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LAKE ERIE OXYGEN REVISITED

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ABSTRACT

The problem of predicting the future hypolimnion oxygen regime in Lake Erie from past records is re-assessed. Instead of comparing oxygen depletion rates, the data were manipulated to reveal comparable concentrations at the end of August each year. By removing confusion caused by variable concentrations at the beginning of stratification, the expected change of 0-2 mg/L from the 1950s to present was revealed. The oxygen regime of the east basin has changed little if at all; the year to year variability being as large as possible trends in concentration. A water sampling device used in the earliest samplings was found to produce incorrect samples under certain conditions thereby lessening confidence in the early data. The trajectory of oxygen concentration after stratification is independent of epilimnion productivity. It is proposed that oxygen depletion depends on average trophic conditions preceeding each stratified season. Modestly improved O_2 concentrations can be expected with, periodically, low concentrations due to lake levels and weather after nutrient loading reductions. The lag of O_2 response to loading reductions is at least 10 years. Lag phenomena may have prevented full O_2 response to loading increases.

INTRODUCTION

The discovery of low oxygen conditions in the central basin hypolimnion of Lake Erie in the late 1950s seemed to indicate that large and harmful changes had occured in the lake generally. The basis for this judgement was the comparison with earlier records of 1929 and 1949-53. In addition, increasing deoxygenation of the bottom layer of the lake in the summer could be expected due to cultural eutrophication of the lake since the area was settled in the late 1850s.

The early oxygen records are potentially of great value in assessing the current trophic state of the lake because they are almost the only chemical measurements available for comparison. Reports on this aspect of the lake's health progressed from guarded surprise at the low concentrations (Carr 1962) to a detailed analysis of the change in the rate at which the oxygen concentrations declined each year (Dobson and Gilbertson 1971). The conclusion of the latter study was that there had been a change towards faster rates of oxygen depletion each year since measurements were begun. Later, Charlton (1979,80a) found that the historical data showed that oxygen conditions had not deteriorated as quickly as had been thought. He also pointed out that that the scientific merit of a judgement as to whether there had been a large change was seriously compromised by the lack of any controls in the trend analysis. An attempt to account for important physical factors which might frustrate the search for a historical trend resulted in the conclusion that there had been very little change in the rate at which oxygen was depleted following the formation of the thermocline each year.

The conclusion that little change in the oxygen regime had occurred was directly opposite to the prevailing wisdom. Indeed, much of the strategy of eutrophication control was directed in the belief that oxygen conditions would become dramatically better with controls and much worse without them. These beliefs were based on experiences with small lakes and on models in which a relationship between oxygen depletion and nutrient loading was supposed. Oxygen depletion is dependent on lake depth and the position of the thermocline as well as productivity and nutrient loading. Correlations with data from the Great Lakes suggest that a large change in Lake Erie's oxygen concentrations would result only if nutrient loadings were reduced enough to effect a reduction in the amount of algae to near Lake Superior levels (Charlton, 1980b).

Other publications have been more or less consistent in that they indicate eutrophication changes to Lake Erie may have been most important just after settlement of the basin (Delorme 1981, Harris and Vollenweider 1981, Schelske et al. 1983). These publications indicate important eutrophication effects occurred before the basin population was very large and before domestic phosphorus sources were connected to the lake with sewer systems which were later modified for phosphorus removal. An extensive analysis of factors which control oxygen depletion was completed with the aid of computer modelling (Lam et al. 1983). These investigators were able to account for the effect of weather on the placement of the thermocline and were thus able to confirm

the importance of weather in controlling oxygen levels and therby introducing variability which may mask trends to different conditions.

The first systematic report on the trend to worsening (lower) oxygen conditions in the central basin hypolimnion was that of Dobson and Gilbertson (1971). Since the concentrations were not observed on consistent dates in the historic data set, they were converted into rates of change each summer to allow for comparisons between summers (The rate of change in concentration can be calculated between two sampling dates but is usually calculated as the slope of a regression line through the decreasing concentrations sampled at several times each season. This is the definition of the term "oxygen depletion rate",the absolute change in concentration is called "oxygen depletion".). Since Dobson and Gilbertson's paper, work on the meaning of the historical data has focussed on the oxygen depletion rates and whether they represent a clear trend and indication of the degree of improvement in oxygen conditions to be expected should the eutrophication process be reversed. The subsequent analyses (Charlton 1979,1980a, and, Rosa and Burns, in Barica, 1982) indicate that the apparent trend to faster rates of observed oxygen depletion was less than one third as rapid as formerly believed. The depletion rate analyses are, however, only partly useful if interest is directed towards the question of whether particular concentrations will be achieved.

The important Lake Erie oxygen/eutrophication question is "will significantly higher oxygen concentrations occur in

response to nutrient loading abatement?". To some extent, studies such as Charlton (1980b), Vollenweider and Janus (1983) and Lam et al.(1983) indicated that oxygen concentrations might be higher at the end of each summer but these concentrations would still be low and would approach zero under certain conditions given the planned nutrient loadings. A sub question is "how large an improvement is significant and useful?". A further question, and the main topic of this report is "what improvements in oxygen concentrations can be expected on the basis of the historical changes in oxygen regime?".

METHODS

Minimum oxygen concentrations in the central basin hypolimnion are reached between mid August and mid September each year. The concentrations in this period are determined by the effects of physics, chemistry, and biology on the net result (depletion) of all the sources and sinks of oxygen. Also, the final concentrations depend on the initial concentration at the beginning of stratification. This latter phenomenon has not been sufficiently recognized; it may account for up to a 2 mg/L difference between years (Charlton, 1979, 1980a) which is independent of eutrophication effects. Apparently, the differences in initial concentration are related to differences in water level (Anderson et al., 1984; El-Shaarawi, 1984).

By simply adjusting the Y intercept (at June 1) of the oxygen/time relationship to be 12 mg/L each year, the observed

depletion rates each year could then be extrapolated to Aug 31 to yield comparable oxygen concentrations at the critical period. A variant of the method is to apply additional corrections for some of the effects of physics on the rate of depletion. The rates of depletion were found to be related to temperature by:

$$mgO_2.L^{-1}.mo^{-1}=0.263T^{1.039} \quad (R=0.67, n=18)$$

Depletion rates were then normalized to 10 °C by simple algebra similar to Charlton's (1979,80a) correction for variations in hypolimnion thickness. The comparable end of season concentrations were then calculated to allow a portrayal of changes that would have occurred if some physical factors had been consistent from year to year.

