appauvrissement en oxygène de l'hypolimnion du bassin central du lac Érié. Une méthode semi-objective, faisant intervenir les taux d'appauvrissement en oxygène ainsi que certaines données chimiques, a servi à déterminer la zone destinée à l'étude des tendances; la grande variabilité dans l'espace qui existe dans le bassin central y est réduite de 80 à 90%, ce qui a permis d'identifier avec plus de précision toute tendance en fonction du temps.

Les taux d'appauvrissement en oxygène entre 1929 et 1980 sont calculés uniquement pour les données recueillies dans cette zone; ils sont corrigés en fonction des effets du mélange vertical, de la température, de l'épaisseur et de la variabilité saisonnière. Une analyses, par régression linéaire en fonction du temps, des taux d'appauvrissement corrigés montre un accroissement important de 0,030 $g.m.^{-3}mo.^{-1}an^{-1}$ du taux annuel moyen d'appauvrissement de l'hypolimnion en oxygène entre 1929 et 1980. Cette augmentation explique une perte d'oxygène de 4-5 $g.m^{-3}$; il est possible de

l'attribuer à un accroissement de la production biologique dû à l'augmentation des charges en phosphore car on a tenu compte de la plupart des variables limnologiques affectant le taux d'appauvrissement. Par contre, si on laisse au lac le temps de s'épurer, la teneur en oxygène de l'hypolimnion peut s'améliorer après réduction des charges en phosphore, ce qui prouve la validité de l'AQEGL.

INTRODUCTION

Hypolimnetic oxygen depletion rates for the Central Basin of Lake Erie have been reported by many authors; each having their own approaches and methods of calculations. (Dobson and Gilbertson 1971, Burns 1976, Charlton 1980, Rosa and Burns 1981, Anderson et al 1984, El-Shaarawi 1984). Dobson and Gilbertson (1971) defined the hypolimnetic waters as water which was no more than 3.0°C warmer than the minimum temperature observed during a sampling survey. In calculating oxygen depletion rates no corrections were made for the effects of vertical mixing, temperature differences, hypolimnion thickness, seasonal variability and East Basin advection. Dobson and Gilbertson analyzed the data from 1929 to 1970 and concluded that the Central Basin oxygen depletion had increased at a rate of 0.075 $gm \cdot m^{-3} \cdot mo.^{-1} \cdot yr^{-1}$, from 1950 to 1970.

Charlton (1980) established the existance of hypolimnion waters, at stations with depths greater than 15 m, by using temperature-depth traces where available. He then calculated a relationship between temperature and hypolimnion thickness. Subsequently he used this relationship to estimate hypolimnion thicknesses for the years when temperature-depth traces were not available. Next, he used the actual and estimated thicknesses in a second regression analysis between oxygen depletion rates and hypolimnion thickness to correct the original oxygen depletion rates to rates which were standarized to the thickness observed in 1970. By this method, Charlton attempted to correct for hypolimnion thickness variation but he did not attempt to correct for reoxygenation resulting from vertical mixing or for different oxygen uptake rates resulting from different temperatures (Q_{10}), or for the effects of advection from the East Basin. Having analyzed the data from 1929 to 1977 in this manner, Charlton concluded that: "the hypothesis of a large long-term trend to increasing oxygen depletion does not seem to be supported by the present analysis of the available data." (Charlton 1980).

On the other hand, Burns (1976) determined the depletion rate for 1970 accurately but did not attempt a time trend analysis. By using the Mesolimnion Exchange Model (Burns 1976), oxygen coming into or leaving the system by water moving horizontally into and out of the East Basin and vertical transport of oxygen by the incorporation of water from the thermocline or loss of water by hypolimnetic erosion, is accounted for. By using temperature change, the model also accounts for the oxygen brought into the system by water exchange, that is, water which enters the hypolimnion and later leaves it causing no change in volume but causes an increase in oxygen concentration and temperature. This model permits correction of rates to a standard temperature but Burns (1976) did not make such a correction.

Dobson and Gilbertson, Charlton, and Burns use the basin-wide approach, subjectively excluding some areas either by temperature or depth definition, in calculating the mean oxygen and temperature concentrations, and oxygen depletion rates. However, the basin-wide approach is good and representative of the basin itself only with an adequate sampling grid, because there exists a marked variability in the chemical concentrations throughout the Central Basin. Rosa and Burns, Anderson et al, and El-Shaarawi first determine sets of observations which form a homogeneous group within the hypolimnetic waters. The data calculations are then performed using only the homogeneous group within each basin thus reducing the variability due to spatial variations in concentrations and non-representative sampling (Anderson et al, 1984).

The different approaches in data analysis and interpretation present some conflicting conclusions in the Lake Erie Central Basin historic oxygen depletion rate trend. The existing differences in data analysis and trend interpretation between Dobson and Gilbertson, and Charlton have been documented by Charlton (1979) and those between Charlton, and Rosa and Burns have been the subject of a special workshop held in 1981 and summarized by Barica (1982).

