Mechanisms of the Deoxygenation of the Hypolimnia of Lakes[1]

G. Fred Lee and Anne Jones-Lee
G. Fred Lee & Associates, El Macero, CA 95618

Abstract

The deoxygenation of the hypolimnia of lakes and reservoirs normally occurs as a combined result of the sediment oxygen demand and the oxygen demand of the algae and other plant materials that grow in the epilimnion. For some waterbodies, there may be appreciable amounts of oxygen-demanding material brought in from the watershed, but this is usually a relatively unimportant source of oxygen demand in the hypolimnion of lakes and reservoirs. This report reviews the work that has been done as part of the US OECD Eutrophication Study during the 1970's on the relationships between the phosphorus loads to waterbodies and their hypolimnetic oxygen depletion rates. In the US OECD Eutrophication Study and follow-on work done by the authors, data for approximately 750 US lakes and reservoirs have been evaluated for P loads and eutrophication-related water quality response. Regressions have been developed for these waterbodies between the normalized phosphorus loads to waterbodies and the planktonic algal chlorophyll, Secchi depth, and areal hypolimnetic oxygen depletion rate. The phosphorus load is normalized based on the waterbody's mean depth, hydraulic residence time and surface area.

Examination of the oxygen profiles in the hypolimnia of many lakes has shown that the primary mechanism of deoxygenation is the oxygen consumption associated with the decomposition of dead algae raining down from the epilimnia. In many waterbodies, the sediment oxygen demand is controlled primarily by inorganic reactions of ferrous iron and sulfide with dissolved oxygen. This demand is normally exerted within 1 to 2 m of the sediment in the waterbody's watercolumn. The relative significance of sediment and algal-related oxygen demand to hypolimnetic oxygen depletion can be assessed through the use of the US OECD load - response models.

Key Words: dissolved oxygen, oxygen depletion, hypolimnion, oxygen demand, BOD, eutrophication, sediment oxygen demand

Introduction

There are basically three factors that contribute to the deoxygenation of the hypolimnetic waters of lakes and reservoirs. One is the biochemical oxygen demand (BOD) of the planktonic algae produced in the epilimnion of lakes, which die and sink into the hypolimnion. Another is the oxygen demand of lake sediments. The third is certain chemicals, such as ammonia and biodegradable organics, developed within the lake or derived from the watershed. There is considerable confusion in the literature surrounding the relative significance of these factors and the influence of other factors on the deoxygenation of hypolimnia. For example, there are discussions in the literature of the role of domestic and other wastewater BOD in such deoxygenation. There is also controversy over the relative significance of the oxygen demand of organic and

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[1] Report of G. Fred Lee & Associates El Macero, CA (1999) gfredlee33@gmail.com www.gfredlee.com

inorganic components of waterbody sediments in the oxygen depletion of hypolimnetic waters. The current understanding of these factors in causing deoxygenation of hypolimnetic waters of lakes and reservoirs is addressed in this paper.

One approach that has been found useful in identifying those factors which have a major impact on hypolimnetic oxygen depletion for a given waterbody was developed in the US OECD Eutrophication Study (Rast and Lee 1978; Lee *et al.* 1978). This study produced empirical regressions between planktonic algal biomass in epilimnetic waters and the rate of oxygen depletion in hypolimnetic waters. The results of the US OECD study indicated that planktonic algal growth is typically the source of greatest importance in dictating the oxygen depletion rate in the hypolimnia of waterbodies. This paper discusses the use of the OECD eutrophication modeling approach for evaluating oxygen depletion in hypolimnia of lakes and reservoirs.

Review of US OECD Eutrophication Study Results

In the early 1970's, the Organization for Economic Cooperation and Development (OECD) initiated an 22-country, 200-waterbody, $50 million, 5-year study to examine the relationships between nutrient (phosphorus) loads to waterbodies and their eutrophication-related water quality. It incorporated as a basis the work of Vollenweider (1968, 1976) which had shown evidence for a regression relationship between the phosphorus load to a waterbody (normalized by mean depth, hydraulic residence time and waterbody area), and the planktonic algal chlorophyll concentration, a measure of algal biomass, in the waterbody. The US portion of this study conducted by the senior author and his associates under contract with the US EPA, involved the investigation of load - response relationships for about 30 US waterbodies or parts of waterbodies. Completed in 1976, this study identified empirical relationships between Vollenweider's normalized P loading term and planktonic algal chlorophyll, Secchi depth, and hypolimnetic oxygen depletion rate. The results of the US OECD Eutrophication Study were published by the US EPA (1977) and summarized by Lee *et al.* (1978). The international OECD eutrophication study results were published by OECD (1982).

Since the completion of the US OECD Eutrophication Study, the authors have continued to evaluate the P load - response relationships developed for the breadth of their applicability to other waterbodies, and published an update of the US OECD study results based on data collected on an additional approximately 50 US waterbodies (Jones and Lee 1982, 1986). Figure 1 presents these updated load - response relationships. Figures 1 A, 1 B and 1 C provide each of the component figures shown in Figure 1. Figure 1 A presents the updated information on the P load Chlorophyll relationship based on the supplemental studies of Jones and Lee (1986). Vollenweider (OECD 1982) found that these relationships were the same as those developed from the international OECD eutrophication study. Rast *et al.* (1983) also demonstrated the capability of these models to predict the eutrophication-related water quality response of waterbodies to alterations in their P loads.

Examination of Figure 1 and 1 A shows that through the P loading term, there is a relationship between epilimnetic, planktonic algal concentration as measured by chlorophyll, Secchi depth, and the hypolimnetic oxygen depletion rate. This would be expected because the phosphorus load to a waterbody