One near bottom datum was used for each sampling station in the historical record. The stations themselves were limited to those with a depth equal to or greater than 15M. This choice eliminates most extreme data caused by spatial variability but some further editing to remove data representing cold east basin incursions was necessary (Charlton,1979,80a). These methods elucidate the strong linear decrease in concentrations each year and do not suppress the observed spatial variability of ca 4mg/L. Lastly, calculations were performed on data from 2-3 stations near Erieau as these were close to the location of the earliest historical sampling sites.

RESULTS

Data used in Fig.1 were from an area south of Erieau which was the only area sampled in the late 1920s, the 1950s, and after 1960. Although only 1-3 stations were included, these data are representative of the means for the Central basin (Charlton,1980a); they were used to avoid possible problems associated with comparing the large (later) and small (early) data sets. Similar results to Fig.1 were obtained by comparing all the data available within the 15M depth contour in the extensive later surveys. Thus, although reducing the spatial variability was unneccessary, the efficacy of a very small scale surveillance effort was demonstrated.

Figure 1A shows the comparable oxygen concentrations reached by the end of August each year. There was a considerable spread in concentrations during the latter 20 years which was not apparent in the scarce earlier data. The concentrations in the 1950s were identical with many of those of the 1970s. Depending on how well the distribution of concentrations was represented by the sparse 1950s data, a difference of 0-2 mg/L may have occurred between the 1950s and the 1970s.

Figure 1B shows the comparable oxygen concentrations as in Fig.1A but the actual depletion rates were adjusted in an attempt to compensate for some of the effects of temperature and hypolimnion thickness. The extremes of 1962 and 1975 were reduced by the compensation procedure and more of a trend to lower concentrations was indicated. The difference in concentrations between the 1950s and 1970s is problematic as the

spread in the latter data is as large as the possible difference. Nevertheless, the data show a difference of 0-2 mg/L and, if the apparent trend is accepted, an average difference of about 2mg/L may have occurred between the 1950s and the 1970s.

DISCUSSION

The analyses in Figs. 1A and 1B are about as simple as possible for the purpose of comparing the historic oxygen data. The only modification to the data in Fig. 1A has been a standardization of the initial concentration prior to the calculation of the mean concentration on Aug 31 based on the depletion slope each year. Correcting slopes for temperature related effects in Fig. 1B reduced the extremes in the data but also caused more variation in the main body of the data. The empirical correction based on temperature was used because temperature was the only depletion related physical factor measured in each year. Application of an empirical correction imparts additional error. The implicit assumption, that the additional errors are small relative to the correcting effect, has not been tested.

The results of this analysis can be used to gain an impression of the changes in O_2 concentrations to be expected due to reductions in nutrient loadings. Under the assumption that loading reductions will return the factors which cause O_2 depletion to conditions of the 1950s, an increase of up to 2mg/L

may occur. This finding is subject to the limitations of the quantity and quality of the available data. Due to the variability of O_2 concentrations revealed by yearly sampling after 1960 and the lack of most physical measurements before 1960, predictions of O_2 concentrations in each future year will not be attempted. The reduced phosphorus loadings under International agreements will be on the order of 10^3 tonnes/Y which would approximate loadings of the early 1950s (Chapra 1977). Accepting the historical data with almost no modification, the resulting improvement in O_2 concentrations would be 2mg/L or less and this is one third the improvement (to 6mg/L) originally desired.

Both detection of change and the degree of change are important. The changes indicate the probability of response should the eutrophication effect on oxygen be reversible. Absolute concentrations determine, in the worst case, whether fish will survive or phosphorus will be released from sediments. All of the concentrations in Fig.1 can be shifted down by 2mg/L to account for the range of initial concentrations observed. Also, the range of final concentrations observed during intensive sampling in the 1970s could occur anytime and this should be included in a "worst case" scenario. The range is 2.0mg/L in Fig.1A and 3.6mg/L in Fig.1B. Therefore, assuming that the 1929 point represents the center of the range, mean concentrations as low as 2.6 and 2.0mg/L respectively could occur given trophic conditions of 1929. The 1929 data probably do not represent the lower part of the range as there would then have been years with almost no depletion. If 1929 was a high oxygen year and if the

slope of the lower two data in Fig.1B is interpolated to 1929 then oxygen concentrations less than 1mg/L are possible in the worst case. The worst case scenario for the 1950s data would produce near zero concentrations at the end of August. An extension of stratification for 2 more weeks and temperatures higher than the standard 10 degrees could also occur. Clearly, under physical conditions which exacerbate O_2 depletion, very low concentrations would still be expected despite nutrient loading reduction. On the other hand, the frequency of slightly higher concentrations should increase due to nutrient loading abatement. A statistical analysis of the relationship between oxygen, temperature, lake level, and phosphorus (El-Shaarawi, 1984) has allowed calculation of the probability of anoxia. At lake levels of 571 ft. or less, the probability of mean oxygen concentration reaching zero is 55%-100% with a phosphorus concentration of 10 ug/L. Indeed, the stochastic aspect of the oxygen depletion phehomenon was demonstrated by occurance of anoxia in mid-August 1985 despite record high lake levels. Since 571 ft. is in the upper range of lake levels historically, and anoxia occurs in the hypolimnion when mean concentrations reach 4 mg/L (DiToro and Connolly 1980) elimination of anoxia cannot be expected under present phosphorus loading restrictions.

One of the problems of the analysis for management of the central basin hypolimnion O_2 is that the change in O_2 conditions has been relatively small. For example, the change in the observed depletion rates has been only about 50% (Barica 1982).

