NIWA
Taihoro Nukurangi

REVIEW OF
OXYGEN DEPLETION PROCESSES IN LAKES

Prepared for
Lakes Programme, NIWA

by
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Hamilton

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June 1993

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NIWA Ecosystems comprises the former Water Quality Centre and part of the former Taupo Research Laboratory (ex-DSIR Marine and Freshwater) based on the University of Waikato campus, plus the ex-MAF Technology Aquatic Plant Group and ex-MAF Freshwater Fisheries Research Group (formerly at Rotorua) based at the Ruakura Agricultural Centre, Hamilton.

OXYGEN DEPLETION PROCESSES IN LAKES

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OXYGEN IN LAKE HYPOLIMNIA

1. Why study oxygen processes?

There are a number of good reasons why an understanding of oxygen processes in the bottom waters of lakes is desirable. They are :

(1) Oxygenated or oxic waters are generally much preferred to anoxic waters because they support desired life forms, do not smell or have an unpleasant taste. We need to know how to preserve these desired conditions.

(2) Oxygen, being an essential element in the hydrosphere, controls or participates in almost all of the important processes in stratified lakes such as:
   (a) the growth and decomposition processes occurring in the different layers of the lake,
   (b) changes in the chemistry and biochemistry prevailing in the lake which are dependent on the presence or absence of oxygen,
   (c) the horizontal and vertical transport processes in the lake.

Thus an understanding of the oxygen processes in a lake requires a knowledge of the fundamental biological, physical and chemical phenomena occurring and the manner of their interaction. Indeed one might say, 'Having a knowledge of the oxygen processes in a lake means having a knowledge of the basic limnology of that lake.'

(3) Changes in the hypolimnetic dissolved oxygen (D.O.) of lakes with time are a good tool to monitor changes in the trophic state of stratified lakes, as proposed by Hutchinson (1957). This capability results from the process of organic material produced in the epilimnion settling into the hypolimnion and decomposing there, taking up oxygen as it does so. Thus as a lake becomes more eutrophic, it produces more

organic matter which subsequently settles into the hypolimnion utilising more oxygen as it decomposes. Other indicators of trophic state used in lake monitoring are chlorophyll and nutrient concentrations, as well as turbidity. The latter three variables are concentration type variables and their values depend to a large extent on the time of sampling. D.O. depletion rates, however, are integrative type variables and they respond to all the phenomena which occur between sampling dates. Thus they are not critically dependent on the time of sampling and in this regard they provide one of the better indicators of lake change. They are therefore worthy of further research to ensure their optimal use. The accelerated D.O. depletion rates of Lake Rotoiti are a good example of use of these rates in documenting increased eutrophication (Vincent et al 1984).

2. Complexities in the determination of the D.O. depletion caused by decomposition of organic matter

Unfortunately, the use of oxygen depletion in monitoring lakes is not straightforward. Simple D.O. depletion rates obtained by dividing the difference between observed D.O. concentrations by the time which elapsed between sampling dates, are of little value in most cases. Oxygen concentrations can be affected by many processes and the observed rates must be adjusted so that only the D.O. depletion which results from oxidation of organic carbon in the hypolimnion (organic uptake rate - OUR) is determined. These are the rates that are comparable from year to year and are useful as indicators of change of trophic state.

The complicating processes which must be considered when determining absolute oxygen depletion rates are described below, together with some of the methods of quantifying their effects and removing them from the observed depletion rates. These processes are:

(1) Variable fraction of production reaching the hypolimnion

The fraction of the epilimnetic production reaching the hypoliminion can vary from year to year. In an important investigation, Mitchell and Burns (1979) determined the site of the decomposition of the epilimnetic production in Lakes Hayes and Johnson. They found that the majority of the decomposition of organic matter occurred in the epilimnion, not the hypolimnion. Their data is shown here in Fig.1.