Figure 1 Relationship Between P Load Eutrophication Response

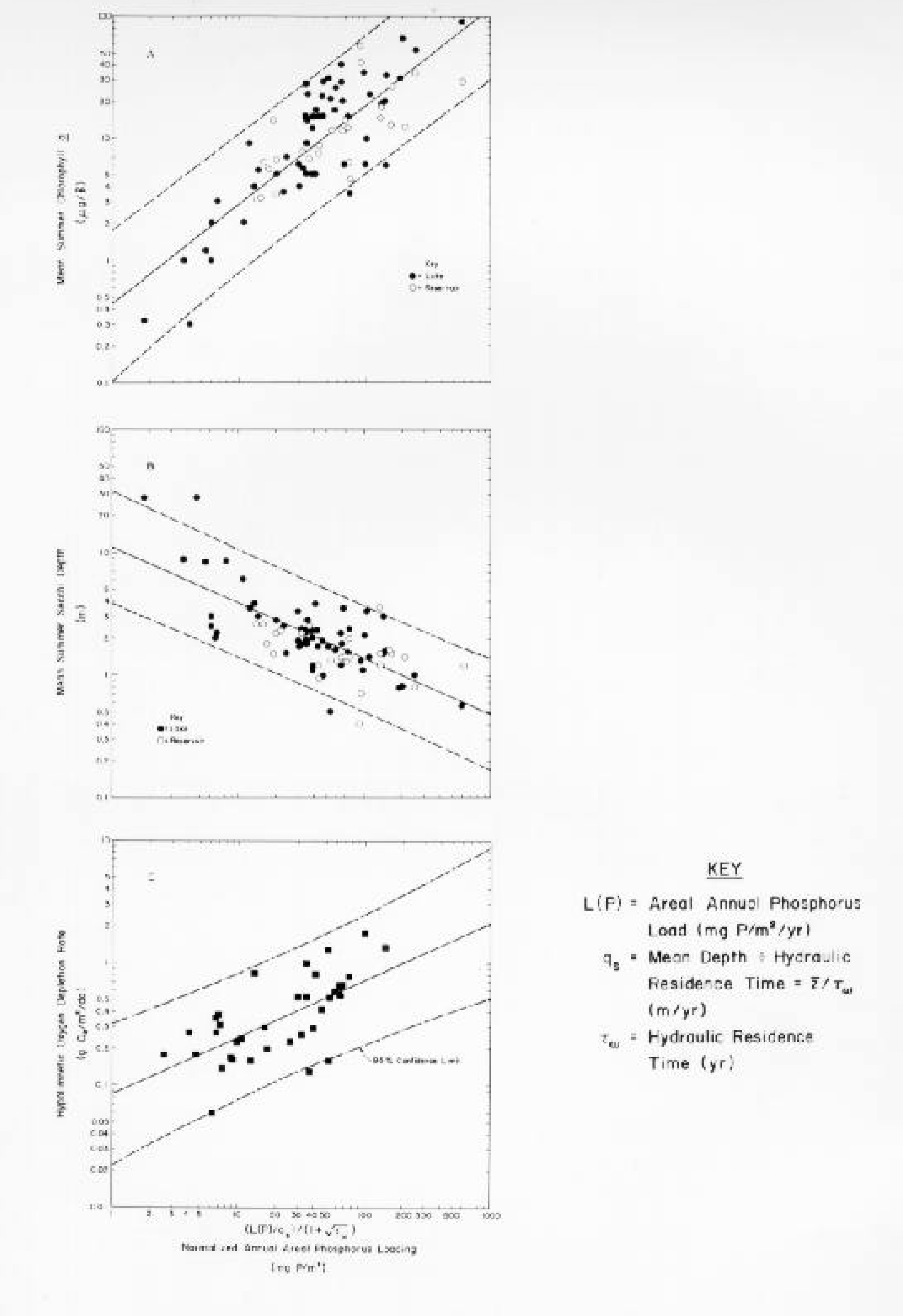
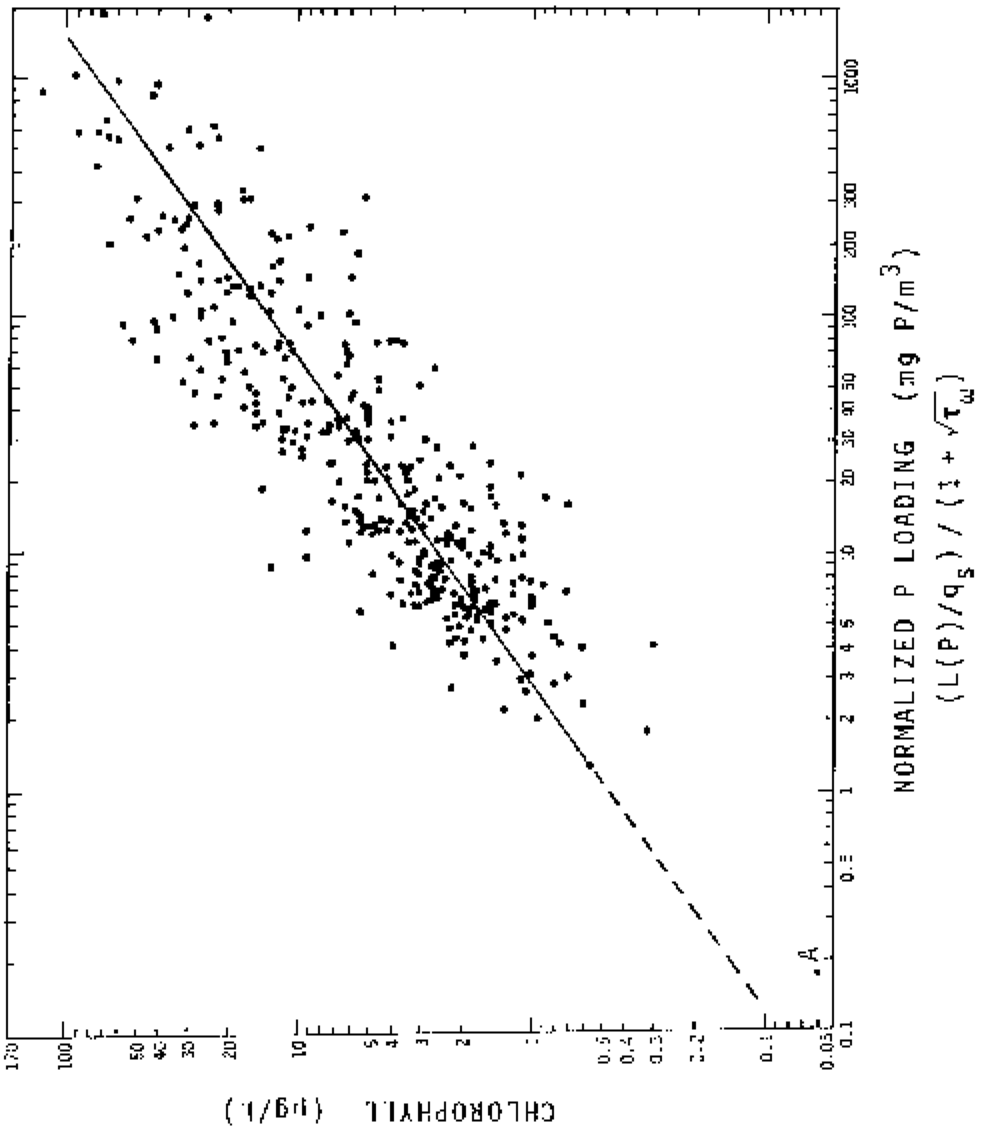


Figure 1 A



NORMALIZED P LOADING (mg P/m^3)
$(L(P)/q_s)/(1+\sqrt{\tau_\omega})$
CHLOROPHYLL (µg/l)
0.1
0.5
1
2
3
4
5
10
20
30
40
50
100
200
300
1000
170
100
50
40
30
20
10
5
4
3
2
1
0.5
0.4
0.3
0.2
0.1
0.05
A

Figure 1 B

Relationship between Normalized P Loading and Water Clarity (Secchi Depth)