Indeed, the concentrations observed in mid August 1929 were reached only 2 weeks earlier in the summer of 1970, one of the "worst" O_2 years. The 1929 concentrations of 4.4-5.6mg/L were already dangerous to fish and if, stratification had persisted for another month at rates of 2-3mg/L/mo, concentrations of 1.4-3.6 mg/L would have resulted. Obviously, significant O_2 depletion occurred in 1929 and low concentrations can be expected even under rigorous loading restrictions. If the depletion rates had doubled or tripled there would be little difficulty in deciding that nutrient management would yield a significant increase in O_2. With the isolated data in 1929, and the possibly incomplete distribution of the 1950s data, there is a great deal of difficulty in extrapolating the meaning of the early data further than has already been done. If oxygen had been monitored at just a few stations each year decisions could be made on a firm scientific base. This highlights the fact that present surveillance programs should never be allowed to lapse if the benefits of public expenditures for eutrophication control are to be demonstrated.

The O_2 depletion pattern in the deeper east basin hypolimnion should be less susceptible to physical fluctuations and thereby more likely to reflect changes in Lake Erie's eutrophication. To show changes in the O_2 regime, near bottom measurements were gathered from unpublished CCIW reports and from Fish (1929,1960). The results for stations deeper than 35M in 1970,77,78,79 and 1928,29 are shown in Fig.2. Year to year variations resulted in a 1mg/L difference between mean concentrations in adjacent years and up to a 4mg/L difference

between individual data at comparable times in adjacent years. The surface saturation values of the 1928 survey were consistently 15% low (solid bars), therefore, the hypolimnion values were adjusted upwards by 15% (broken bars). These earliest data are near the bottom of the present distribution and, alone, would indicate little change in the lake. Four of the 1929 data are completely outside the lower edge of the modern data and this may indicate a problem with sampling or analysis which may have also been present in the contigous survey of the central basin. The remainder of the data are, except for one, near the upper part of the modern data envelope. In the June-Sept period, the slopes (depletion rates) between the 1929 data are mirrored by the modern data as well. Thus, two conclusions may be proposed: (1): In a long term trend analysis, isolated data, such as those of 1929, must be fitted into a context which includes inter-year variability. (2): There is insufficient quantity and quality of long term data to allow a determination of whether there was a real change in the O_2 regime of the east basin hypolimnion. This is not to imply that a change to higher depletion rates or lower concentrations did not or could not occur. Rather, given that the earliest data straddle the latest data, the changes one might expect do not seem to be reliably detectable.

THE "CONTROVERSY"

The reanalyses of depletion rates (Charlton 1979, 1980a,b) were followed by other welcome analyses and inquiries. One analysis, by F.Rosa and N.Burns, concluded that, if physical factors were accounted for, O_2 depletion rates had increased more than Charlton claimed but less than Dobson and Gilbertson (1971) claimed. A corollary was that the historical data lead to expectations of significant improvement in oxygen conditions following nutrient loading controls. The apparent disagreement between the two analyses precipitated a workshop on Lake Erie oxygen depletion which was summarized in a report by Barica (1982). Some of the differences between the analyses are discussed in this section.

Rosa and Burns' report consisted of two parts: a reanalysis of the historic data with a recalculation of observed depletion rates and a series of corrections designed to remove various physical effects from the analysis of the long-term trend in depletion rates. The authors reduced spatial variability by using only the historic data from an area containing stations with oxygen data within one standard deviation of the mean concentration in extensive surveys of 1977-78. In contrast, Charlton (1979,1980a) used limnological delimiters of depth and temperature and found no benefit in further reducing the spatial variability. Despite the different approches, the results of the basic analyses were almost identical (Barica 1982). Differences were that the Rosa/Burns criteria excluded depletion rates in 1952 and 1953 which were as high as those in the 1970s. Rates for 1949 and 1950 were lower and the 1951 rate was higher than

Charlton's, apparently, due to the inclusion of slightly more data (Charlton 1979). The trends in observed depletion rates were similar and depended largely on whether the isolated 1929 data were included (Barica 1982). Thus, the controversy did not result from differences in the basic analyses of observed oxygen depletion.

The main differences in the conclusions result from the different methods used to account for physical effects which, otherwise, interfere somewhat in the analysis for a long term trend. Hypolimnion thickness (Zh) is a major factor controlling hypolimnion oxygen in the Great Lakes (Charlton 1980b). Extending this finding to central Erie, the annual variations in depletion rate and Zh were found to exhibit an empirical relationship which could predict depletion in the East Basin and the other Great Lakes. Since other physical factors such as temperature and lake level were also related to Zh, the empirical relationship between Zh and depletion rates was used to adjust the historic rates up or down relative to a reference year. After this treatment, the historical rates showed little or no upward trend with time (Charlton 1980a).

Rosa and Burns (1985) adjusted depletion rates (Ro) with serial corrections for vertical mixing (Rv), Q_{10} temperature (Rq), residual Zh effects (Rt), and seasonal effects (Rc). Table 1 shows the effects of the corrections on regressions of mean annual depletion rate against year for different periods of the historic record. The first correction (Rv) was to account for variable amounts of oxygen added to the hypolimnion by turbulent

exchange with warmer, more oxygenated, thermocline water. Rates of hypolimnion temperature increase were used to indicate the extent of turbulent exchange. The oxygen additions are affected by meteorological events and serve to partially ameliorate oxygen depletion caused by the total consumption occurring in the hypolimnion. Thus, the Rv corrected rates represent the depletion which would have occurred if the thermocline was a perfect barrier not the net depletion which actually occurred. Since the effect of oxygen additions increases with decreases of hypolimnion oxygen (Rosa and Burns 1985), the Rv correction should tend to increase with the increase in depletion rates historically. This is shown by the relationship between the correction (Rv-Ro) and the uncorrected rates in Table 1. Assuming the Rv correction is accurate, the difference between the trend slopes of annual mean rates (Ro and Rv) represents the degree to which effects of increasing consumption on depletion rates were ameliorated by oxygen addition phenomena. Since the effects of oxygen additions were simply added to the observed rates each year, the end results represent consumption and are not actually analogous to net depletion. Thus, comparisons of Rosa and Burns (1985) with Charlton (1979, 1980a) may be invalid.