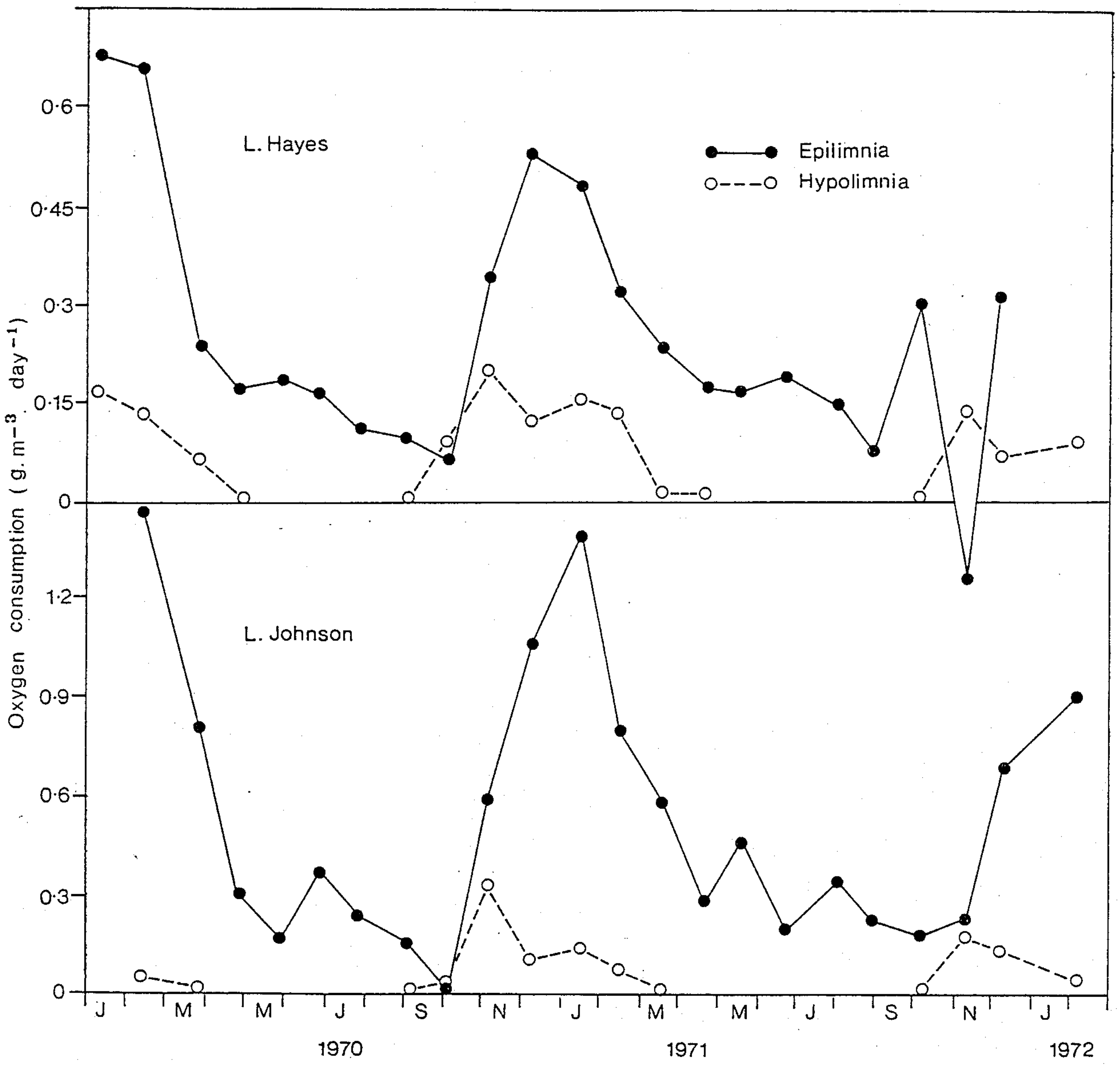

Fig. 1. Oxygen consumption per m^3 in the epilimnia and hypolimnia of Lakes Hayes and Johnson, Jan 1970–Feb 1972.