METHODS

An example of the spatial variability in the temperature and oxygen concentration rates is shown in Fig. 1 a. Also oxygen depletion rates (Fig. 1b) and the rate of hypolimnion temperature increase (Fib. 1c) vary across the basin; showing the rates in the western part of the Central Basin to be far higher than those in the eastern part. This means that data collected from a set of stations restricted to the western part of the basin cannot be compared with data collected subsequently from stations sited predominantly in the eastern part of the basin. This difference shows the necessity of determining an area in the basin which provides comparative information over the entire time period and reduced spatial variability. Lake Erie Central Basin surveys after 1967 were mostly basin-wide, but before this date, as far back as 1929, only certain localized areas were sampled. Therefore, if we wish to establish a time trend, we must establish a method for determining oxygen depletion rates which is compatible with the early data.

The accuracy in determining the homogeneous groups depends upon the intensity of sampling in space and time, such as a high density of stations, and frequent surveys. The 1977 and 1978 surveys were designed to establish the spatial variability within the Central Basin, and to provide ample data for the application of the Mesolimnion Exchange Model. In this study, the 1977 and 1978 data sets are used to semi-objectively identify, and isolate non-representative groups to alleviate much of the non-homogeneity of the Central Basin, before a time-trend analysis can be assessed with greater precision, by using only homogeneous groups.

The observed interval oxygen depletion rates for each station in the basin are then determined and inspected to permit the identification of the homogeneous group, henceforth referred to as the trend study area, where spatial variability could be sufficiently reduced. The uncertainty, in the concentration of three major parameters, due to temporal and spatial variability in the trend study area is then computed and compared with that for the whole basin. Finally, the observed, interval oxygen depletion rates using only data within this area for the the years 1929 to 1980 are calculated. These rates are then corrected for effects of vertical mixing using hypolimnion temperature increase, Q_{10} adjusted to a standard temperature of 10° C, standarized to a mean thickness of 4.7m, and finally adjusted for seasonal variability. These corrections permit the computation of oxygen depletion rates which are independent of variability induced by the different weather, prevailing in different years. This type of information permits reliable comparisons of data from different years. The dissolved oxygen concentrations were determined in 1977 and 1978 by using the modified Winkler iodometric method (Philbert and Traversy 1973).

RESULTS

The trend study area for each basin were defined by first determining the mean summmer depletion rates for each station for 1977 and 1978. These were then plotted for the two basins, thus giving a depletion rate distribution map. The arithmetic mean and standard deviation (S.D.) were also calculated for each basin, to identify the homogeneous groups. Next all the stations that were within one S.D. from the mean were marked, and with the exception of a few, were all found to lie in one area in each basin. The boundaries for these areas were defined and that part of each respective basin inside the boundary became the trend study area (Fig. 2). These areas, which can be defined by polygons, occupy the offshore regions of each basin. To see the effect of using the trend study area on reducing the spatial variability, the simple hypolimnion mean and S.D. for 3 major parameter (temperature, dissolved oxygen, and oxygen depletion rates) were calculated for both the Central Basin trend study area and the whole basin (Table 1). From the table it can be seen that the spatial variability (mean variance) is substantially reduced (80-90%) in the trend study area. This reduction in the spatial variability is probably due to the exclusion of non-representative sampling and shallow zones in the basin, where physical turbulence and point sources are responsible for their heterogeneous nature (Lam et al, 1983).

The trend study area method for calculating historical oxygen depletion rate was used for data collected in the years and the number of stations shown on Table 2. The data collected from stations lying outside these areas were rejected at once, and the remaining data were carefully scrutinized, retaining only that data maintaining a consistent temperature-depth relation. The observed interval oxygen depletion rates for the trend study area were calculated by using oxygen concentration differences between surveys. The hypolimnion oxygen depletion rate, for each station, was calculated using the expression

$$Y_i = \frac{(Y_{iA} - Y_{iB})}{(T_{iB} - T_{iA})} \quad (\mathrm{gm \cdot m^{-3} \cdot DAY^{-1}})$$

where: Y and T are oxygen concentrations ($\mathrm{gm \cdot m^{-3}}$) and temperature (°C) respectively, i is the station, and A, B are the mid survey dates used to calculate the observed interval depletion rate.

The arithmetic mean observed hypolimnion oxygen depletion rate for n stations is given by (R_o)

$$R_o = \left(\sum_{i=1}^{n} Y_i \right)/n \quad (\mathrm{gm \cdot m^{-3} \cdot day^{-1}})$$

The available data from 1929 to 1980 was analyzed for each survey interval and the results are shown in Table 3 and Fig. 3A. The equation for the regression line between year (X) and observed depletion rate (R_o) is,

$$R_o = 0.022X + 1.61 \qquad (P < .01)$$

As mentioned, in order that these observed rates may be compared, for trend analysis, corrections and adjustments must be made for either physical or chemical factors that may have altered the actual rate. The most important of these factors are: VERTICAL MIXING, TEMPERATURE DIFFERENCES, HYPOLIMNION THICKNESS, AND SEASONAL VARIABILITY; the methods used in correcting the observed depletion rates for these processes are described in the following section.