Table 1 shows that the vertical mixing correction caused half of the increase in the historic trend slope due to the corrections. The correlation coefficient was slightly reduced and this is consistent with the hypothesis that a new calculation, ie: consumption, was produced. Consideration of the equations in Rosa and Burns (1985) indicates that, since

hypolimnion oxygen is a function of temperature and Zh, the reduced R is probably due to the accentuation of temperature and Zh effects which are partially attenuated by reoxygenation effects inherent in the uncorrected rates. This may be one reason why the subsequent corrections for temperature and Zh residuals increased the R so much. Some improvement may be made in the vertical mixing correction historically by considering the 2mg/L range in initial oxygen concentrations. Also, the diffusive (non turbulent) heat flux into the hypolimnion can approach 50% of the total heat gain and this would occur regardless of meteorological events (Boyce and Ivey 1981). A full calculation of a heat budget is required to verify the assertion of Rosa and Burns (1985) that all the hypolimnion heat gain represents water and oxygen exchange.

The attempts to compensate for the effect of Zh on the historic comparisons were quite different in the two papers. In Rosa and Burns (1985) the, vertical mixing and temperature corrected (Rq) trend slope was used to identify residuals which were found to correlate with Zh. The residuals were then removed to produce the Zh corrected rates. As Table 1 shows, the removal of just one data point results in an Rq slope with P greater than 5%. One is forced to wonder whether the trend slope was reliable enough to identify residuals and whether a different result would have occurred if the effect of Zh itself, instead of Zh related residuals, had been examined.

Finally, the reliability of trends in depletion or consumption rates needs to be examined. The data available are in three era: 1929, early 1950s, and 1961 to 1980s. The best

data in terms of continuity are in the period 1961 to 1980. Table 1 shows that a long term slope in the depletion rates of 1961-80 cannot be detected. Thus, the long term trend in all the data in, for example, Rosa and Burns (1985) is due to the differences between data groups and the reliability of the trend may be no better than that of a three point regression. The 1929 data point may be suspect (see next section) and if the phosphorus concentration was 10ug/L the probability of anoxia would have been about 50% according to El-Shaarwi (1984). For most of the other years in the 1920s and 1930s, the probability of anoxia would approach 100% with depletion rates equal to those of the 1960s and 1970s. If those years had been sampled, the historic trend might appear quite different. Similar comments apply to early 1950s data except, as mentioned above, there actually were two years, 1952 and 1953, with depletion rates equal to the 1960s and 1970s (Charlton 1980a). Without knowing the variability of depletion rates in each era, the significance of the scant amount of early data to the long term trend cannot be judged. Variability consistent with this concern and the probability levels of El-Shaarwi (1984) is shown by the differences of up to 1mg/L/mo between adjacent years in Rosa and Burns' (1985) fully corrected "depletion" rates. The missing historic data impose severe limitations on all trend studies including Charlton's (1979, 80a). We cannot, however, manufacture the missing data. Thus, a long term trend based on the early oxygen data may be misleading for management purposes.

RELIABILITY OF EARLY DATA

The correlation of oxygen depletion rates with time or phosphorus loadings is highly dependent on the few data gathered during some of the first surveys of Lake Erie in 1929 (Barica 1982). Since these data enhance the impression of a trend in oxygen conditions their validation is important.

The early O_2 data of 1929 (Fish 1960) were collected during general surveys intended to reveal the cause of declining fish stocks. Whereas the early surveys discovered the extent of thermal and chemical stratification, the later surveys (post 1949) were often conducted with the specific task of documenting O_2 depletion as a goal. While the different purposes of the surveys may have been important, the different sampling gear and procedures may also have affected the accuracy of the O_2 information gathered.

In 1929, a "Greene-Bigelow" bottle was used to collect water samples. This bottle was similar to a Nansen bottle in that it had restrictive stopcock valves in each end. A funnel was fastened on the lower end to facilitate water movement through the bottle during descent. On arriving at a station, the early Limnologists sounded the bottom, took top and bottom water samples, and then used reversing themometers to measure the temperature at several depths. Since the actual temperature of the water samples was not recorded, there was no confirmation that the sample was actually obtained from the depth or stratum intended. Thus the performance of the water sampler and lowering

gear was important to the reliability of data.

Normally, in deep unstratified water columns the sampler performance is of little consequence. In central Erie, however, sampler performance is important due to strong gradients and the thinness of the bottom layer. If the sampler retains even a small amount of eplimnion or thermocline water after descent into the hypolimnion an error in oxygen concentration will occur. The size of the error will depend on the amount of retained water and the difference in concentration between the retained water and the ambient water.

An illustration is provided, in 1929, of how critical the sampler performance was. A mid-lake station (#40) was stratified: 20M-20.3°, 21M-14.3°, 23M-11.2°, 24.5M-bottom. Oxygen concentration was 8.3mg/L in the surface water and 7.1mg/L in the 23M sample. The 2M difference between the mid-thermocline and the 23M sample means that the sampler would have to flush completely in less than 2M to obtain a proper sample from 23M. Since bottom O_2 at nearby stations ranged from 4.4mg/L to 8.3mg/L one must be suspicious that the sampler contained some mixture of epilimnion, thermocline and hypolimnion water. Indeed, there seem to be clear cases of sampling error in some of the 1929 data (Charlton 1980a). The problem is to decide whether any of the data can be shown to be trustworthy.

One reason to suspect the data is that water cannot flow through a bottle with restrictions at the same rate as the bottle is being lowered through the water column. Indeed, Weiss (1971) found that a sampler of the style used in 1929 would have a

flushing length of 2 to 4 M. Tests of a Greene-Bigelow replica (F.Roy and M.N.Charlton in prep) in a flowing water flume yielded a flushing length or lag of 3.6M. When the same sampler was lowered through, and stopped below, a sharp thermal gradient in a model water column, the time required for warm water to float out of the sampler was 1 to 2 minutes under depth and temperature conditions simulating Lake Erie. By way of contrast, no lag or float out time could be detected with standard VanDorn samplers.

In addition to hydraulic problems with the sampler the uncertainty of sample depth is increased by the inaccuracy in the lowering procedure and the error in depth (1M) caused by the rocking of the sampling boat. The Greene-Bigelow replica was found to move water downwards while oscillating up and down. Thus, in a swell, the sampler would tend further to contain water from above the desired sample depth.