The site of the organic decomposition would not be particularly important if the proportion of each year's organic production settling into the hypolimnion was constant. However, this is not necessarily the case and the variation of the organic load to the hypolimnion is magnified by the fact that the load to the hypolimnion is normally only a small fraction of the total organic production as shown in Fig. 1. For example, if only 10% of the epilimnetic production normally reaches the hypolimnion, and a year suddenly occurred when 20% of the total production reached the hypolimnion, this would cause a 100% increase in the loading of organic material to the hypolimnion. The fraction of the production which settles vertically can be largely dependent on the phytoplankton species present (Burns and Rosa 1980). In fact Edmonson (1966) postulated that because the species in Lake Washington shifted to colonial Myxophyceae species which neither sank nor were deposited in zooplankton faeces, their occurrence produced a shift in respiration toward the epilimnion, with a greater proportion of the total decay occurring there.

Further, on occasion high numbers of zooplankton can persist to the extent that they effectively restrict the growth of phytoplankton in the epilimnion (Mazumder *et al.*). The result of this is that less algal remains settle into the hypolimnion and the increased clarity of the surface waters permits oxygen production in the hypolimnion from primary production in that zone.

The situation that the hypolimnetic oxygen depletion rate can be altered by the species of algae or the numbers of zooplankton in the eplimnion has to be accepted as a limit on its usefulness as an indicator of trophic state. It is not possible to make quantitative corrections to observed depletion rates on the basis of the algal species present. Nevertheless, increased nutrient loadings usually cause an increase in the flux of organic matter into hypolimnia, with a corresponding increase in the D.O. depletion rate. Lake Rotoiti did have a shift to blue-greens with increased with increased nutrient loading but still showed a showed a big increase in the D.O. depletion rate (Vincent et al 1984) with increasing eutrophy. However, the high variability common in phytoplankton populations is probably a part cause of the high variance often encountered when determining D.O. depletion rates (Charlton 1980b, Rosa and Burns 1987).

(2) Ambient D.O. concentration effects

The ambient concentration of hypolimnetic oxygen can affect the D.O. depletion rates but in many cases does not do so. The question of whether the ambient oxygen concentration controls the rate of respiration reactions in lakes is a confusing one. Some evidence indicates that oxygen concentrations do not affect organic decomposition rates (ie. D.O. depletion rates are zero order). However there is much evidence to the contrary which indicates that higher D.O. concentrations cause higher depletion rates and that these rates are first order with respect to D.O.

Cornett and Rigler (1984) studied oxygen depletion in 10 lakes in Quebec, Canada and observed the D.O. concentrations to decrease linearly with time throughout the season while oxygen was present in adequate concentration. From this they concluded that "hypolimnetic oxygen deficit can be modelled as a zero order chemical process that is independent of oxygen concentration". Lasenby (1975) found a similar situation with 14 Ontario lakes In fact many deeper lakes have almost linear oxygen depletion rates over an entire stratified season. Gibbs (1992) also found that the oxygen depletion rate was linear in Lake Rotoiti between the occurrences of reoxygenation by underflow.

The hypolimnetic oxygen uptake which results from decomposition in the water column is called the water oxygen demand, K_W and the uptake at the sediment-water interface is called the sediment oxygen demand, K_S. (Methods for measuring K_W and K_S are described in the following section). Campbell and Rigler (1986) investigated the dependence of K_S on oxygen concentrations and they concluded that K_S was independent of ambient oxygen concentration above 3 mg /L, with the dependence of K_S on oxygen concentration showing up strongly below 2 mg /L. In experiments on the K_W dependence on ambient oxygen levels , Cornett and Rigler (1986) found no dependence on oxygen levels above 2 mg /L.

The results of Edberg (1976), however, contradict those of Rigler and his co-workers because Edberg found that the K_W in his experiments was proportional to the amount of oxygen present (i.e. K_W was a first order reaction with respect to oxygen). He also found that the K_S in his experiments was proportional to the oxygen concentrations in the water overlying the sediments up to 11 mg/L. Trimbee and Prepas (1988) also found that D.O. uptake was higher when the D.O. concentrations were higher in an ice-covered lake.

No clear picture thus emerges of the dependence of the decomposition of organic matter in lakes on the oxygen concentration. However, the degree of variability in the laboratory experiments of all these investigators was fairly high. Futher there are many lakes which have near constant oxygen depletion rates, until low oxygen concentrations are encountered. Generally oxygen depeletion rates are constant until oxygen concentrations of 2 to 3 mg/L are encountered. But this cannot be considered to be a general rule.