OBSERVED RATES CORRECTED FOR DIFFERENT PROCESSES

i) Vertical Mixing

The correction for vertical mixing can be made by using the hypolimnion temperature increase, and the thermocline oxygen and temperature gradients estimated for each survey interval. The following expression is derived using the basic principles outlined by Burns (1976) in his Mesolimnion Exchange Model corrections for downward incorporation of oxygen contained in the thermocline water which is entrained into the hypolimnion from the thermocline:

$$\Delta O = \frac{(O_e - O_h)}{(T_e - T_h)} \Delta T \qquad \text{Eqn. 1}$$

where; ΔO is the increase in hypolimnion oxygen concentration due to mixing processes, T_e, T_h are the mean epilimnion and hypolimnion temperatures, O_e, O_h are the mean epilimnion and hypolimnion oxygen concentrations, and ΔT is the hypolimnion temperature increase.

Vertical mixing and turbulent diffusion introduce oxygen into the hypolimnion (Burns 1976, Lam et al, 1983) which cannot be accounted for by measuring concentration changes only, therefore this addition of oxygen to the hypolimnion must be calculated and added to the simple rates, to account for differences in depletion rates due to these processes. Central Basins field measurements have shown that downward entrainment processes were contributing enough oxygen to the hypolimnion to account for about 10% of the oxygen depletion during a 13-day period in August 1979 (Ivey and Boyce 1982). However, although the downward mixing of oxygen can be substantial it can vary markedly within and between years and must be allowed for differently in each case. In 1977 and 1978 this process introduced 19% and 7% respectively, of the total oxygen consumed in the hypolimnion. The observed rates corrected for vertical mixing (R_V) are shown in Table 3, and the equation for the regression between time and depletion rates is shown in Table 4.

ii) <u>Temperature</u>

Hypolimnion temperature increases during the stratified season and increases the biochemical oxygen uptake rate. Metabolic rates are very dependent on temperature with the reaction rate usually doubling with every 10°C rise in temperature, ($Q_{10}=2$). In order that depletion rates within the summer, and among different years, can be compared, they should be standarized to a single temperature. This temperature is taken to be 10°C, which is close to the seasonal mean hypolimnion temperature. The following equation will be used for this correction (Salisbury and Ross 1978):

$$\text{Log } Q_{10} = \left[\frac{10}{T_2 - T_1}\right] \text{ Log } \left[\frac{k_2}{K_1}\right] \qquad \text{Eqn. 2}$$

where T_1 and T_2 are temperatures with $T_2 > T_1$, K_1 and K_2 are depletion rates with $K_2 > K_1$. The rates for each survey interval after standardization to a mean temperature of 10°C (R_q) are shown in Table 3, and the regression equation is shown in Table 4.

iii) **Thickness**

This relationship allows the rates to be corrected for hypolimnion thickness by the method which is described below. The volumetric oxygen depletion rate (R_q) is made up of oxygen uptake which occurs in the water column (K_w) and the uptake that occurs at the sediment water interface (K_s) Burns 1976, such that:

$$R_q = \frac{Ks}{d} + Kw \qquad \text{Eqn. 3}$$

The sediment oxygen demand is inversely proportional to hypolimnion thickness (d). The equation shows also that the value of R_q is dependent on K_w as well as K_s, and that the hypolimnion thickness only partially effects the value of R_q. Equation 3 has the form of a two-coefficient polynomial function, namely:

$$y = ax + b$$

Hypolimnion thicknesses were only observed from 1961 onward, and before the thickness corretion can be applied to the years prior to 1961, these thicknesses must be estimated. Since hypolimnetic oxygen depletion rates have a high negative correlation with water levels (El Shaarawi, 1984) and hypolimnion thickness (Charlton, 1979), these two variables were tested for dependence from 1961 onward. The following relationship, best described by a linear equation of the form $y = cx + d$ was established;

$$y = 5.15\ x - 0.40$$
$$(n = 17,\ r = 0.83,\ P < .001)$$

where y is the hypolimnion thickness, x is the water level difference (water level-datum). By using this relationship the hypolimnion thicknesses for the years 1929, 1949, 1950 and 1951 were calculted at 5.1, 2.8, 3.5 and 4.8 m respectively.

Before the correction for the effect of thickness on depletion rate can be applied, the relationship between thickness alone and depletion rate must be found. This is easily achieved by residual analysis to remove the effect of time on depletion rates as established above. Thus, the survey interval oxygen depletion rates which are considered to be independent of effects related to increasing time, (O_T) were calculated by removing the annual rate of increase of 0.028 $gm \cdot m^{-3} \cdot mo.^{-1}\ yr^{-1}$ from R_q as previously determined (see Table 4).

$$Q_T = \text{Rate for year, } R_q - \left((T-1929)\ 0.028\right)$$

the residual rates were correlated with the inverse of thickness and a relationship showing the effects of thickness alone on depletion rate was obtained, as shown

$$y = 5.89\ x + 1.90 \quad (P < .01) \qquad \text{Eqn. 4}$$

Thus substituting the values of Eqn. 4 into Eqn. 3 we obtain,

$y = Q_T$ = Residual Depletion Rate ($gm \cdot m^{-3} \cdot mo.^{-1}$),

$x = 1/d$ = Inverse of thickness (m^{-1}),

$K_w = 1.90\ gm \cdot m^{-3} mo.^{-1}$, $K_s = 5.89\ gm \cdot m^{-2} \cdot mo.^{-1}$.