Field tests of the Greene-Bigelow (G-B) sampler replica were conducted on Lake Erie Sept 13-15, 1983. The water column was sharply stratified at 18M and O_2 concentrations were zero or close to zero throughout the hypolimnion. The G-B sampler was allowed to dwell for 10,30 or 60s at depth before triggering. A "rosette" sampler was allowed to dwell for 30s and an oxygen probe provided in situ readings for comparison. The depth selected for comparison was usually 1 to 1.5M below the thermocline in analogy to depths sampled in the 1929 study. Table 2 shows that occasionally, due to errors in lowering depth, the G-B contained water from below the intended depth with a lower oxygen concentration than expected. Except when the G-B was lowered some metres through the hypolimnion, the majority of

the values indicated that the sampler contained water from above the intended depth with a higher oxygen concentration than was actually present at the depth of closing. Those sampling errors, if they occurred throughout the 1929 surveys, may have caused the low depletion rate, which looks so appealing in the long term trend. Of course, if the sampler was left at depth long enough for warmer water to float out and be replaced by cold water, an accurate sample could be obtained. On the other hand, dwell times of even 30s were not sufficient to ensure accurate samples.

The Greene-Bigelow sampler would not be used on Lake Erie today without elaborate precautions. In the published material, there is no indication that precautions consistent with the sampler's design limitations were recognized and followed. While this does not constitute proof, there is some possibility that oxygen measurements in 1929 were biased to the high side due to sampling problems. Therefore, great caution should be used if the 1929 data are included in studies of O_2 trends and prognosis for the future.

RESPONSE TO LAKE PRODUCTIVITY

Excessive productivity results in algal blooms and the accumulation of unpleasent organic material on shorelines. Since oxygen depletion requires organic matter and occurs at the same time as summer algal blooms there has been the conclusion that a reduction in algal biomass or production would cause less oxygen depletion. The nature of the linkage between algae and oxygen

depletion is, however, likely to be more complicated than expected. An example is shown in Fig. 3. During 1979, primary production was measured and calculated in a method similar to that of Glooschenko et al. (1974a). Chlorophyll a and hypolimnion oxygen concentrations (Charlton and Lean, in prep) were also measured and are shown in Fig.3. Despite 10 years of nutrient loading reductions, there was little difference between primary production in 1979 and 1970. Epilimnion chlorophyll concentrations, in 1979, were quite low at less than 3ug/L for 2 months and these were slightly lower than in 1970 (Glooschenko et al. 1974b). More important is the observation that the O_2 depletion pattern continued unchanged despite the threefold variation in chlorophyll and the sixfold variation in primary production during the summer. Thus, one may conclude that O_2 depletion is partially independent of the summertime productivity. A corollary is that O_2 depletion is a reflection of year round conditions and may represent the integration of effects over many years. Clearly, some factors which determine the depletion rate each year are present just before stratification and there is some stabilizing influence during stratification. To the extent which these factors, such as, water/sediment mixing, resuspension, and phosphorus regeneration during winter, are unaffected by changes in nutrient loading, the oxygen regime will remain unchanged.

For lake management purposes it is important to understand why we cannot predict the complete elimination of anoxia or even concentrations high enough for fish given that billions of

dollars have been expended on nutrient loading controls. The scenario of O_2 concentrations in the future inferred from the past (Fig.1) is in agreement with the results of more elegant computer modelling by Lam et al. (1983). Of course, the predictions in the present paper, at least, are imprecise due both to the difficulty in determining a trend and the year to year variability which was not sampled prior to 1960. Nevertheless, an explanation would be desirable if the loading reductions do not result in a large improvement in oxygen conditions.

The assumption that O_2 concentrations are low because P loading increased led to the expectation that O_2 concentrations will increase if P loading decreases. A part of this assumption is that oxygen depletion responded to, or was in equilibrium with, the loading increases. We can now begin to test these assumptions by examining results of the loading changes that have already taken place. Between 1941 and 1966, the human population of the Lake Erie basin increased by 58%, the per capita use of detergents rose by 1000-1500%, and municipal phosphorus loadings increased by 430% (Gilbertson et al. 1972). The maximum difference in observed depletion rates was about 50% between 1929 and 1966. Loadings of total P and SRP declined 40% and 52% respectively between 1968 and 1974. The controlled portion of municipal loadings (SRP) had declined by 50% by 1973 (Fraser and Willson 1981). Oxygen depletion in 1979, 1983, and 1984 was similar to 1970, and even 1960 (Charlton, unpublished data) despite the loading reductions. Thus, the lag in response of

oxygen depletion to loading reductions is at least 10 and possibly 15 years.

The period of rapidly increasing phosphorus loadings lasted only about 30 years and this is not a long time relative to the 10-15 year lag in response to loading decreases. If we assume that the O_2 response to loading increases is the same, except for sign, as to decreases, then O_2 depletion in the 70s represented loadings of the 60s or earlier. Further, depletion in the 60s represented loadings of the 50s or earlier but depletion in the 60s and 70s was similar. One hypothesis consistent with these observations is that O_2 depletion never actually responded fully to the largest increase in loadings because these loadings did not exist long enough to overcome the lag phenomenon. If this hypothesis is correct, the lag phenomenon was extremely fortuitous for Lake Erie but, also, the expectations of improved O_2 in proportion to loading reductions were exaggerated.

The processes of the lag phenomenon are important to lake management. One can envision a sort of bi-stable scenario in which either negative or positive feedback occurs. In the loading increase phase, the lake absorbs the loadings (negative feedback) through adsorbtion by eroded sediment and semi-permanent burial while exibiting minor changes in algal blooms and species abundance. Responses of sediment oxygen consumption would be delayed by mixing of new, enriched sediment with old, unenriched sediment. Eventually, a positive feedback phase would occur in which a strong oxygen response eliminates all hypolimnion oxygen shortly after the onset of stratification each summer. This condition would result in regeneration of sediment

P and effective recycling (internal loading) to the epilimnion where excessive productivity would occur throughout the summer. Although this latter condition has, thankfully, never occurred in Lake Erie, the few weeks of anoxia that occasionally occur do allow temporary increases in hypolimnion SRP and these are a clear warning of the need for maintaining loading reductions.

