Use of Hypolimnetic Oxygen Depletion Rate as a Trophic State Index for Lakes

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The feasibility of lake water quality management planning has been greatly increased over the past 10 years with the development of relatively simple, empirical methods for assessing eutrophication problems. These relate phosphorus loading, hydrology, and morphometry to such traditional trophic state indices as phosphorus concentration, chlorophyll-a concentration, and transparency. One of the difficulties associated with use of these methods is that water quality criteria, as related to beneficial use, do not generally correspond to subjective definitions of "trophic state." This paper attempts to improve upon existing methods by relating measures of phosphorus, chlorophyll-a, and/or transparency to hypolimnetic dissolved oxygen, which is of direct relevance to existing water quality standards, particularly for fisheries management. A modified version of Carlson's (1977) trophic state index summarizes relationships among summer, epilimnetic measurements of total phosphorus, chlorophyll-a, and transparency. On the basis of data from 30 lakes this index is shown to be highly correlated with areal hypolimnetic oxygen depletion rate when the apparent effects of mean depth are also taken into account ($R^2 = 0.96$). Tests of the empirical model on a separate data base of 86 lakes indicate that the approach can be used to predict oxygen status based upon lake morphometry and trophic index. The methodology provides a link between phosphorus mass balance models and existing water quality criteria for dissolved oxygen.

INTRODUCTION

Traditional strategies for classifying lakes with respect to eutrophication have relied primarily upon subjective assessments of one or more types of water quality or biological characteristics. Recently, the increased availability of data has made it possible to develop more objective criteria for ranking and classifying lakes at a regional level on the basis of observed lake conditions [Shannon and Brezonik, 1972; U.S. Environmental Protection Agency, (EPA), 1974; Carlson, 1977] or the factors governing them, such as nutrient loading, hydrology, and morphometry [Dillon, 1975; Vollenweider, 1976]. The development of these methods has greatly increased the feasibility of lake management planning.

The development of an objective basis for specifying standards or criteria with regard to lake water quality is generally lacking and can be considered a weak link in the planning process. This has arisen partially out of the fact that water quality concerns are related to beneficial use and do not always correspond with traditional trophic state criteria. While some states may have considered or be considering phosphorus standards, the nutrient, in itself, does not hinder water use. It is the indirect effects of the nutrient on such water quality aspects as transparency, odor, and dissolved oxygen that are of concern from a water use standpoint. Both theoretical developments and empirical evidence indicate that the effects of phosphorus supply on primary production and water quality vary with impoundment morphometric and hydrologic characteristics and depend upon supplies of other nutrients. Thus it may not be advisable to establish universal phosphorus standards. Standards should be based on those water quality responses which are of direct concern to water use. To do this, we need to develop methodology for predicting such effects.

The trophic state index discussed below provides a simple basis for describing and ranking impoundments based upon one or more types of measurements. By relating dissolved oxygen to other traditional trophic state indices (phosphorus, transparency, and chlorophyll-a) the system provides a link between the empirical models designed to predict eutrophication and existing water quality standards. As shown in Figure 1, the index can be used in combination with a phosphorus mass balance model [Dillon, 1975; Vollenweider, 1976] to predict and compare the effects of alternative phosphorus loadings on lake phosphorus, chlorophyll-a, transparency, and hypolimnetic dissolved oxygen levels. The data base, development, testing, and applications of the index are discussed in detail below.

DATA BASE

Because this study has been initiated for use in Connecticut, over half of the data base is derived from surveys of 24 Connecticut impoundments (17 natural and 7 artificial) by the Connecticut Agricultural Experiment Station [Norvell and Frink, 1975] and the Environmental Protection Agency's (EPA) National Eutrophication Survey [EPA, 1975]. These data have been screened to eliminate lakes or reservoirs with questionable data (as acknowledged by the respective authors) or with extremely eutrophic conditions (total $P$ greater than 250 mg/m$^3$). To provide a more extensive data base for study of hypolimnetic oxygen depletion rates, survey data have also been used from 13 Canadian lakes [Dillon and Rigler, 1974; Lasenby, 1975] and from 8 lakes in the U.S. portion of the Organization for Economic Cooperation and Development (OECD) North American Project [Rast and Lee, 1978; Sevob and Randolph, 1977; W. Rast, personal communication, 1978].