Thus the relationship between oxygen depletion rate and thickness has been established by regression analysis using only the residual interval depletion rate and hypolimnion thicknesses from 1929 to 1980.

The proportion of the oxygen depleted as SOD versus WOD is considered to remain constant with time, thus the time independent interval oxygen depletion (Q_T) at any time, $t(Q_{T,t})$ is considered to consist of two parts namely,

$$Q_{T,t} = F_t \left(\frac{k_s}{d_t} + K_w\right)$$

$$= \frac{F_t\ K_s}{d_t} + F_t\ K_w \qquad \text{Eqn. 5}$$

where; F_t is a factor for the observation interval, t,

and d_t is the hypo-thickness during interval, t.

Thus $\quad SOD_t = \dfrac{F_t\ K_s}{d_t}$, and $\quad WOD_t = F_t\ K_w$

$$F_t = \frac{Q_{T,t}}{K_{s/d_t} + K_w}$$

Since the mean hypolimnion thicknesses observed from 1961 to 1980 is 4.7 m, the part of the observed depletion rate affected by thickness, the SOD, was corrected to a standard thickness of 4.7 m in each case as follows,

$$SOD_t = \frac{F_t\ K_s}{dt} \cdot \frac{dt}{4.7} \qquad \text{Eqn. 6}$$

Thus the thickness corrected oxygen depletion rate for the interval t, readjusted for the rate increase due to time (R_q - Q_T), previously removed to calculate the residuals, is

$$R_t = Q_{T,t,c} = \frac{F_t K_s}{4.7} + F_t \cdot K_w + (R_q - Q_T) \qquad \text{Eqn. 7}$$

Since the values of K_w and K_s are known, the values of oxygen depletion with observed thicknesses were corrected using Eqns. 5 and 7. The thickness corrected rates are shown in Table 3, with regression equation shown in Table 4.

iv) **Seasonal Adjustment**

At this point, there is one final correction to be made, that is, the rates must be adjusted for seasonal variability. Past research has shown that the depletion rates tend to decrease at oxygen concentrations less than 2.0 $mg \cdot L^{-1}$, (Mathias and Barica 1980); although Cornett and Rigler, 1984 attribute this decrease to an increase in the oxygen transport by turbulent mixing across the upper boundary of the hypolimnion (vertical mixing), and the rates are shown (this paper, Table 3) to be variable within the season. The results of a regression analysis between R_t and time of year shows that a decreasing trend with season does exist. Thus, the thickness corrected rates (R_t) have a relationship with time of season:

$R_t = -0.012\beta + 4.35$ ($P < .01$), where β = Time in J. Days (May 1 = 1)

Therefore within any season (100 days) there is a decline in oxygen depletion rate of 1.20 $gm \cdot m^{-3} \cdot seas.^{-1}$ or 0.012 $gm \cdot m^{-3} \cdot day^{-1}$ as the season progresses. The thickness corrected rates (R_t) were adjusted to mid-stratified season (taken as July 14 or J. Day 75, May 1 = 1) by using the following procedure:

$$R_c = R_t + (J.DAY - 75)\ 0.012$$

The final corrected rates, independent of the time of season, are shown in Fig. 3B with regression equation

$$R_c = 0.028X + 1.55 \qquad (P < .001)$$

In order to make the depletion rates comparable to other investigators (yearly mean) the final corrected interval oxygen depletion rates (R_c) were averaged for each year and plotted against time, results are shown on Fig. 3C with regression equation

$$R_A = 0.033X + 1.20 \qquad (P < .001)$$

Using the average rates (R_A) to determine the trend, each year has a weighting factor of one (1) in the correlation, while in using the interval rates the weighting factor for each year is equal to the number of interval rates (R_C)for that year. For this reason, the regression coefficient changes when the yearly averages are used, the weighting factor (no. of interval rates), Table 2, is higher for the latter years (1977 to 1980) because of the greater number of surveys conducted. In order to account for the appropriate weighting factor for each year on the average rate (R_A), a multiple regression analysis between time and weighted depletion rate (R_{AW}) was run. Each year was given a weighting factor equal to the square root of the number of interval rates from Table 2 (El-Shaarawi, personal communication). This procedure decreased the regression coefficient between time and depletion rate from 0.033 to 0.030 $gm.m^{-3} mo.^{-1} yr^{-1}$ (Table 4). This weighting procedure as a final correction in the oxygen depletion trend is very important since the trend may be highly influenced by weighted regression (Anderson et al, 1984).

CONCLUSIONS

The trend study area approach was devised because there exists west to east variability in the Central Basin hypolimnion oxygen and temperature concentrations Fig. 1(A). For this reason, the interval oxygen depletion rates using arithmetic mean concentration from different parts of the basin cannot be used. The variability in the basin means (spatial) is greater then the difference between basin means (temporal). The trend study area has much less spatial variability (80%) enabling the temporal differences to be more significant (Anderson et al, 1984) allowing the calculation of the interval oxygen depletion rate with greater precision. Another reason for choosing this approach was to retain consistency in the area used. The trend study area remains stratified throughout the summer and the East Basin advection is restricted to the eastern-third of the Central Basin, Boyce et al (1980), and therefore, does not affect this area. Chiocchio (1981), found that strong winds from the South West blowing consistently for 14 days could possibly effect the Central Basin up to 60 to 80 km, west of the Pennsylvania Channel. Thus the concentration difference, if any, between the water masses would have a negligible effect on the trend study area, but a profound effect on the eastern end of the Central Basin Fig. 1(A), (B), illustrating a further need for the trend study area approach.