The eventual O_2 response to loading reduction may only be known with certainty perhaps 10 to 20 years from now. This is due to the modest response expected, the lag effect, and natural variability which occurs even when P concentrations, lake level, and temperature are held constant (El-Shaarawi 1984). If the Rosa and Burns (1985) and Dobson and Gilbertson (1971) scenario is correct, oxygen conditions in the central basin should be better on the average although worst cases (Fig.1) would still occur. The scenario of Charlton (1980a) is more consistent with a significant response lag effect. If the Charlton (1980a) scenario is correct, the phosphorus loading reductions would be successful in preventing further degredation. Both scenarios seem to have some plausibility. A significant improvement in O_2 conditions would be only one of several symptoms of the success of the nutrient control program.

THE VALUE OF HIGHER OXYGEN CONCENTRATIONS

There does not seem to be a recent analysis of the socio-economic benefits of higher oxygen concentrations. Fish require 4mg/L and anoxic situations occur only briefly and can be avoided by only a slight reduction in oxygen consuming processes. There is no guarantee that higher oxygen concentrations would restore the fisheries of the 1940s. Indeed, the present resurgence of

the Walleye is generally thought to be due to the ban on commercial fishing imposed due to mercury contamination in the early 70s. The restoration of the fisheries would require action on many fronts to ensure that adequate areas for spawning and the nurturing of fry exist and that reasonable fishing practices prevail. One may speculate that the thermocline area provides a refuge from low oxygen and high temperature and high light. It is perhaps just this feature of Lake Erie that renders the traditional fishery so susceptible to overfishing. In any case, the role of O_2 depletion in controlling fish stocks is not well understood and this is an important gap in knowledge.

While the value of higher O_2 concentrations is perhaps debatable, there is little doubt that O_2 conditions represent the trophic state of the lake, albeit with both unequaled inertia and confusion due to weather and lake morphometry. A significant improvement in O_2 conditions would be preceeded by noticeable reductions in mean chlorophyll and phosphorus concentrations. Critical concentrations of oxygen for fish survival or P regeneration can be specified and these should be continually monitored as one of the suite of standard parameters in surveillance programs.

CONCLUSIONS

1. Based on the historic oxygen data, the oxygen concentration at the end of August may improve by 0-2mg/L if trophic conditions revert to those of the 1950s as a result of P loading controls.

2. Variability in initial concentrations and depletion rates may allow some anoxia even though mean O_2 conditions may improve.

3. Poor oxygen conditions still persist in spite of the fairly good quality of offshore surface water in the summer. Oxygen depletion is a result of processes year-round and may not correlate directly with improvements in summer water quality.

4. Oxygen conditions in the East Basin hypolimnion have changed little in the last 50 years.

5. Due to sampling difficulties, the earliest Central Basin oxygen data of 1929 may have been biased upwards and caution should be used if these data are included in trend analyses.

6. Standardising the initial concentration and extrapolating the depletion slope to a standard date is a suitable method to detect trends and display variability essential to a worst case analysis.

7. A response lag phenomenon may have prevented full development of low oxygen conditions resulting from short lived increases in P loading.