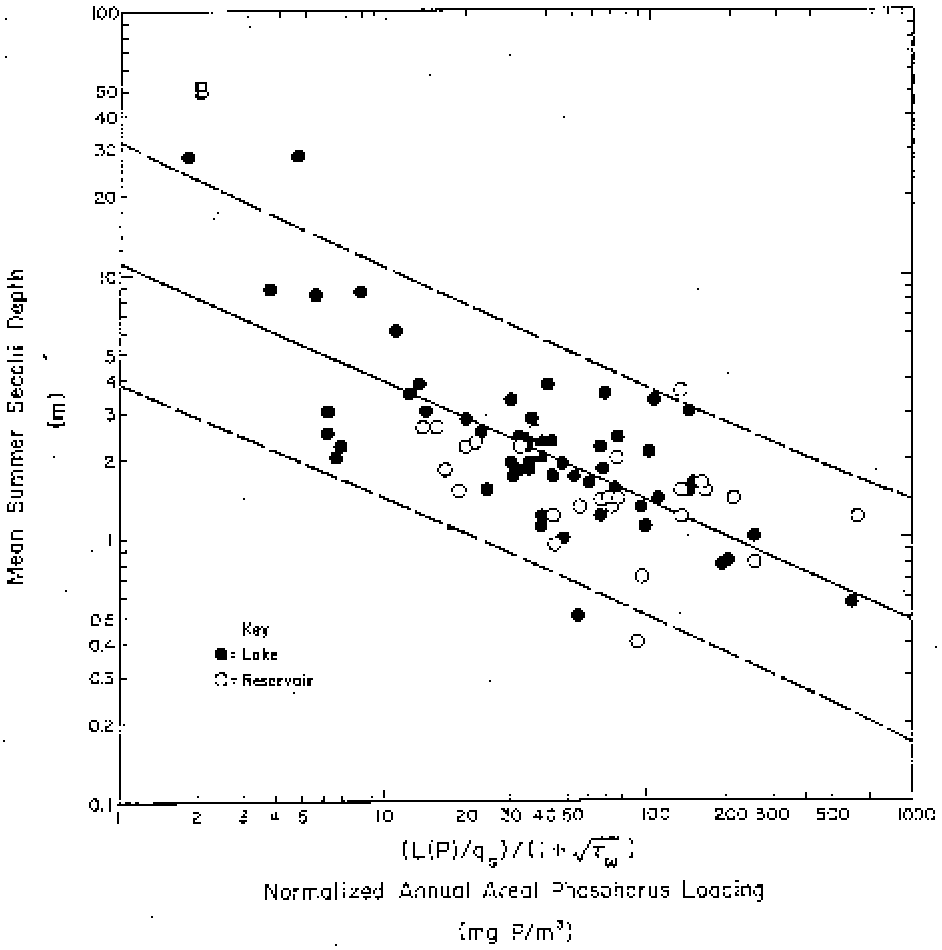
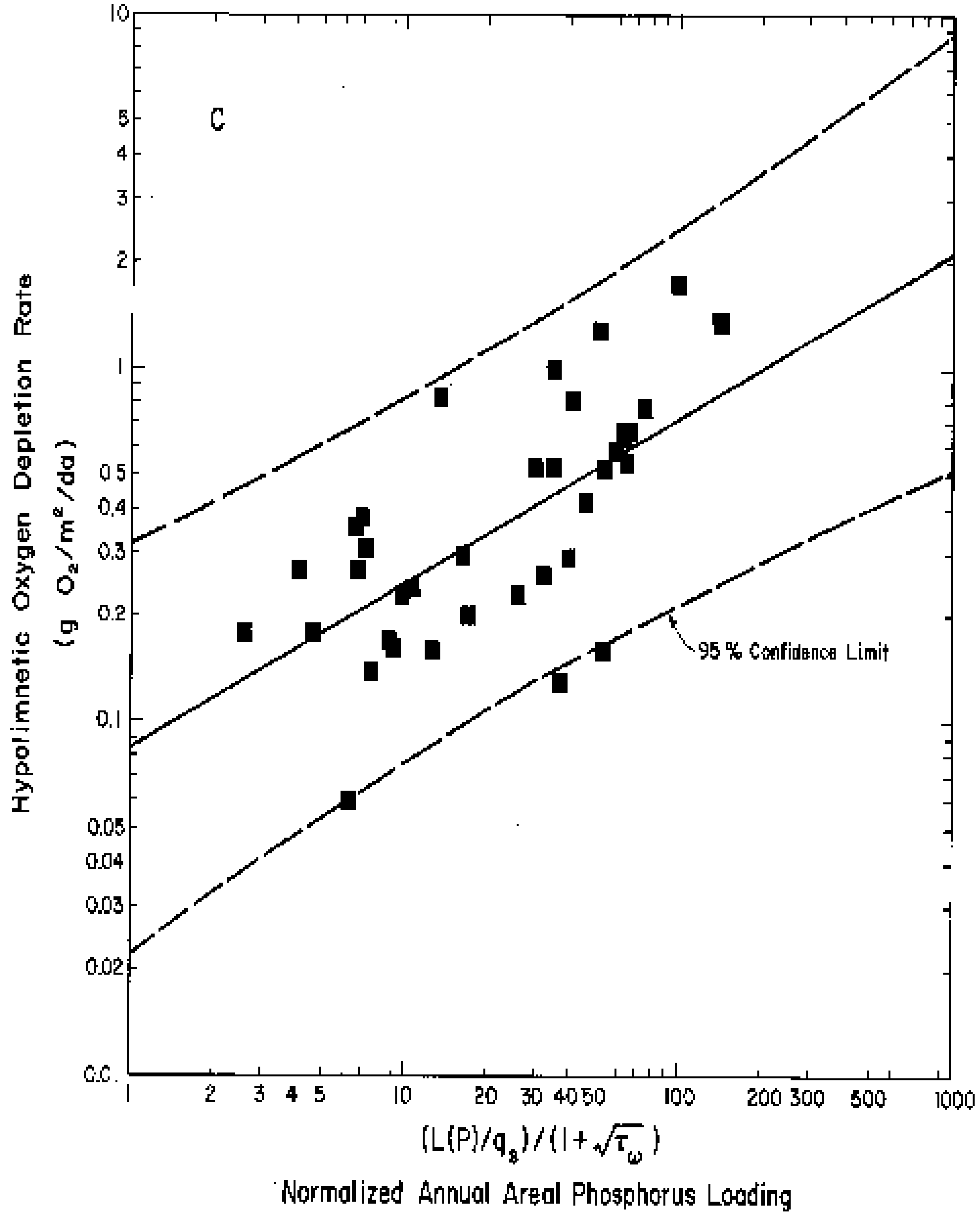


Figure 1 C


C
10
5
4
3
2
1
0.5
0.4
0.3
0.2
0.1
0.05
0.04
0.03
0.02
0.C.
Hypolimnetic Oxygen Depletion Rate
(g $O_2/m^2/da$)
95% Confidence Limit
1
2
3
4
5
10
20
30
40
50
100
200
300
500
1000
$(L(P)/q_s)/(1+\sqrt{\tau_\omega})$
Normalized Annual Areal Phosphorus Loading
(mg P/m^3)

is related to the phosphorus concentration within the watercolumn, which in turn, is related to the amount of algal biomass that can be supported in the water, and thus the water clarity. The phytoplankton produced in the surface waters represent for most waterbodies, the most significant source of oxygen demand in the waterbody's hypolimnion. This arises from the fact that for every phosphorus atom incorporated into an algal cell, approximately 16 nitrogen atoms and 106 carbon atoms are also incorporated into the cell. Upon the death of an algal cell, 212 oxygen atoms are required to oxidize to CO_2 the 106 algal carbon atoms associated with one atom of P. If the oxidation of the nitrogen in the cell to nitrate is also considered, then one phosphorus atom will ultimately "consume" 276 oxygen atoms in the exertion of planktonic algal BOD in the hypolimnion of a waterbody.