Summer average transparencies and epilimnetic concentrations of chlorophyll-a and total phosphorus have been compiled for each impoundment. Because summer values were not available for the Canadian lakes, spring total $P$ values have been substituted. Areal rates of dissolved oxygen depletion below the thermocline reflect conditions from the onset of spring stratification through August or until anoxic conditions develop in the hypolimnion. Basic morphometric and hydrologic characteristics have also been compiled. A statistical summary of the data is given in Table 1.
To provide a basis for comparisons with oxygen depletion rate, modified versions of the Trophic State Indices proposed by Carlson [1977] have been used to summarize relationships among chlorophyll-a, phosphorus, and transparency for this collection of lakes. Carlson based his index scale upon equivalent transparency values, which were suggested as relative indicators of biomass. Since transparency is partially influenced by factors which are independent of algal standing crop, the modified scale is based upon equivalent chlorophyll-a values rather than transparency. Certainly, chlorophyll-a is neither a direct nor a proportional measure of biomass, but it is probably less sensitive than transparency to such orthogonal factors as dissolved color and inorganic suspended solids. There are also a variety of methods for measuring chlorophyll-a, which may introduce variabilities in these types of studies. Modifications to Carlson's index scheme seemed appropriate for these lakes because of an apparent positive bias in the transparency index when compared with the chlorophyll-a or phosphorus indices.

The location and scale of the modified index are arbitrarily defined so that an index value of zero corresponds to a chlorophyll-a concentration of 0.25 mg/m$^3$ and concentration doubles for each increase of 10 index units. This is equivalent to the following expression:

$$I_B = 20.0 + 33.2 \log_{10} B$$

where

$I_B$ = chlorophyll-a index,

$B$ = chlorophyll-a concentration, mg/m$^3$.

The results of regression analyses relating chlorophyll-a to phosphorus and to transparency have been transformed to develop the following expressions for phosphorus- and transparency-based indices:

$$I_P = 75.3 + 44.8 \log_{10} (1/Z_\alpha - \alpha)$$

where

$P$ = total phosphorus concentration, mg/m$^3$;

$Z_\alpha$ = Secchi depth, m;

$\alpha$ = term representing nonalgal influence on transparency, m$^{-1}$.

Relationships among the three versions of the index are shown in Figures 2-4.

The slope of the chlorophyll-a/total phosphorus relationship for these lakes is 1.39, not significantly different from the values found by Dillon and Rigler [1974], Jones and Bachman [1976], and Carlson [1977]. The second term inside the parentheses of (3) represents a correction factor for the effects of nonalgal materials on the transparency measurement. On the basis of the analysis of limited data from Connecticut lakes the influence of dissolved color on $\alpha$ can be approximately represented by

$$\alpha = 0.04 + 0.0025C$$

where $C$ is the true color (Pt-Co units). This model essentially assumes that the Secchi depth is inversely related to the light extinction coefficient, which, in turn, is a linear function of dissolved color [Meta Systems, Inc., 1978; Rast and Lee, 1978]. The size of the color correction term for the Connecticut lakes is small, since average color values are less than or equal to 25 Pt-Co units. The slope of the color dependence is not significantly different from the result derived by Brezonik [1978] on the basis of data from Florida lakes with color values up to 550 Pt-Co units. While an additional linear term in nonalgal suspended solids concentration seems appropriate for (4), the required data are not available.

Because neither suspended solids nor color data were available for many of these lakes, an average $\alpha$ value of 0.08 m$^{-1}$ has been used in deriving (3). Some adjustment in this value would obviously be necessary for lakes with high color. high nonalgal turbidity, or, on the other hand. high clarity (transparency greater than 12 m). Because of dependence on $\alpha$ the Secchi depth measurement is not a very reliable measure of chlorophyll-a in less productive lakes. Generally, deviations from the chlorophyll-a/transparency relationship may be in-
indicative of the differences in the relative magnitudes of the algal versus nonalgal components of the light extinction coefficient.

Observed differences among the various versions of the index can be interpreted as combinations of model error and measurement error. The former is attributed to the effects of factors which are not accounted for in these simple relationships. These would include, for instance, the effects of nitrogen limitation or high mineral turbidity. Measurement error includes the usual errors associated with analytical procedures for phosphorus and chlorophyll-a and with field measurements of Secchi depth. Another type of measurement error, probably more important in this case, is actually a form of statistical sampling error resulting from the use of discrete samples in time and space to estimate average conditions. To quantify this type of error, the individual observations made in a given lake could be used to estimate a standard error of the mean for each variable on the basis of the corresponding standard deviation, number of samples, and any observed serial correlation. This could be converted, in turn, to an estimate of the standard error of the corresponding index. An error analysis of this type could be used to assess the adequacy of sampling frequency in a monitoring program designed to gather data for assessing lake conditions and interpreting lake response using the index system. Currently lacking, however, are the assessments of within-lake spatial and temporal variabilities needed to apply this approach to this collection of lakes.