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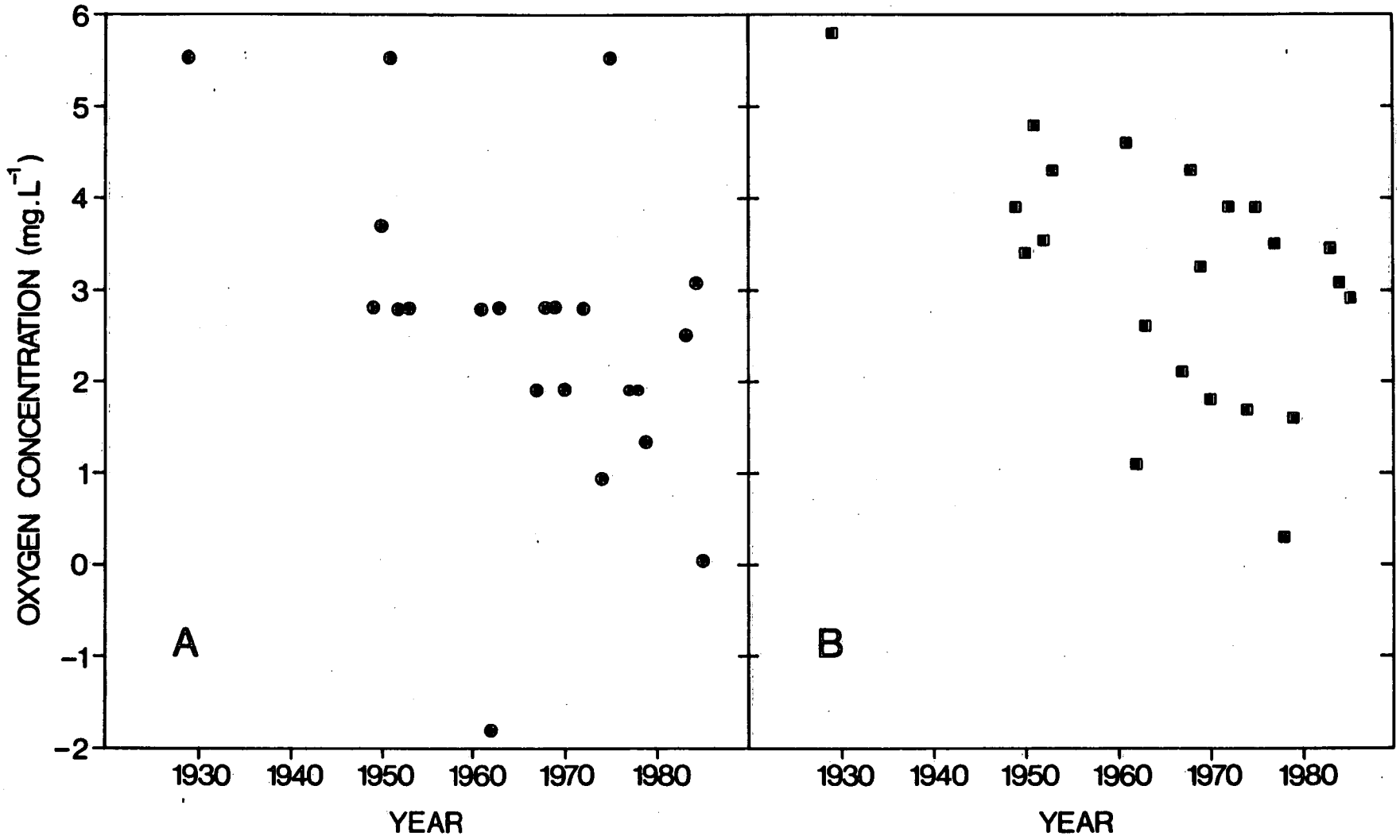
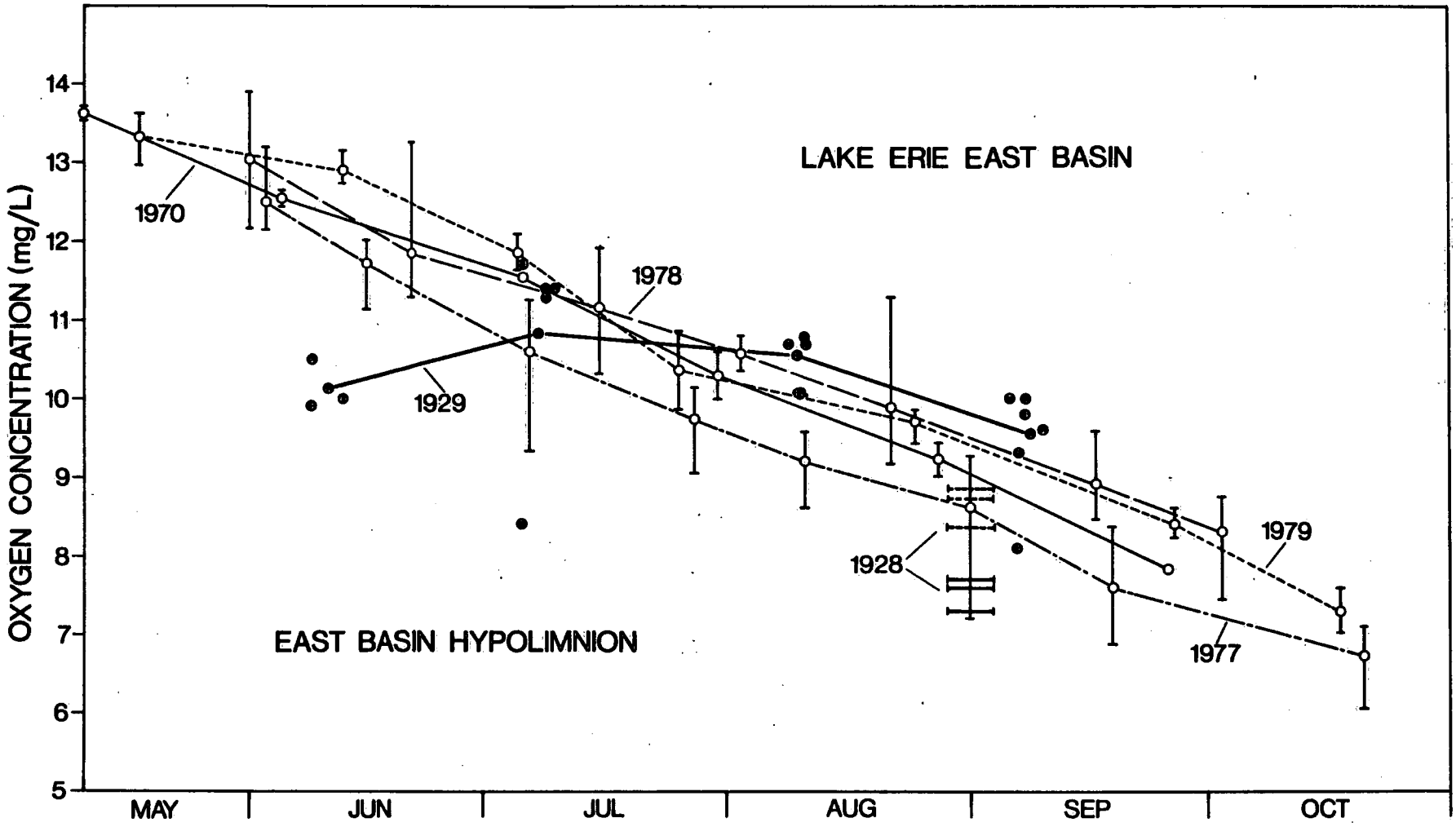
FIGURE CAPTIONS