Hutchinson (1938) noted a proportionality between hypolimnetic oxygen deficit normalized by hypolimnion area, and the standing crop of seston in a waterbody. Lasenby (1975) described a correlation between areal hypolimnetic oxygen depletion rate and Secchi depth for 20 waterbodies. Following these investigators' work, Rast and Lee (1978) normalized their oxygen depletion rate data by the area of the hypolimnion to develop the regression shown in Figure 1 C. As discussed in a subsequent section, a number of investigators have reported that the areal rate of oxygen depletion changes over the depth profile of the hypolimnion but that the errors in overall depletion rate estimation caused by this variable rate would not likely be great. Variations in the depths at which the dissolved oxygen concentrations were measured may, however, have contributed to the deviation of the data from the regression line in Figure 1 C.

Vollenweider (Vollenweider and Janus 1982) has continued to explore empirical relationships to describe the hypolimnetic oxygen depletion rate as a function of epilimnetic chlorophyll concentration. The models he has developed describe the monthly, volumetric, hypolimnetic oxygen depletion rate as various functions of average, annual chlorophyll concentration modified by various combinations of morphological characteristics of the waterbody. As indicated by Vollenweider (Vollenweider and Janus 1982), the oxygen depletion rates estimated correspond well with those values measured, and can be translated into P load via the OECD P load - response relationships. It should be noted, however, that the Vollenweider relationships would not have significant applicability to waterbodies in which the oxygen depletion rate in the hypolimnion is controlled primarily by the abiotic reactions that occur in the sediments. This point is discussed further in a subsequent section.

Mechanisms of Oxygen Depletion

Studies by Conway (1972) on Lake Mendota, WI showed that there are three regions in the hypolimnion of this and other lakes which should be recognized in assessing hypolimnetic oxygen depletion rates and mechanisms of depletion. One of these is the area immediately beneath the thermocline which may at times be under the influence of the epilimnetic waters. The second is the water near the sediment/water interface (beneath the area of influence of the thermocline). The third is the open water between the two above mentioned zones. The oxygen depletion and depletion rate of the first zone is of concern because this area in some waterbodies is apparently a micro-environment which will support cold water fish when the main body of the hypolimnion becomes anoxic and the epilimnetic waters become too warm. It is not an area in which oxygen depletion can be readily modeled, however, in that its characteristics are influenced largely by diffusion of oxygen from the epilimnion to the hypolimnion and thermocline migration which is controlled primarily by climatic conditions. It is also not the region addressed by the P load - response models shown in Figure 1C. In the other two zones oxygen depletion occurs by distinctly different mechanisms.

Oxygen Depletion in the Watercolumn

In most waterbodies, the oxygen depletion in the main body of water in the hypolimnion is related to the trophic state-algal production of the waterbody. It is primarily the bacterial decomposition of the algae which had been produced in the epilimnion and settled through the thermocline into the hypolimnion that exerts the BOD in these waters. Fitzgerald (1964) measured the BOD of living and dead algal cultures and found that the oxygen consumption associated with incubation of dead algae for 5 days, 0.44 to 0.48 mg O_2 mg/L suspended solids (algae), was about 4 times that of dark incubation of living cultures. In his test systems 1 mg suspended solids contained about 1 x 10^8 algal cells. If it is assumed that algal cells contain on the order of 0.1 to 0.4 mg P/100 mg algae (Fitzgerald and Uttormark 1973), Fitzgerald's cultures were consuming 100 to 450 mg O_2 mg/L P in 5 days, which is on the same order as the theoretical oxygen consumption based on the N:P:C ratios previously discussed and the amount of oxygen required to convert algal carbon to CO_2. The BOD or respiration of living algae would not be expected to be of great significance in the depletion of oxygen in the hypolimnion because of its comparatively slow rate and because the hypolimnion is generally beneath the photic zone.

Allegations are sometimes made that the BOD of a domestic or industrial wastewater added to a waterbody or its tributaries will be of significance in the depletion of oxygen in the waterbody. While this is possible under certain conditions, it is not true for many waterbodies. The waters of most eutrophic lakes or reservoirs have 5 day BOD values on the order of 2 to 3 mg O_2/L. Because of the tremendous assimilative capacity of most epilimnetic waters, or of a waterbody as a whole during nonstratified periods, it would take a massive BOD loading to reduce the dissolved oxygen concentration significantly. To affect the hypolimnetic dissolved oxygen, the high-BOD wastewater would have to enter this part of the lake directly. This would not likely occur unless there were appreciable density currents within the waterbody that would transport the tributary or discharge waters to the hypolimnion during periods of stratification. The distinction between the potential impact of wastewater BOD discharged to a stream and that discharged directly to a lake or reservoir should be recognized.

Sediment Oxygen Demand

The bottom sediments of a hypolimnion (outside of the area impacted by the thermocline) can affect oxygen depletion of hypolimnetic waters but their sphere of influence is usually restricted to 1 to 2 m above the sediment/water interface. Except in certain systems having shallow hypolimnia, sediment oxygen demand is generally not of major significance to the overall oxygen depletion or oxygen depletion rate of the hypolimnion. The demand of the sediment and the exertion of this demand are controlled primarily by abiotic processes: oxidation of reduced chemical species in the sediments, and the hydrodynamics of the system.

Inorganic Chemical Oxidation

Aquatic sediments and their interstitial waters are largely anoxic (Lee and Jones 1983) and contain reduced forms of a variety of chemicals which can be oxidized when they come in contact with oxygen-containing waters. The oxidation of sulfide (Chen and Morris 1972) and ferrous iron (Stumm and Lee 1960, 1961) is essentially instantaneous under most natural water pH conditions. As reported by Lee and Jones (1983) iron sulfide and polysulfide precipitates associated with sediments react somewhat more slowly with oxygen because of the build-up of hydrous iron oxides on their surfaces. The rates of these reactions appear to be controlled by the rates of oxygen diffusion through this coating and are thus site-specific.

Another chemical species present in many lake and reservoir sediments in sufficient concentrations to exert a potentially significant oxygen demand at the sediment/water interface is manganese II. However, as discussed by Delfino and Lee (1968, 1971) the kinetics of the reactions between dissolved oxygen and manganese II are sufficiently slow at typical hypolimnetic pH values to cause this reaction to be of limited importance as a source of oxygen demand in most lakes.