In the progression of correcting for the different processes, (the final interval, and yearly mean corrected rates are shown on Fig. 3B and 3C respectively) the fit of the data points around the regression line improves as each successive correction was applied to the observed rates, thus improving the correlation coefficient between depletion rate and time (Table 4). After all the corrections are applied to the observed rates there is a considerable improvement on the line fit, whereby the regression coefficient increases by 23%, the correlation coefficient increases by 42% and the total sum of squared deviations and the error of regression decreases by 45%. Thus, the vertical mixing correction, adjustment to a standard temperature, standardization to a mean hypo-thickness, and removing seasonal variability, further strengthens the regression relationship between time and depletion rates to establish an increasing historic trend.

We can see that in trying to establish changes in the oxygen depletion rates is a complex matter because many factors (physical, chemical and biological) affect the rate. This study provides an example of how to undertake this difficult topic.

The sequence of applying the corrections is very important with the most independent processes being done first, i.e. the vertical mixing correction is mainly dependent on the interval temperature increase (ΔT). This correction has to be applied to the observed depletion rates in order to arrive at the actual depletion rate, before any other corrections are applied. Next, the rates are corrected to a standard temperature and then they are standardized to a mean hypolimnion thickness, after the actual temperature independent rate was calculated. The seasonal variability has to be corrected for, after all the other corrections are applied because the earlier corrections are required to reveal any seasonal trend that may exist with the other variables removed.

By using the trend study area approach for the Central Basin of Lake Erie and applying the knowledge in the limnology of the lake, the difference in interpretation between Dobson and Gilbertson and Charlton has been resolved and we are confident that there has been an increase in the oxygen depletion rates between 1929 and 1980. There is no doubt that the Lake Erie Central Basin water quality has deteriorated in the past 50 to 60 years. By using diatom records, Harris and Vollenweider (1982) state that Lake Erie had undergone initial eutrophication as early as 1850, although the main evolution toward eutrophic systems occurred during this century. The Central Basin anoxic area has increased substantially from 1930 to the early seventies, Hendendorf (1980). Finally, phosphorus loading to the lake has been increasing from 4,000 metric tons in 1900 to 27,000 metric tons in 1970, Sly (1976).

The increase in phosphorus loadings to Lake Erie in the last century has caused an increase in biological productivity. An increase in productivity in the euphotic zone would result in greater amount of organic material settling into the hypolimnion (Hargrave, 1975). Decomposition of this organic material has had a greater stress in the hypolimnetic oxygen reserve thus increasing the hypolimnetic depletion rate. Furthermore, since the phosphorus concentrations in Lake Erie have been decreasing in the past decade (Rosa, 1985), a decrease in the oxygen depletion rates should be observed (El-Shaarawi, 1984) after the lake has undergone a stabilization or lag time period. The present analysis accounts for most of the known limnological factors which affect the oxygen depletion rates, so that these corrected rates may be compared from year to year in testing for time-trends; thus any observed trend may be related to trophic level changes in the Central Basin of Lake Erie. The data reported does not show a decrease in the depletion rates in the early seventies, but after 1974 (Fig 3C), the rates seem to show a lowering trend, although not statistically significant. We are hopeful that in the 1980's an even lower trend in the hypolimnetic oxygen depletion rates will be observed. It seems then, that the phosphorus loading reductions, one of the Great Lakes Water Quality Agreement's objectives, is beginning to show its effects in decreasing the oxygen depletion rates in the Central Basin of Lake Erie.

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TABLE 1

Central Basin Hypolimnion Mean concentrations, depletion rates, and S.D.

		Whole Basin				Trend Study Area		
Survey No.	Ni	Temp. °C	Oxygen MG/L	Depletion Rate $gm.m^{-3}\ mo.^{-1}$	Ni	Temp. °C	Oxygen MG/L	Depletion Rate $gm.mm^{-3}\ mo^{-1}$
1977								
1	31	8.30±1.30	10.33±1.00		10	7.73±0.71	9.96±0.88	
				3.63±2.49				2.58±0.96
2	41	11.47±1.95	8.76±1.31		15	11.50±1.34	8.84±1.00	
				2.25±2.19				3.19±1.08
3	43	11.19±1.77	7.18±1.82		15	11.63±0.39	6.61±0.81	
				3.63±1.77				3.60±0.87
4	46	12.17±1.58	4.64±2.01		15	12.18±0.47	4.09±1.10	
				2.76±2.88				3.60±1.08
5	45	12.81±1.39	3.35±2.18		15	12.81±0.42	2.41±0.56	
Mean Variance		2.6	3.0	5.6		0.6	0.8	1.0
1978								
1	44	7.20±1.68	11.71±1.73		9	6.75±0.57	12.42±1.10	
				3.15±2.85				3.15±1.05
2	49	7.87±1.99	9.44±1.87		14	7.42±0.63	9.83±0.61	
				1.80±1.68				2.60±0.96
3	47	8.65±1.58	8.02±2.42		14	8.70±0.71	7.69±0.84	
				2.22±2.31				2.32±1.17
4	39	9.26±1.88	6.72±2.51		14	9.08±0.67	5.79±1.10	
				2.97±1.95				2.97±0.96
5	44	10.03±1.89	4.81±2.20		14	9.59±0.66	4.22±1.22	
Mean Variance		3.3	4.7	5.0		0.4	1.0	1.1