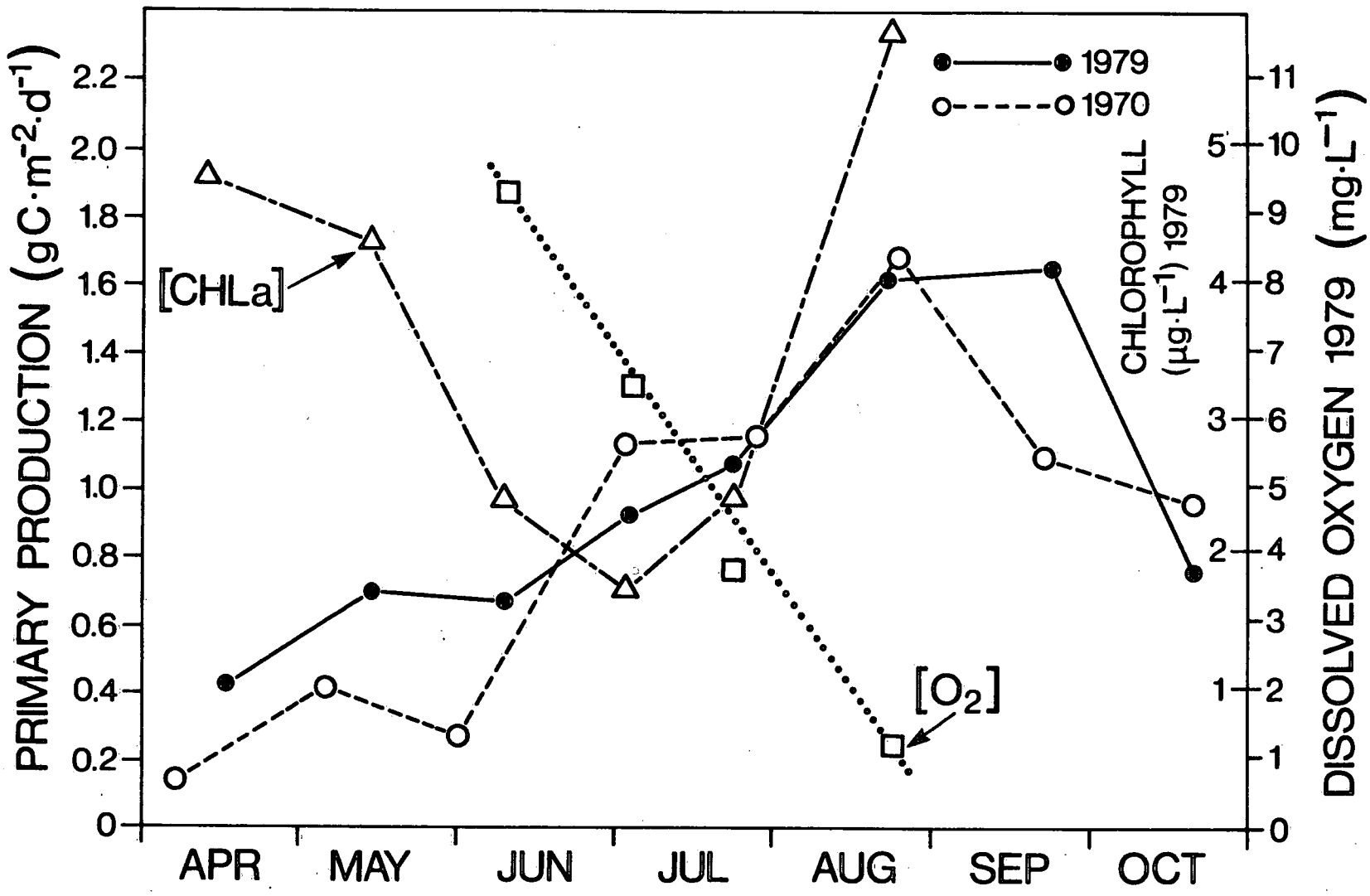
FIG.1. The historical (1929-1985) record of comparable oxygen concentrations at the end of August in the central basin hypolimnion. A: Initial concentrations set to 12 mg/L and slopes extrapolated to Aug 31. B: As in A except slopes were adjusted for effects of temperature and hypolimnion thickness as per relationship in text.

FIG.2. Summer oxygen changes in the east basin hypolimnion. Mean and range shown for 1970,77,78,79; individual data shown for 1929, and range of dates with tentatively corrected concentrations shown for 1928. The three 1928 data happen to coincide with a samplimg episode in 1977.

FIG.3. Primary production in 1970 and 1979 compared with changes in chlorophyll a and oxygen concentration in the central basin in 1979.


OXYGEN CONCENTRATION (mg.L^{-1})
6
5
4
3
2
1
0
−1
−2
A
B
1930
1940
1950
1960
1970
1980
YEAR
1930
1940
1950
1960
1970
1980
YEAR


LAKE ERIE EAST BASIN
EAST BASIN HYPOLIMNION
OXYGEN CONCENTRATION (mg/L)
14
13
12
11
10
9
8
7
6
5
MAY
JUN
JUL
AUG
SEP
OCT
1970
1978
1929
1928
1979
1977



CENTRAL BASIN LAKE ERIE PRIMARY PRODUCTION

TABLE 1. Effect of corrections on trends of mean annual oxygen depletion rate with various combinations of data from Rosa and Burns (1985).

Period	Ro vs Year		Rv vs Year		Rq vs Year		n
	Slope	R	Slope	R	Slope	R	
1929-80	0.022	0.53*	0.027	0.49*	0.028	0.58**	18
1949-80	0.20	0.37	0.023	0.34	0.024	0.40	17
1961-80	-0.017	-0.22	-0.036	-0.37	-0.016	-0.19	14

Period	Rt vs Year		Rc vs Year		(Rv-Ro) vs Ro		n
	Slope	R	Slope	R	Slope	R	
1929-80	0.032	0.74**	0.032	0.76**	0.252	0.51*	18
1949-80	0.034	0.65**	0.033	0.66**	0.259	0.49*	17
1961-80	0.008	0.13	0.005	0.09	0.193	0.33	14

*P < 5%, **P < 1%, slope is $mgO_2/L/mo/yr$, R is correlation coefficient

TABLE 2. Comparison of oxygen values (mg/L) from a Greene-Bigelow (replica) bottle, Rosette sampler, and insitu oxygen probe. Lake Erie, 13-15 September, 1983.

Station	Depth (M)	Greene-Bigelow		Rosette		Probe
		O_2	Dwell(s)	O_2	Dwell(s)	O_2
9	17.5	10.05	10	10.11	30	8.50
	19.0	5.76	10	9.98	30	8.44
	20.5	0.73	60	2.31	30	2.24
	20.5	5.09	10	2.31	30	2.24
	20.5	4.38	10	2.31	30	2.24
	20.8	3.09	10	2.31	30	2.24
8	21.5	5.14	10	0.45	30	2.00
	21.5	3.05	30	0.45	30	2.00
7	21.0	0.89	10	0.37	30	0.35
	21.0	0.64	30	0.37	30	0.35
6	20.5	3.48	10	2.34	30	2.43
	20.5	3.54	30	2.34	30	2.43
2	22.0	4.47	10	3.42	30	3.66
	22.0	5.58	30	3.42	30	3.66
20	20.0	4.20	10	2.91	30	1.08
	23.0	0.38	10	0.36	30	0.00