The chemical that in some instances exerts an appreciable oxygen demand in the hypolimnia of lakes is ammonia. Every mg N of ammonia consumes about 4.6 mg O_2 when the ammonia is oxidized (nitrified) to nitrate. This reaction is a biotic reaction which proceeds at a relatively slow rate, having a half-life of days to weeks depending on the characteristics of the aquatic system. Since lake sediments typically contain large amounts of ammonia, the release of ammonia from the sediment/interstitial water system into the overlying waters is a source of oxygen demand in essentially all waterbodies. Newbry *et al.* (1981) found that ammonia present in Cherokee Reservoir of the TVA system at the onset of thermal stratification likely accounted for as much as 40% of the total oxygen demand in the hypolimnion of that reservoir. If the total ammonia at the time of thermal stratification of a waterbody is greater than about 0.5 mg N/L, then the nitrification of ammonia is likely to be an important factor in deoxygenation of the hypolimnion of the waterbody. The deoxygenation due to ammonia occurs as long as oxygen is present. When the dissolved oxygen concentration is at or below about 1 mg/L, denitrification can become an important reaction, in which nitrate would serve as an electron acceptor, with the resultant formation of nitrogen gas and possibly some gaseous oxides of nitrogen.

Organic Material Oxidation

There are several types of organic materials that should be considered in evaluating the deoxygenation of the hypolimnion of a lake or reservoir associated with bottom sediments. First and foremost is the BOD of the dead algae. These biotic reactions take place not only in the watercolumn but also in the oxic area of the sediments. The relative distribution of watercolumn versus sediment demand depends on the rate of settling of the dead algae and the depth of the hypolimnion. However, the inorganic oxygen demand of the sediments generally far exceeds the oxygen demand of any recently deposited algae. While the much of the inorganic oxygen demand reactions can take place in a few minutes to a few hours, the organic oxygen demand take place over a week or more dependent on temperature of the water. In many waterbodies, oxygen depletion near the sediment/water interface is due principally to abiotic rather than biotic reactions. However, the biotic oxygen demand is important in maintaining the reducing conditions within the sediments. It was the original deoxygenation of the sediments by the BOD of algae that enabled the build-up of large amounts of ferrous iron and sulfide in the sediments. If it were not for the annual deoxygenation of the hypolimnion arising primarily from the BOD of the algae produced in the epilimnion, the reduced species in the surficial sediments would eventually be oxidized.

Hyrodynamics/Mixing

Generally the most important factor governing the rate and degree of exertion of oxygen demand by organic and inorganic constituents of the sediments and interstitial waters is the amount of mixing that occurs both within the sediments and between the sediments and the overlying waters (Lee 1970). The suspension of sediments into the watercolumn by wind-induced currents, by the activities of aquatic organisms, or by man's activities (e.g., boat traffic) serves not only to expose reduced chemical species associated with particulates not otherwise exposed to the watercolumn, but also to mix-exchange interstitial water with the overlying waters thus accelerating the diffusion of reduced species such as ferrous iron, sulfide, and ammonia out of the anoxic interstitial waters into the watercolumn where they can be oxidized, and promoting the diffusion of oxygen into the interstitial waters.

As discussed by Lee (1970), organism-induced mixing of contaminants within the sediment/interstitial water system and between sediments and overlying water is a much more important factor in sediment/water exchange of contaminants than has generally been recognized. The relative significance of these physical processes in determining the oxygen depletion that occurs at the sediment/water interface, is sediment-system-specific, but the overall mass transport between the sediments/interstitial waters and the overlying waters is likely to be primarily controlled by physical mixing of the interstitial water with the overlying waters.

Coupling of Sediment Oxygen Demand with Watercolumn Oxygen Demand

Hutchinson (1957) suggested that the oxygen demand profile of the hypolimnia of many lakes having a high sediment oxygen demand resembles an exponential curve, with the greatest demand being exerted near the sediment/water interface. Conway (1972) and Lee *et al.* (1983) pointed out that the rate of exertion of oxygen demand in the watercolumn of Lake Mendota, as well as other waterbodies, was zero order with respect to O_2 the water column and first order with respect to O_2 near the sediment/water interface. A zero order expression would be expected for the watercolumn not influenced by the sediments because the rate of oxygen utilization by bacteria in the decomposition of algae is normally independent of the oxygen concentration. The rate of oxygen depletion near the sediment/water interface however is controlled by the rate of diffusion of oxygen and other chemicals and can thus be described by first order kinetics. In most lakes, the rates for these two reactions can be determined by plotting dissolved oxygen concentrations as a function of time from the onset of thermal stratification at a meter or two below the thermocline and at about a meter above the sediment/water interface.

Implications of Hypolimnetic Deoxygenation Mechanisms for Application of US OECD Eutrophication Study Results

As discussed earlier, the US OECD Eutrophication Study results provide a basis for estimating the areal rate of deoxygenation in the hypolimnion of a lake or reservoir. Through that study a regression was developed between the phosphorus load to a waterbody (normalized by mean depth, hydraulic residence time, and waterbody area) and the watercolumn hypolimnetic oxygen depletion rate normalized by hypolimnetic area (Figure 1 C). Examination of this figure shows that there is considerable scatter about the line of best fit. This scatter is expected when consideration is given to the wide variety of factors that influence the areal rate deoxygenation of the hypolimnia of lakes and reservoirs, including initial temperature and the depth of measurement. It is somewhat surprising that a sufficiently close fit has been developed to enable this relationship to be used for some waterbodies to estimate the impact of altering phosphorus loads on the rate of hypolimnetic deoxygenation.

Certain precautions should be exercised in using these results in predicting the impact of altering phosphorus loads on hypolimnetic deoxygenation. First and foremost, these results should be applied only to waterbodies whose hypolimnetic oxygen depletion rates are controlled primarily by planktonic algal BOD. Those waterbodies in which the abiotic oxygen demand of the sediment dominates the deoxygenation of the hypolimnion will not likely show a high degree of correlation between the normalized phosphorus load and areal hypolimnetic oxygen depletion rate. The measurement of oxygen concentration with depth in the hypolimnion at about weekly intervals over the period of stratification can be used as a guide to estimate the relative significance of the BOD of algae raining down from the epilimnion and the abiotic diffusion-controlled sediment oxygen demand.

A sediment demand would be manifested primarily near the sediment/water interface unless the hypolimnion of the lake is rapidly mixed. The sediment demand should be evident from profiles of dissolved oxygen with those samples taken just above the sediment/water interface showing the greatest depletion rate due to this source. Most waterbodies that show significant differences in the hypolimnetic deoxygenation rates over the bottom few meters just above the deepest-water sediment/water interface, will likely show fairly predictable responses in areal hypolimnetic oxygen depletion rates based on altered phosphorus loads provided that the depletion rate is based on dissolved oxygen measurements made a meter or so below the thermocline.