TABLE 2

YEAR	# OF INTERVAL RATES	DATA SOURCE	# OF STATIONS IN T.S. AREA USED
1929	2	FISH	6
1949	1	POWERS	5
1950	1	POWERS	7
1951	2	POWERS	7
1961	1	GLI-LANDS&FOREST	12/13
1962	1	GLI	16
1963	2	GLI	16
1967	3	CCIW	8
1969	2	CCIW	8
1970	2	CCIW	7
1971	1	CCIW	5
1973	2	CCIW/CLEAR	8/10
1974	2	CLEAR	8
1975	2	CCIW/CLEAR	8
1977	4	CCIW	15
1978	4	CCIW	15
1979	5	CCIW/CLEAR	6/7
1980	2	CLEAR	8

TABLE 3

LAKE ERIE INTERVAL OXYGEN DEPLETION RATES

YEAR	(R_o)	(R_v)	(R_q)	(R_t)	(R_c)	J-DAY
1929	2.26	2.43	2.30	2.37	2.20	61.0
1929	2.01	2.37	2.05	2.12	2.32	91.4
1949	2.55	2.67	2.40	2.22	2.30	81.0
1950	2.43	2.67	2.91	2.64	2.60	69.3
1951	2.13	2.39	2.78	2.80	2.64	61.3
1951	2.67	2.96	3.04	3.06	3.38	99.5
1961	3.99	4.79	3.88	3.35	3.61	97.2
1962	3.50	4.41	4.11	3.36	3.35	74.2
1963	3.60	3.80	3.83	4.11	4.05	69.6
1963	2.48	3.72	3.38	3.16	3.48	101.8
1967	3.90	3.90	3.80	4.02	3.72	50.0
1967	3.40	3.40	3.30	3.32	3.15	62.0
1967	2.84	2.99	2.95	2.78	2.88	82.0
1969	2.38	3.28	3.47	3.60	3.30	49.0
1969	2.85	3.45	3.09	3.08	3.11	78.0
1970	3.39	3.99	4.51	4.69	4.40	50.0
1970	2.76	3.01	3.07	3.16	3.20	78.0
1971	3.43	3.77	3.54	3.58	3.76	89.0
1973	3.09	3.51	3.44	3.49	3.70	89.0
1973	2.50	3.07	2.93	3.10	3.50	104.7
1974	4.11	4.83	5.23	5.05	4.77	51.5
1974	4.07	4.97	4.77	4.24	4.29	79.0
1975	2.54	3.03	3.07	3.20	3.26	79.5
1975	2.53	2.82	3.01	3.32	3.63	100.6
1977	2.59	4.00	4.29	4.16	3.75	41.0
1977	3.19	3.80	3.52	3.66	3.46	58.0
1977	3.60	3.91	3.43	3.35	3.40	78.5
1977	4.24	4.97	4.18	3.49	3.74	96.0
1978	3.15	3.21	3.81	3.79	3.37	42.5
1978	2.60	2.65	3.14	3.35	3.24	65.5
1978	2.32	2.43	2.74	2.75	3.00	85.9
1978	2.97	3.26	3.34	3.28	3.66	104.5
1979	3.81	4.32	4.50	4.31	3.64	55.0
1979	4.38	4.38	4.41	4.22	4.24	76.0
1979	2.61	3.79	3.61	3.31	3.70	105.0
1979	3.78	4.15	4.43	4.22	3.70	34.5
1979	3.13	3.44	3.28	3.28	3.33	71.0
1980	3.02	3.27	2.81	3.02	3.10	82.4
1980	3.62	3.88	3.26	3.49	3.75	104.0

TABLE 4.

INTERVAL OXYGEN DEPLETION RATES TREND ANALYSIS
STATISTICAL RESULTS

X	Y (Rates)	Regression Coefficient ± Standard Error	Significance Level	Correlation Coefficient	N
Year	R_o	0.022 ±.008	$P < .01$	0.45	39
Year	R_v	0.025 ±.007	$P < .01$	0.46	39
Year	R_q	0.028 ±.007	$P < .001$	0.53	39
Year	R_t	0.029 ±.006	$P < .001$	0.58	39
Year	R_c	0.028 ±.005	$P < .001$	0.64	39
Year	R_A	0.033 ±.006	$P < .001$	0.76	18
Year	R_{AW}	0.030 ±.006	$P < .001$	0.76	18

R_o = observed interval rates.

R_v = R_o, corrected for vertical mixing.

R_q = R_v, corrected for temperature.

R_t = R_q, corrected for thickness.

R_c = R_t, corrected for seasonal variability; (final corrected rates).

R_A = Average of R_c for each year; (yearly average).

R_{AW}= R_A, corrected by using weighting factor for each year.