The outcome of the above discussion is that D.O. depletion rates can be calculated in waters with D.O. concentrations above 3 mg/L D.O. but should be calculated with caution in waters containing between 2 to 3 mg/L of oxygen. They should not really be calculated for waters containing less than 2 mg/L because the depletion rates are probably then controlled by oxygen concentration. Low D.O. concentrations probably do not affect the K_W rates until very low concentrations are reached but the K_S rates are definitely affected in the 2 to 3 mg/L and lower concentration ranges. The dependence of D.O. uptake rates on oxygen concentrations in different lakes remains an important topic for further research.

(3) Sites of D.O. uptake and the effect of hypolimnion thickness

Hutchinson (1938), first put forward the idea that hypolimnion thickness did not effect the areal hypolimnetic depletion rate (AHDR) and that this parameter would reflect the productivity of a lake. Thus AHDR would enable the comparison of the trophic state of lakes having quite different morphometries. This concept seemed viable at first, but subsequent investigations revealed that the depth of a lake can have a stronger effect than the trophic state of a lake in determining its AHDR. Table 1. reproduced from Charlton (1980a) shows that Lake Superior, which is very clean, has a higher AHDR than the Central Basin of Lake Erie which is mesotrophic. As a result of this, limnologists have shied away from using AHDR (g. O_2 m^{-2} day^{-1}) and have preferred to use the volumetric hypolimnion oxygen depletion rate (VHDR g O_2 m^{-3} day^{-1}) (Vollenveider and Janus 1982). The high AHDR of Lake Superior is a result of its thick hypolmnion, with most of the material settling into it being decomposed in the water column and not reaching the sediments. In the Central Basin of Lake Erie only part of the organic material decomposes in the water column and much of it settles onto the sediments and decomposes at a relatively slower rate.

Table 1. Comparison of AHDR, hypolimnion thickness, temperature, and surface chlorophyll in the Laurentian Great Lakes.

Lake	AHDR ($gO_2.m^{-2}.d^{-1}$)	$\overline{Z}_n$(m)	$\overline{Chl}\,a$ ($\mu g.L^{-1}$)	$\overline{T}_n$(°C)
Superior	0.40	125	1.1	4.0
Georgian Bay	0.24	25	1.2	4.0
Ontario	1.25	70	4.8	4.0
Central Basin Erie	0.33	3.3	5.5	11.0
East Basin Erie	0.61	13.4	4.3	8.0
Michigan	0.88	84	2.3	4.0

$\overline{Z}_n$ = mean hypolimnion thickness
$\overline{Chl}\,a$ = mean annual chlorophyll concentration
$\overline{T}_n$ = mean hypolimnion temperature

The oxygen uptake in the water column and at the sediment - water interface combine in the following forms;

$$\text{AHOD} = K_W.d + K_S \quad (1)$$

$$\text{VHDR} = K_W + K_S/d \quad (2)$$

where

K_W = water oxygen uptake (g O_2 m^{-3} day^{-1})

K_S = sediment oxygen uptake (g O_2 m^{-2} day^{-1})

d = hypolimnion thickness

The above equations show that if K_W and K_S remain constant in a lake over a period of time, then AHDR and VHDR can be significantly altered by changes in the hypolimnion thickness, d. This was found to be very much the case in Lake Erie. Rosa and Burns (1987) examined this problem and utilized a method to correct VHDR at different hypolimnion thicknesses back to what it would have been at a standard thickness. However, this correction process cannot be used without knowledge of the relative values of K_S and K_W.

K_W is usually measured by placing lake water in BOD bottles and submerging them in the lake or maintaining them at the in situ temperature in the laboratory. K_S can be measured either by lowering circulation chambers containing D.O. probes onto the bed of the lake or by taking cores with intact sediment-water interfaces and maintaining them at set temperatures in the laboratory.