On the other hand, hypolimnia that show little or no vertical deoxygenation gradients, but contain large amounts of readily oxidizable ferrous iron and sulfide in the surficial sediments, will likely have areal oxygen depletion rates which are higher than would be predicted based on altered phosphorus loads. Ultimately, there may be some impact of altering phosphorus loads on the abiotic deoxygenation rate since the magnitude of the ferrous iron and sulfide present in the sediments is ultimately controlled to a considerable extent by the epilimnetic primary production. However, the rate of recovery of the hypolimnetic oxygen depletion rate will likely be far longer than that predicted based on the three times the phosphorus residence time model discussed by Sonzogni *et al.* (Rast *et al.* 1983, Sonzogni *et al.* 1976).

It is important in predicting rates of recovery of hypolimnetic deoxygenation to sort out to the degree possible for a particular waterbody, the mechanisms and factors influencing the rates of deoxygenation. Obviously, if factors other than algal-related BOD are important, then altering the phosphorus load to a waterbody may have limited impact on that waterbody's hypolimnetic oxygen depletion rate. Usually waterbodies of this type can be identified because the deoxygenation rate just below the thermocline would be much greater than that predicted based on the line of best fit for the US OECD Eutrophication Study waterbodies (Figure 1 C).

A special situation exists in some reservoirs that must be considered in utilizing the normalized phosphorus load-oxygen depletion rate relationship developed by Rast and Lee (1978). This is related to the withdrawal of water from the hypolimnion. Such withdrawal could significantly affect the volume of the hypolimnion. Depending on when the planktonic algal primary production occurs, it could be found that the normal lake and reservoir deoxygenation rates would be significantly affected. These rates could be either increased or decreased by hypolimnetic water withdrawal depending on the morphology of the waterbody.

Another aspect of hypolimnetic water removal which affects deoxygenation of the hypolimnia of reservoirs is that some water intake structures, located in the hypolimnion, create flow lines into the structure which remove a mixture of epilimnetic and hypolimnetic waters. This situation was found by Lee and Jones in their study of Fossil Creek Reservoir located near Fort Collins, CO (Lee and Jones 1982). The withdrawal of epilimnetic waters with the hypolimnetic waters significantly affected the deoxygenation of the hypolimnion of this reservoir.

It is important in predicting the impact of altering the phosphorus loads on the hypolimnetic oxygen depletion to also carefully evaluate the dominant water flow regimes into and out of the waterbody, such as short-circuiting and density currents, since this could significantly affect the deoxygenation rates of the hypolimnion. An example of the importance of understanding the hydrodynamic regimes existing in a reservoir occurs in systems in which there is a series of reservoirs on a particular river. The hypolimnetic release of an upstream reservoir would normally be colder than downstream reservoir surface waters and, therefore, would tend to enter the hypolimnion of the downstream reservoir. If the upstream reservoir hypolimnion is appreciably deoxygenated, then this reservoir's releases could exert additional oxygen demand on the hypolimnion of the downstream reservoir. It is important in applying the US OECD Eutrophication Study results to properly account for such demands since they are not related to the phosphorus loads to the downstream reservoir.

Hypolimnetic Oxygen Demand in Lake Mendota, WI

Conway (1972) and Lee *et al.* (1983) found that the zero order oxygen depletion rate in the Lake Mendota, WI watercolumn 8 m or so above the sediment/water interface (in the main body of the hypolimnion) had increased significantly over the 60-year period (1910 to 1970) for which there were oxygen depletion data. These changes were attributed to the increase in intensity of agriculture and urbanization in the Lake Mendota watershed which had occurred during that period, and which would have increased the phosphorus load to the lake (Conway 1972; Lee *et al.* 1983). If the oxygen depletion rates computed are normalized by hypolimnetic area and are translated through the OECD normalized P loading term in Figure 1 B, to corresponding Secchi depth values, Lee *et al.* (1983) showed that the predicted Secchi depths for that period matched the recorded Secchi depth values.

It was evident from the studies of Conway (1972) that the zero order watercolumn hypolimnetic oxygen depletion rate of a lake shows marked year-to-year variations. One of the factors that would influence this rate is the temperature of the water at the time of thermal stratification. A thermocline that sets in earlier than normal in the spring would tend to produce a colder hypolimnion. As a result, the rate of exertion of algal BOD will be slower, leading to less oxygen depletion in the hypolimnion of the waterbody. Another variable that would cause variations in the oxygen depletion rate from year to year is the phosphorus load. It is well known (Jones and Lee 1982) that the P load to, and hence the response of, a waterbody has considerable variability year to year, being related to such factors as rainfall. There is evidence from the work of Conway (1972) that the combination of the cold hypolimnion and a smaller than normal spring rainfall resulted in a watercolumn hypolimnetic oxygen depletion rate for Lake Mendota in 1972 that was significantly lower than had been experienced during the 1960's and the 1970's. It is important in assessing the watercolumn hypolimnetic oxygen depletion rate of a lake to be certain that if a single year's data are used, they be representative of "typical" conditions, or that at least three years of data are evaluated. The latter is the preferable approach.

The studies of Conway (1972) and Lee *et al.* (1983) have shown that the first order oxygen depletion rates for the Lake Mendota waters just above the sediment/water interface have not changed during the 60-year period for which there is data. This is to be expected since these rates are not controlled by the trophic state of the waterbody, but rather by mixing and diffusion controlled processes involving abiotic, fairly rapid reactions between oxygen and iron and sulfide species. The chemical conditions of the sediments are maintained by the hypolimnion's becoming anoxic each summer.

While not experienced in Lake Mendota, there are waterbodies which have fairly shallow, well-mixed hypolimnia (such as Lake Erie) which do not show the two distinct deoxygenation rates. Under these conditions, the sediment oxygen demand plays a much greater role in watercolumn hypolimnetic deoxygenation than it does in many waterbodies having deeper hypolimnia. The situation in Lake Erie is complicated by the fact that, at times, the watercolumn of this lake is sufficiently clear so that sufficient light can reach the bottom to stimulate photosynthesis there. According to Burns and Ross (1972), an appreciable benthic algal mat forms at the sediment/water interface of Lake Erie. During the periods of photosynthesis, oxygen is added to the watercolumn. However, eventually, sufficient phytoplankton growth occurs to cause the algal mat to become a significant source of oxygen demand. Normally this type of phenomenon would not occur except in very shallow waters.

Hypolimnetic Deoxygenation as a Trophic State Parameter

The deoxygenation of the hypolimnion is frequently used by limnologists and others to assess the trophic state of a waterbody. This is based on the observation that many eutrophic lakes and reservoirs tend to show appreciable hypolimnetic oxygen depletion. It is well-known, however, that the degree of deoxygenation of the hypolimnion by itself is not a reliable indicator of trophic state because, as discussed previously, the degree of deoxygenation, or decrease in dissolved oxygen concentration, depends on factors other than algal growth, principally the temperature and volume of the hypolimnion which often depend on climatic factors. Thus, there are some waterbodies that are highly eutrophic based on phytoplankton biomass in the surface waters that show little or no deoxygenation in the hypolimnion. A comparison of Lakes Erie and Ontario illustrates this point. These two waterbodies have similar surface areas and support about the same planktonic algal biomass in their surface waters, yet the hypolimnion of Lake Erie shows appreciable deoxygenation while there is essentially no deoxygenation of the hypolimnion of Lake Ontario. This is the direct result of the difference in volume of the hypolimnia of the two lakes.