N = No. of rates used in the regression.

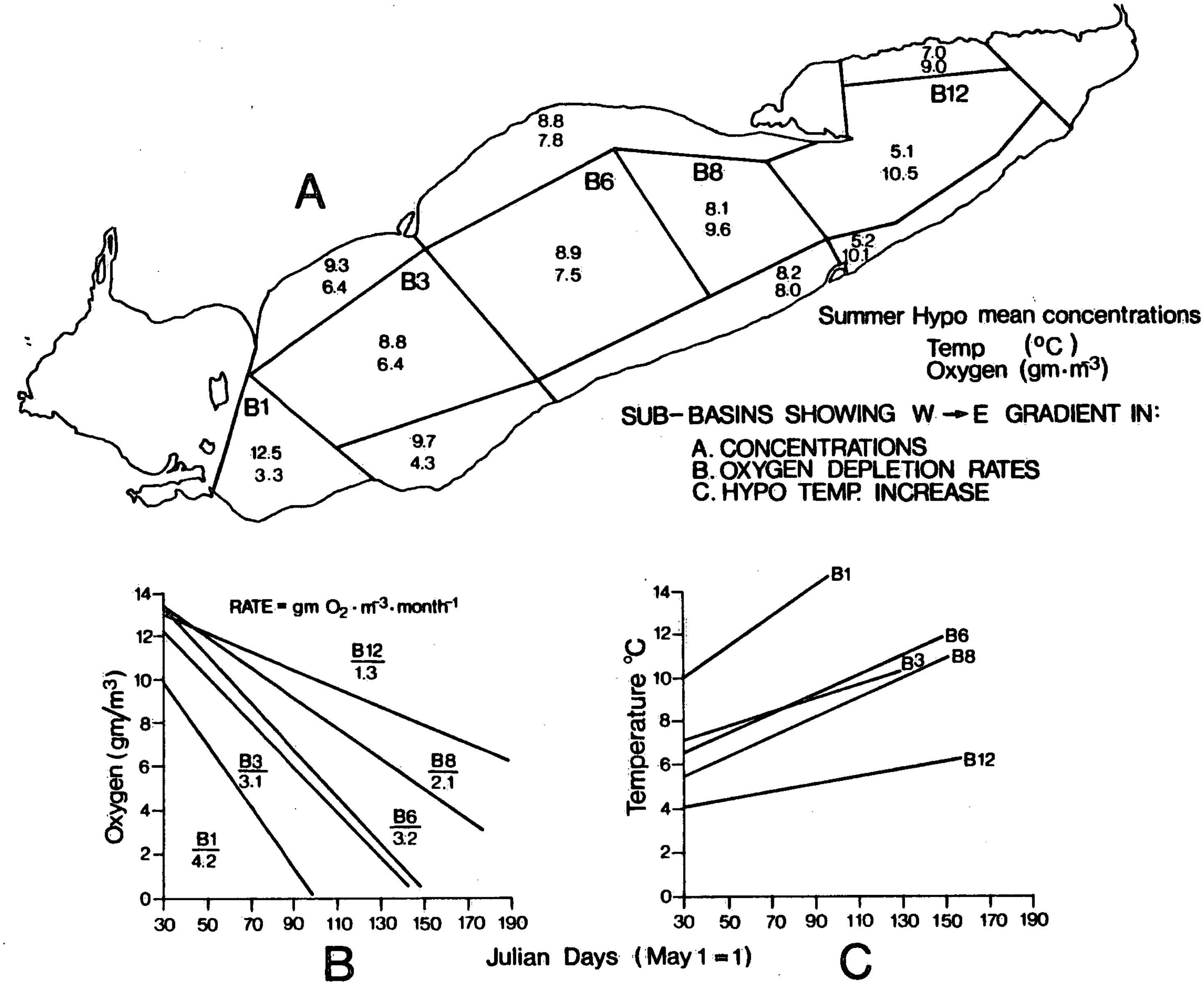

Figure 1 LAKE ERIE SUB-BASINS

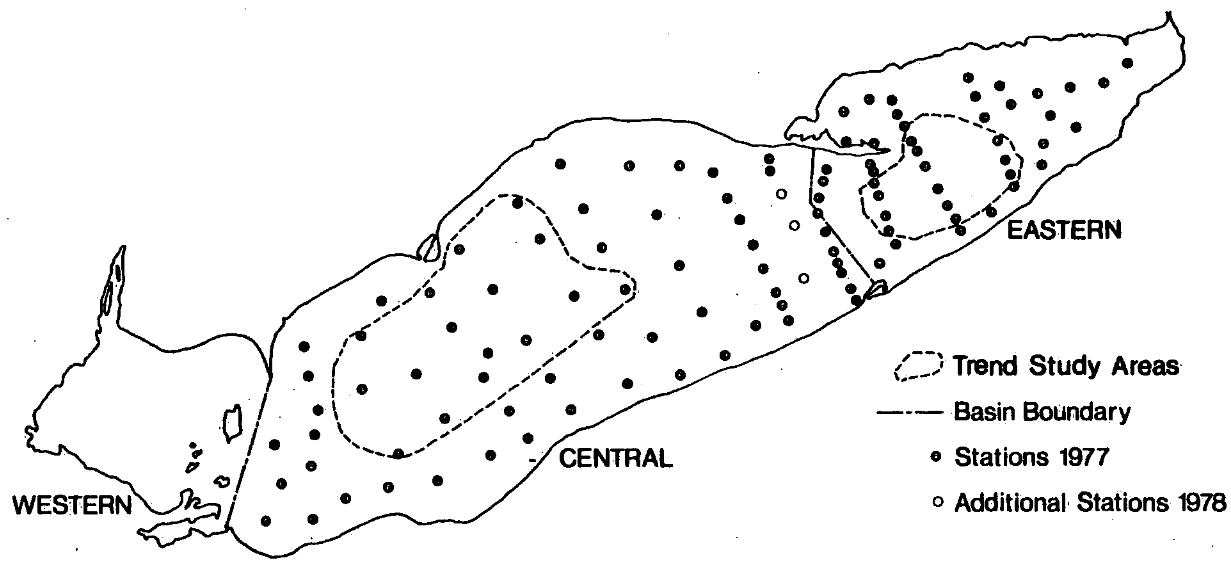