Unfortunately the correct evaluation of K_S and K_W and the subsequent partitioning of the VHDR and AHDR into the water and sediment uptake components is unexpectedly difficult. Snodgrass (1987) has reviewed a number of simultaneous measurements of K_W and K_S and found that "A comparison of in situ measurements of water column oxygen demand (K_W) and sediment oxygen demand (K_S) with VHDR suggests that measurements are typically 50 to

100% too high". K_W was measured, as is usually done, by using a BOD bottle type technique and the measured values appeared to be too high. The K_S values were measured using sediment chambers and were also too high.

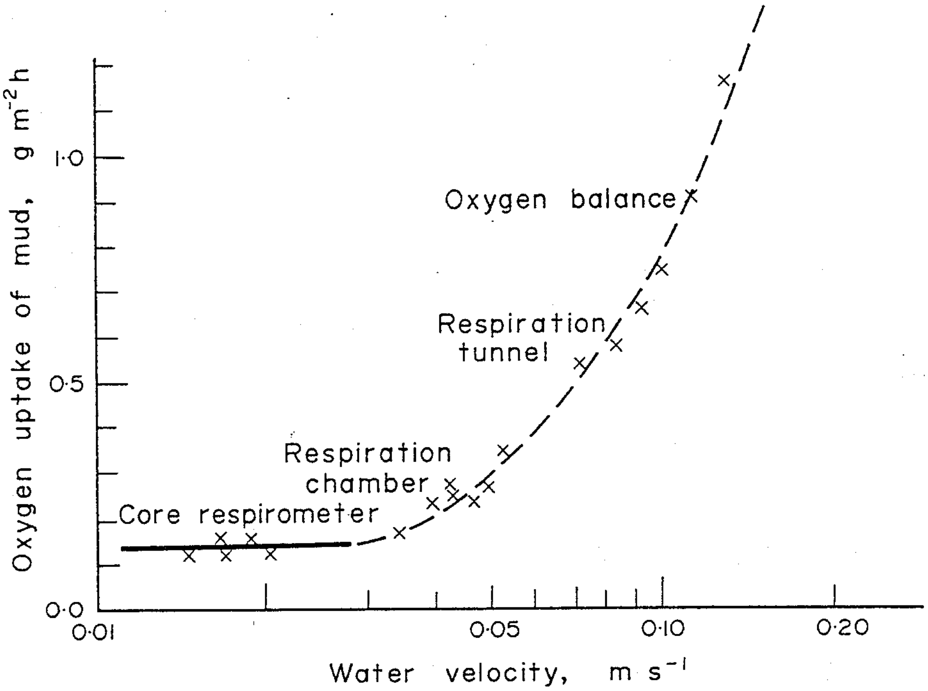

Fig. 2.

The major problem with measuring K_S is that it is very sensitive to the degree of stirring in either the circulation chambers or cores. Figure 2 from James (1974) illustrates this sensitivity and demonstrates the importance of that the current velocities close to the interface in a sediment chamber mimicing those which occur in the lake. The rapid increase of the oxygen uptake rate with current velocity is most interesting and leads one to speculate that the water containing oxygen is driven increasingly into the boundary layer at the sediment-water interface with the higher velocities and this increased contact causes greater removal of the oxygen from the water. Also, the higher current velocities may drive some of the overlying water into sediments displacing some of the interstitial water. Since the interstitial water will be low in oxygen or even anoxic, this exchange of water will also cause an increased D.O. depletion rate. The cause of the rapid increase of the sediment oxygen depletion rate, Ks with current velocity is worthy of research because it will shed light on both oxygen uptake mechanisms and those controlling the release of nutrients contained in interstitial water.

Linsey and Lasenby (1985), however, achieved relatively good reconciliation of measured uptake rates and observed water column oxygen depletion. K_W and K_S were combined to give a computed VHDR of 0.047 g O_2 m^{-3} day^{-1} which was within 18% of the observed changes from vertical profiles at 0.040 g m^{-3} day^{-1}. They determined K_W using BOD bottles and K_S using cores with an intact sediment-water interface incubated in the dark at in situ temperatures. Linsey and Lasenby were thus able to reproduce the in lake conditions successfully in the laboratory. Rosa and Burns (1987) determined K_W and K_S for the Central Basin differently by analysing VHDR data for different hypolimnion thicknesses collected over many years. In this case these investigators were not constrained by methodological difficulties but by variability in their data.