It is evident from the discussions presented in this report that the proper approach for using hypolimnetic oxygen depletion as a trophic state parameter is to compare the areal rates of deoxygenation of hypolimnetic waters just below the thermocline. In this way, the planktonic algal chlorophyll produced in the surface waters can be related to the deoxygenation rates. However, caution should be exercised in using this approach for waterbodies with hypolimnia only a few meters thick and those that have hypolimnia that tend to be well-mixed. Under these conditions, the abiotic sediment oxygen demand may play a dominant role in determining the hypolimnetic watercolumn deoxygenation rate.

Lee *et al.* (1995) have discussed the importance of clearly distinguishing between limnological and water quality (beneficial use-related) trophic state classifications. Limnological trophic state classifications may evoke hypolimnetic oxygen depletion or depletion rate as a descriptive parameter for whole-lake functioning. However, water quality trophic state classification would focus on hypolimnetic-oxygen depletion rate as a tool for deriving or describing oxygen concentrations in hypolimnia which would be used in evaluating the impact of the resultant dissolved oxygen concentrations on designated beneficial uses of the water such as fisheries, and on potential water quality problems in downstream waters associated with hypolimnetic releases from reservoirs which contain large amounts of iron II, manganese II, and sulfide.

Lee and Jones (1991) discussed the impact of eutrophication on fisheries. They pointed out that the phosphorus loads to waterbodies correlate not only with fish production but also with the quality-desirability of the fishery. Hypolimnetic oxygen depletion rates are of particular importance in North America in influencing fish quality since North Americans as well as many Europeans tend to prefer to eat cold water fish such as trout and salmon over warm water fish. Cold water fish cannot survive in the surface waters of the typical North American lake or impoundment in the summer months because of the high water temperatures, i.e., in excess of 20 C. In order for a lake or impoundment to maintain a cold water fishery, the dissolved oxygen concentration in the hypolimnetic waters must generally be above about 4 mg/L throughout the summer. Whenever the dissolved oxygen drops below this level, some fish are likely to be killed. This does not mean the cold water fish cannot survive in waters containing less than 4 mg/L dissolved oxygen. It mean that the fish are in a more precarious position for finding the right combination of factors to allow their survival.

Effects of Hypolimnetic Deoxygenation on Phosphorus Cycling within Lakes and Reservoirs

It is widely believed that the development of an anoxic hypolimnion in a waterbody significantly affects the internal phosphorus loading of the waterbody which, in turn, contributes to the overall deterioration in the waterbody's overall eutrophication-related water quality. This belief is based on observations of the build-up of phosphorus in anoxic hypolimnia of lakes and reservoirs. However, while there is appreciable phosphorus released under anoxic conditions, there is also appreciable phosphorus released under oxic conditions (Lee *et al.* 1977). Normally, most of the oxic release of phosphorus occurs when the waterbody is mixed and hence the P released can be readily cycled into the photic zone of the waterbody. Anoxic release, on the other hand, occurs below the thermocline, where it cannot generally be mixed to any significant degree into surface waters. Therefore, hypolimnetic phosphorus release normally has limited impact on eutrophication-related water quality during the critical summer months of the year. From a water quality management point of view, an algal bloom associated with fall overturn does not generally impair most beneficial uses of a waterbody.

Terrestrial Vegetation Deoxygenation

A special case of deoxygenation of reservoirs occurs in new reservoirs in which there is flooding of terrestrial vegetation, or in existing reservoirs where the draw down of the reservoir exposes large areas of formerly submerged land for a sufficient time to allow terrestrial vegetation to develop. This terrestrial vegetation, when flooded, can exert a significant oxygen demand on the waters of the reservoir. In the case of the existing reservoirs however, the terrestrial vegetation deoxygenation would usually occur in the shallow areas - epilimnetic waters, not creating a significant oxygen depletion problem for the reservoir. For new reservoirs, in which the flooding covers deeper areas, there will likely be a significant additional deoxygenation during the first year that would probably not occur in subsequent years. The significance of the terrestrial vegetation causing deoxygenation in a particular reservoir has to be evaluated on a site-specific basis.

Prediction of Water Quality in New Reservoirs

One of the key issues that those responsible for the design of a new impoundment that is to be used for hydropower production and/or domestic water supply is the extent of deoxygenation of the hypolimnia that will occur in the waterbody. The relationships shown in Figure 1, 1 C provide a basis by which estimates of the oxygen depletion of the hypolimnion can be made prior to construction of the reservoir. Lee and Jones (1984a, 1984b) have discussed the use of the relationships shown in Figure 1, 1 C for predicting the deoxygenation of the hypolimnion of a new reservoir. This information then can be used to guide the design of the reservoir to address, at the time of construction, potential problems that can develop in the hypolimnion due to low dissolved oxygen on downstream waters associated with hydropower production or for a water utility that wishes to use the higher quality hypolimnetic waters for domestic water supply.

Summary and Conclusions

The oxygen depletion of the hypolimnia of lakes and reservoirs is a two component process. The oxygen depletion of the hypolimnetic watercolumn roughly between the thermocline and several meters or more above the sediments, is due primarily to the biochemical oxygen demand of dead algae raining down from the epilimnion. The rate expression for this reaction is zero order with respect to oxygen. Near the sediment/water interface, oxygen depletion occurs as dissolved oxygen reacts with ferrous iron, sulfide, and polysulfides. The rate of oxygen depletion can be described as first order with respect to oxygen and is controlled by the rate of oxygen diffusion into the sediments and the rates of migration of reduced inorganic species (Fe and S), out of the interstitial waters into the overlying waters. The sediment/water interface oxygen demand is independent of the current trophic status of the waterbody although the trophic status maintains the surplus inorganic oxygen demand of sediments.

The two-component oxygen demand of the hypolimnion of lakes can be formulated into an exponential expression in which the oxygen demand at any depth is the sum of the watercolumn and sediment demand. The coupling of these two demands is accomplished through a vertical mixing coefficient that describes how well the hypolimnion of a particular waterbody is mixed. Measurements of oxygen depletion rates at a depth of 1 to 2 m below the thermocline and 1 to 2 m above the sediment/water interface, coupled with the estimated mixing coefficient produces oxygen concentration - depth profiles for the hypolimnia of the lakes. This approach should be applicable to many waterbodies. However, some have sufficient mixing in the hypolimnion so that the sediment and watercolumn oxygen demands are exerted simultaneously at all depths.