Figure 2 LAKE ERIE BASINS, TREND STUDY AREAS, AND STATION GRID

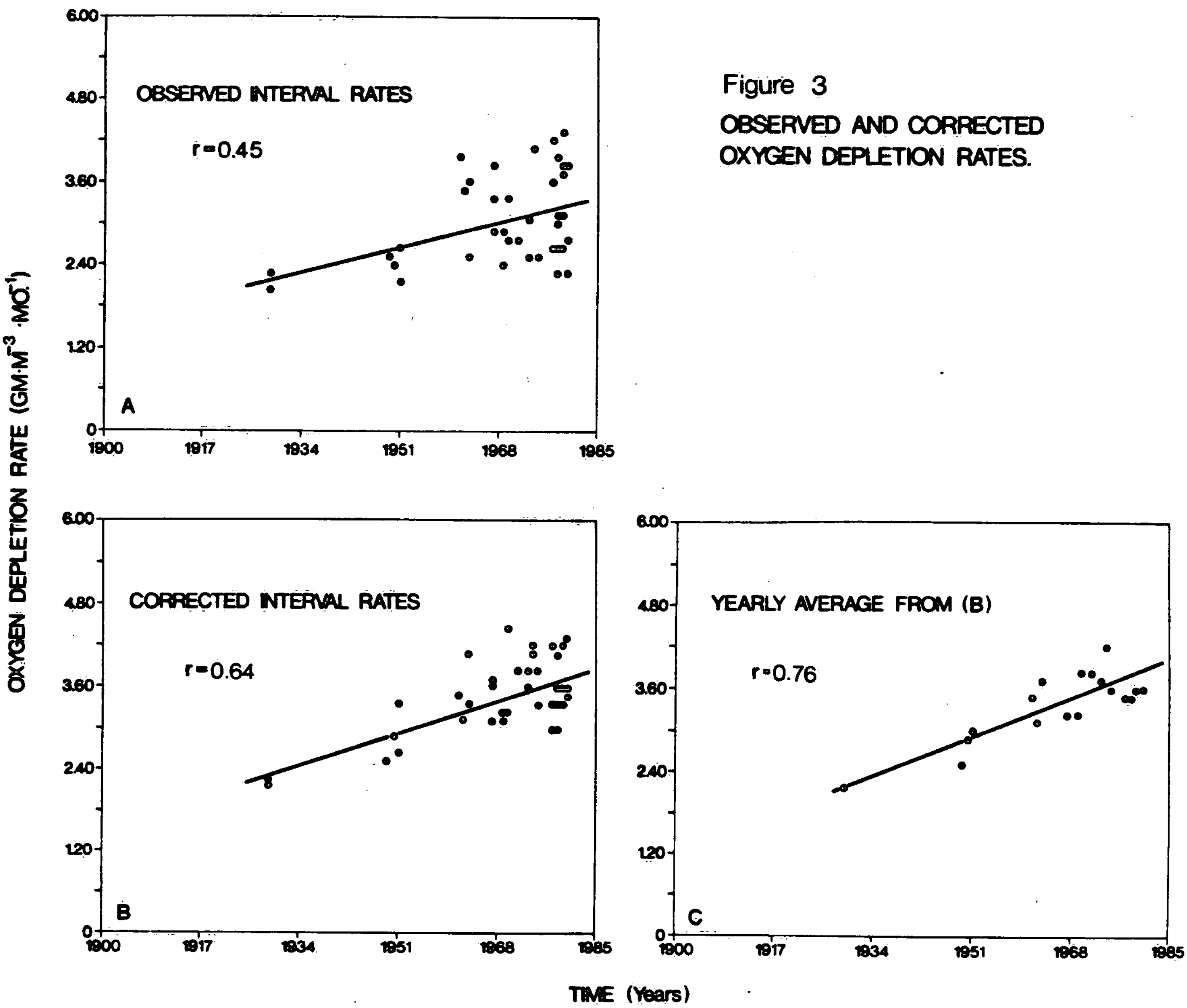

Figure 3

OBSERVED AND CORRECTED OXYGEN DEPLETION RATES.