4) Within-season variation in depletion rates

The D.O. depletion rates within the same season can vary because of the availability of decomposable organic matter. Care must be taken not to measure a depletion rate over part of a season and assume it to be indicative of the whole season rate. As indicated in (a) above, the flux of organic matter can vary substantially which results in changes in the depletion rate. In the Central Basin of Lake Erie, the D.O. depletion rate is usually higher just after stratification as a result of the decrease in the turbulence of the water column. This change causes a large number of the denser diatom species to settle out. The increased flux of organic matter into the hypolimnion results in the early season depletion rates being higher than the later rates (Rosa and Burns 1987).

(5) Temperature effects on oxygen uptake

Biochemical reaction rates are known to be temperature dependent with many authors using a $Q_{10} = 2.0$ for the factor for the change in rate for a 10 degree C rise in temperature (Charlton 1980, Vollenweider and Janus 1982, Rosa and Burns 1987, Edberg 1976). Edberg (1976) used two values; $Q_{10} = 4.3$ for temperatures from 4 to 10°C and $Q_{10} = 2.0$ from 10 to 20°C.

Since temperature corrections can be quite large, they have to be made when comparing results from different lakes, or from the same lake at different temperatures. There has been little work done on biological temperature effects in lakes and most investigators rely on the work of Salisbury and Ross(1978), so the standard temperatures chosen should be as close as possible to the naturally occurring ones to keep the corrections as small as possible.

(6) Downward transport of oxygen

Transport and diffusion of oxygen downward into the hypolimnion occurs in most lakes to a lesser or greater degree and these downward fluxes of oxygen must be taken into account when calculating D.O. depletion rates. Since the upper waters which supply the diffused oxygen are also warmer, increased hypolimnion temperatures usually indicate the incidence of downward diffusion or incorporation of thermocline water into the hypolimnion.

The downward incorporation of thermocline water is relatively rare but it does occur (Ivey and Boyce 1982) and methods of correcting for the effect of such entrainment are given by Burns (1976). Estimation of vertical eddy diffusion below the thermocline in lakes has been carefully examined by Powell and Jassby (1974). They have developed the Flux Gradient method for determining the vertical eddy diffusion coefficient at different depths in lakes if the temperature profile has been carefully measured and there is also information on the absorbance of the water and the radiation energy content of the sunlight. Thus vertical eddy diffusion coefficients can be determined and the downward flux of oxygen from diffusion can be estimated.

(7) Photosynthesis in the hypolimnion

Photosynthetic production of oxygen in the hypolimnia of lakes does occur and may need to be taken into account when calculating D.O. depletion rates. Jassby and Powell (1975) found heating from sunlight below the thermocline down to 25m in Castle Lake and Lucas and Thomas (1970) observed oxygen production on the bottom of Lake Erie at 24m depth. Mitchell and Burns (1979) also found significant oxygen production in the lower layers of Lakes Hayes and Johnson. Shallenberg and Kalff (submitted) found a number of lakes with significant hypolimnetic production.

Measurement of production in hypolimnia will not be necessary in every case because it is not likely to be large and in many situations it can be calculated with adequate accuracy. If one knows the absorbance of the lake water and the secchi disk depth, an estimate can be made of the light intensity likely to be present in the hypolimnion. This together with the equations of McBride (1992) would permit estimation of the hypolimnetic oxygen production.

(8) Delayed decomposition of organic matter

Some of the organic material settling onto the sediments does not decompose in the stratified period when it is laid down. This weakens the correlation between organic matter settling into the hypolimnion and the subsequent uptake of oxygen. In shallower stratified lakes, a good fraction of the material settling onto the sediments may decompose in the isothermal period following the breakdown of stratification. In particular, this carryover of settled material for later decomposition can be unpredictable and can introduce unexplained variability in depletion rates.