While the degree of oxygen depletion is frequently used as a trophic state indicator for waterbodies, this is an unreliable approach because it does not properly consider the hypolimnetic volume and the role of the abiotic components of sediments in deoxygenation of the hypolimnia. Water quality-oriented trophic state classification should focus on the concentrations of DO in the hypolimnion needed to maintain the designated beneficial use of the waterbody. In order to properly model hypolimnetic oxygen depletion rates in lakes and reservoirs, it is necessary that a much better understanding of the sediment/water exchange phenomenon be developed.

References

Burns, N. M. and C. Ross. "Project Hypo - An Intensive Study of the Lake Erie Central Basin Hypolimnion and Related Surface Water Phenomena," US EPA TS-05-71-208-24 (1972).

Chen, K. Y. and J. C. Morris.. "Kinetics of Oxidation of Aqueous Sulfide by Oxygen," Environ. Sci. and Technol. 6:529 (1972).

Conway, C. J., "Oxygen Depletion in the Hypolimnion," MS Thesis Water Chemistry. University of Wisconsin, Madison (1972).

Delfino, J. J. and G. F. Lee, "Chemistry of Manganese in Lake Mendota, Wisconsin," Environ. Sci. and Technol. 2:1094-1100 (1968).

Delfino, J. J. and G. F. Lee, "Variation of Manganese, Dissolved Oxygen and Related Chemical Parameters in the Bottom Waters of Lake Mendota, Wisconsin," J. Wat. Res. 5:1207-1217 (1971).

Fitzgerald, G. P., “The Effect of Algae on BOD Measurements,” J. Wat. Pollut. Control Fed. 36:1524 (1964).

Fitzgerald, G. P. and P. D. Uttormark. “Applications of Growth and Sorption Algal Assays,” EPA 660/3-73-023, US EPA (1973).

Hutchinson, G. E., “On the Relation Between Oxygen Deficit and the Productivity and Typology of Lakes,” Int. Rev. Gesamten Hydrobiol. Hydrogr. 36:336 (1938).

Hutchinson, G. E., “A Treatise on Limnology”, Vol. I. John Wiley and Sons, New York (1957).

Jones, R. A. and G. F. Lee, “Recent Advances in Assessing the Impact of Phosphorus in Eutrophication-related Water Quality,” J. Water Res. 16:503-515 (1982).

Jones, R. A. and G. F. Lee, “Eutrophication Modeling for Water Quality Management: An Update of the Vollenweider-OECD Model,” World Health Organization's Wat. Qual. Bull. 11:67-74, 118 (1986).

Lasenby, D. C., “Development of Oxygen Deficits in 14 Southern Ontario Lakes,” Limnol. and Oceanogr. 20:993 (1975).

Lee, G. F., “Factors Affecting the Transfer of Materials Between Water and Sediments,” University of Wisconsin, Eutrophication Information Program, Literature Review No. 1, 50 p (1970).

Lee, G. F. and R. A. Jones, “Impact of Fort Collins Domestic Wastewater Discharges on Water Quality in Fossil Creek and Timnath Reservoirs,” Report to Fort Collins Department of Public Works, G. Fred Lee Associates, El Macero, CA (1982).

Lee, G. F. and R. A. Jones, “Oxygen Demand of US Waterway Sediments,” Report of G. Fred Lee & Associates, El Macero, CA (1983). (Updated in 1999).

Lee, G. F. and R. A. Jones, “Prediction of Water Quality in Proposed Hydropower Impoundments,” Proc. International Conf. on Hydropower, Vol. III, University of Tennessee, p. 1254-1273 (1984a).

Lee, G. F. and R. A. Jones, “Predicting Domestic Water Supply Raw Water Quality in Proposed Impoundments,” *In* Proc American Water Works Association 1984 Annual Conference Proceedings. p. 1611-1630 (1984b).

Lee, G. F. and R. A. Jones, “Effects of Eutrophication on Fisheries,” Reviews in Aquatic Sci. CRC Press, Boca Raton, FL. 5:287-305 (1991).

Lee, G. F., C. Conway and G. Veith, “Oxygen Depletion in the Hypolimnion of Lake Mendota, Wisconsin - Relationship to the Demise of the Cisco,” Report of G. Fred Lee & Associates, El Macero, CA (1983).

Lee, G. F., A. Jones-Lee and W. Rast, “Alternative Approaches for Trophic State Classification for Water Quality Management, Part I: Suitability of Existing Trophic State Classification Systems, Part II: Application of Vollenweider-OECD Eutrophication Modeling Approach,” Report G. Fred Lee & Associates, El Macero, California (1995).

Lee, G. F., W. Rast and R. A. Jones, “Eutrophication of Waterbodies: Insights for an Age-old Problem,” Environ. Sci. and Tech. 12:900-908 (1978).

Lee, G. F., W. C. Sonzogni and R. D. Spear, “Significance of Oxic versus Anoxic Conditions for Lake Mendota Sediment Phosphorus Release,”. *In* Proceedings of International Symposium on Interactions between Sediments and Fresh Water. W. Junk, Purdoc, The Hague, p. 294-306 (1977).

Newbry, B. W., R. A. Jones and G. F. Lee, “Assessment and Analysis of Eutrophication of Tennessee River System Impoundments,” Proceedings ASCE Symposium on Surface Water Impoundments, American Society of Civil Engineers p. 413-424, (1981).

OECD, “Eutrophication of Waters. Monitoring, Assessment and Control,” Final Report of the OECD Cooperative Programme on Monitoring of Inland Waters (Eutrophication Control), Organanization for Economic Cooperation and Development, Paris, (97 82 03 1) (1982).

Rast, W. and G. F. Lee, “Summary Analysis of the North American (US Portion) OECD Eutrophication Project: Nutrient Loading-Lake Response Relationships and Trophic State Indices,” EPA 600/3-78-008, US EPA, Corvallis (1978).

Rast, W., R. A. Jones and G. F. Lee, “Predictive Capability of US OECD Phosphorus Loading - Eutrophication Response Models,” J. Wat. Poll. Control Fed. 55:990-1003 (1983).

Sonzogni, W. C., P. C. Uttormark and G. F. Lee, “A Phosphorus Residence Time Model: Theory and Application,” Wat. Res. 10:429-435 (1976).

Stumm, W. and Lee, G. F., "The Chemistry of Aqueous Iron," Schweizerische Zeitschruft fur Hydrology XXII:95-139 (1960).

Stumm, W. and Lee, G. F., "Oxygenation of Ferrous Iron," Ind. Eng. Chem. 53:143-146 (1961).

Vollenweider, R. A., “Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication,” Technical Report DAS/CSI/68.27, Organization for Economic Cooperation and Development, Paris. 250 p (1968).

Vollenweider, R. A., "Advances in Defining Critical Loading Levels for Phosphorus in Lake Eutrophication," Mem. 1st. Ital. Idrobio. 33:53-83 (1976).

Vollenweider, R. A. and L. L. Janus, "Statistical Models for Predicting Hypolimnetic Oxygen Depletion Rates," Mem. 1st. Ital. Idrobio. 39 (1982).

US EPA, "North American Project-A Study of US Water Bodies," US Environmental Protection Agency EPA 600/3-77-086 Corvallis, OR (1977).