The delayed decomposition of organic material can have quite significant effects, especially when there has been a decrease in nutrient loading to a lake with a consequent decrease in loading of organic matter to the sediments. The oxygen uptake of the sediments may then be significantly higher than anticipated because of the delayed oxidation of large amounts of previously sedimented organic material. Di Toro et al. (1987) have addressed this matter seriously and divided the sediment oxygen uptake into the short-term oxygen uptake from surficial organic matter and the long term oxygen uptake from the deep sediment oxygen demand. This 'historical' oxygen demand should be taken into account when considering lake response to decreased external load. This remains an area requiring further research.

(9) Effects of inflows

River inflows to lakes can transport oxygen to the hypolimnion if they plunge after entering the lake. Rivers entering a lake can be colder than the lake water and the inflow can submerge under the epilimnion and enter the hypolimnion directly. This can happen in Lake Taupo (Gibbs pers comm) and does happen in Lake Rotoiti (Vincent et al 1984, Gibbs 1992). The oxygen added to the hypolimnion by this process would have to be quantified, probably by extensive field work.

(10) Effects of allocthonous input

Unexpectedly high D.O. depletion rates can result from a significant amount of allocthonous organic matter entering lakes. In small lakes this material can be blown in, and in both big and small lakes, the organic content of inflowing rivers waters may need to be taken into account when calculating D.O.depletion rates. Gibbs (1986) has demonstrated the effect of different BOD concentrations in the Lake Rotorua water flowing into Lake Rotioti on the hypolimnetic oxygen concentrations in that lake.

3. The use of D.O. depletion rates

One could wonder whether D.O. depletion rates are worth determining in light of the 10 complicating processes described above as they all alter the D.O. depletion rates and thereby weaken the relationship between observed oxygen depletion and trophic state. Further, does making the appropriate adjustments to depletion rates to obtain values for D.O. depletion rate for the decomposition of autocthonous organic carbon (OUR) turn each determination of the organic uptake rate (OUR) into a major investigation?

These are valid questions but fortunately only a few complicating processes occur in each case and the calculation of the OUR can be relatively straightforward for many lakes. However, this is not always the case and the interpretation of D.O. depletion rates can cause consternation.

The Central Basin of Lake Erie provides an example of the problems which can arise in depletion rate calculations. This basin was documented as having areas of anoxic water which could vary considerably in extent each year (Burns 1985, Di Toro et al. 1987). The residents of this lake's catchment wished to eliminate the occurrence of anoxia to improve the condition of the lake. This could be done by decreasing phosphorus loads to the lake. The question then arose as to how much the phosphorus loading should be reduced to eliminate the anoxia. This issue became very involved because some scientists claimed that there was no trend of increasing hypolimnetic D.O. depletion rates with time or with increased phosphorus loads (Barica 1982) while others claimed that there was such a relationship. The reason for this confusing state of affairs was that almost all of the complicating factors described in sections 2(1) to 2(10) above operated in the Central Basin.

The Central Basin of Lake Erie is large basin of approximately 15000 km^2 but having a maximum depth of only 25 m and a hypolimnion thickness which varies significantly each year. The algal sequences vary from year to year as does the length of the stratified season. Both the hypolimnion temperature and its warming rate vary each year and so does the magnitude of downward transfer of oxygen from thermocline and surface waters. Hypolimnetic interflows also occur between the Central and East Basins. Thus the final VHDRs calculated by the various scientists differed according to the various correction factors and assumptions which they made. Charlton (1980b) corrected the available data for variations in hypolimnion thickness and temperature. He found no increase in his adjusted D.O. depletion rates with time from 1929 to 1978. Rosa and Burns (1987) corrected for hypolimnion interflow, thickness, temperature and downward mixing of oxygen as well as the dependence of the depletion rates on the period within each season. They found an increase in their standardised VHDR rates with time from 1929 to 1975 which paralleled the phosphorus load which had increased until 1968 (Fraser 1987). Their values for the VHDR levelled out after 1975 giving an indication of a 7 year time lag in the D.O. depletion rate response to the phosphorus load. At the same time a very sophisticated modelling exercise was carried out by Lam, Schertzer and Fraser (1987) to interrelate the weather effects, phosphorus loadings, algal production and sediment oxygen demand on oxygen depletion in the years 1967 to 1982. After filtering out the effects of the weather and phosphorus loadings in the different years, they showed quite clearly that the extent of anoxia had decreased from about 1975 onwards, in basic agreement with the results of Rosa and Burns (1987).

4. Modelling oxygen depletion rates.

Further evidence that oxygen depletion rates are predictable in spite of the many complex factors involved, is that a number of models exist which can predict D.O. depletion rates if the limits of the models are observed.

Cornett and Rigler (1979) proposed a model based on three dominant factors namely; the phosphorus retention factor, hypolimnion temperatures, and hypolimnion thickness. Charlton's (1980a) model is similar to Cornett and Rigler's but replaces the phosphorus retention factor with Chla, a measure of chlorophyll concentration. Both of these models predicted areal depletion rates, AHDR, with reasonable accuracy over a wide range of rates. Vollenweider and Janus (1982) modelled the volumetric depletion rate, VHDR, after standardising all the depletion rates to a temperature of $4^{\circ}C$ using a Q_{10} of 2.0. Their model depended on Chla and the ratio of V_e / V_h, where V_e is the volume of the photic zone and V_h is the volume of the tropholytic zone. (The tropholytic zone is that part of a lake where no photosynthesis takes place). Their model also provides good approximate predictions. Molot et al (1990) also developed a model based on 32 northern Canadian lakes which would predict end-of-summer oxygen concentrations at number of depths in each lake. Their model works well for the type of lake modelled and only requires input data on spring oxygen concentrations, lake morphometry and total phosphorus concentrations. Interestingly, the model demonstrated that the oxygen conditions in the lakes were extremely sensitive to the epilimnetic total phosphorus concentrations. Naturally none of the models can provide a precise prediction of depletion rates, with many of the predictions being incorrect by 100% or more. However, these predictions are relatively good considering the order of magnitude differences in the rates being modelled.

Conclusions on hypolimnetic oxygen depletion

1. Simple hypolimnetic oxygen depletion rates, VHDR are seldom the rates resulting from degradation of organic materials since they have been altered by physical and biological perturbations.

2. Accurate determination of the hypolimnetic volumetric oxygen uptake rate due to decomposition of organic carbon, OUR, is possible but does require knowledge of the physical phenomena occurring in the lakes under investigation. Adjustments can then be made so as to calculate the depletion rates due to organic uptake.

3. Corrections cannot be easily made for biological factors such as the variable fraction of epiliminetic production settling into the hypolimnion. In cases of high variability from biological causes, depletion rates will have to be determined for a number of years until underlying trends become manifest.

4. Changes in OUR are probably most easily detected when oligotrophic lakes become more eutrophic, because significant increases in the depletion rate are often obsereved when this happens. When changes occur in lakes that are already eutrophied there is

probably relatively less change to the depletion rates because of modification of algal behaviour and the increased storage of organic carbon in the sediments.

5. OUR are a very good tool to monitor oligotrophic lakes (with average secchi disk readings above 5m) but are less effective with more eutrophic lakes. However if these rates are combined with observations on water clarity, algal species and nutrient concentrations while corrections are made for physical perturbations to the systems, OUR will be an effective monitoring tool with eutrophic systems as well.

6. Research needs to be carried out on determining correct depletion rates due to organic degradation in New Zealand because of the many different types of stratified lakes found in this country. OUR would provide a most useful monitoring tool for New Zealand lakes.

7. Research should be conducted into the dependence of OUR on oxygen concentration in water.

8. Research into the reasons for the strong dependence of sediment oxygen uptake, Ks, on the velocity of the overlying water would be important for the modelling of oxygen uptake by the sediments and nutrient release from the sediments.

9. After the decrease in the external loading of nutrients to a lake, there is always an excess oxygen demand in the sediments. An important research investigation would be into the magnitude of the residual excess sediment oxygen demand and its decrease with time until it is in equilibrium with the external loads to the lake. This process largely controls the rate at which a lake adjusts to its new equilibrium state after a change in external loading. This topic links strongly with No. 8 above.

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