If, on the basis of a comparison of the various indices, one is willing to accept that a given lake conforms to the index scheme, a useful aggregate estimate of the index can be obtained by using a weighted averaging procedure. The simplest averaging rule would be the following:

$$I = \left( I_a + I_p + I_s \right) / 3$$

(Average rule would be the following:)

where each component of the index in inverse proportion to its measurement variance, which could be estimated using the approach described above. This weighting procedure would provide a mean index estimate with minimum variance but would require more data and analysis to implement than (5).

The computed mean index values for these lakes can be compared with subjective trophic state classifications derived from the original data sources. Figure 5 depicts the stratification of the various trophic states along the axis defined by mean index values (equation (5)). The separations among the oligotrophic, mesotrophic, and eutrophic states appear to be well defined, with transition zones approximately located between 25 and 30 and between 45 and 50 index units. The eutrophic/highly eutrophic boundary is less distinct and has been arbitrarily set between 65 and 70 index units. These results provide some perspective as to the significance of the index in relation to traditional classification schemes.

**OXYGEN INDEX**

The rate of dissolved oxygen depletion below the thermocline has been suggested as an indicator of the rate of primary production in the surface waters of stratified lakes. This depletion has commonly been represented on an areal basis as the rate of change of the hypolimnetic oxygen deficit (ΔHOD, g/m² day) [Mortimer, 1941]. Oxygen depletion rates were avail-

![Fig. 3. Chlorophyll-a index versus transparency index.](image1)

![Fig. 4. Transparency index versus phosphorus index.](image2)

![Fig. 5. Stratification of mean trophic indices across lake trophic states.](image3)
able for 30 of the lakes studied above. A regression analysis
summarizes the relationship between oxygen depletion rate
trophic index:

\[ \log_{10}(\Delta H) = -1.06 + 0.016I \quad r^2 = 0.57 \quad s_e = 0.21 \] (6)

where \( \Delta H \) is the hypolimnetic oxygen depletion rate (in
grams per square meter day). The relationship is shown in
Figure 6 in comparison with predictions from the equation
derived by Lasenby [1975] on the basis of data from 21 natural
lakes:

\[ \log_{10}(\Delta H) = 0.35 - 1.35 \log_{10}I \] (7)

To develop an expression of Lasenby's model which is analo­
gous to (6), Secchi depths have been transformed to corre­
sponding index values using (3) and assuming an average
value of 0.8 m. While about half of the data used by La­
сенбy is also included in this analysis (Canadian lakes). Fig­
ure 6 shows that there is essentially no difference in the pre­
dictive abilities of the above two equations when they are
compared in the context of the data examined here.

Mortimer [1941] suggested that a characteristic upper
\( \Delta H \) limit for oligotrophic lakes is about 0.25 g/m² day,
while eutrophic lakes have values generally greater than 0.55
\( \Delta H \) g/m² day. According to (6), Mortimer's criteria correspond to
mean index values of 29 and 50, respectively. These values are
in reasonable agreement with the trophic state transition
zones depicted in Figure 5.

Lasenby excluded shallow lakes from his analysis on the basis of the
20-m maximum depth criterion suggested by Huc­
chinson [1957]. Shallow lakes are also of concern from a water
quality management point of view, however, and, when strat­
ified, can be more susceptible to hypolimnetic dissolved oxy­
gen problems than deep lakes, which generally have greater
supplies of dissolved oxygen per unit area at the onset of strat­
fication. For these reasons, shallow lakes are included in this
analysis. To test for morphometric effects, the residuals from
(6) have been examined against mean depth. A positive depth
dependence is apparent in lakes with mean depths less than
about 10 m, while a flat or slightly negative relationship is in­
dicated in deeper lakes. This dependence is described in more
detail below.

Equation (6) has been modified to account for morpho­
metric effects using a multiple regression model of the follow­
ing form:

\[ \log_{10}(\Delta H) = a_0 + a_1I + a_2 \log_{10}I + a_3(\log_{10}I)^2 \] (8)

where \( I \) is the mean depth (in meters) and \( a_0, a_1, a_2, \) and \( a_3 \)
are the empirical coefficients. As shown in Figure 7, a model
of this type explains 91% of the variance in the data with a
standard error of 0.10. Optimal coefficients and corresponding
standard errors are as follows:

- \( a_0 = -3.58 \)
- \( a_1 = 0.0204 \pm 0.0013 \)
- \( a_2 = 4.55 \pm 0.52 \)
- \( a_3 = -2.04 \pm 0.25 \)

An additional characterization of the relationship is given by
the correlation matrix of regression coefficients in Table 2.
Note that the correlation between \( a_2 \) and \( a_3 \) is high. This sug­
gests that the exact shape of the curvilinear depth dependence
is quite uncertain. The \( a \) coefficient, however, is only weakly
correlated with the other two. This indicates that reasonable
separation of the trophic state and depth influences on the oxy­
gen depletion rate has been achieved.

The apparent nonlinear dependence of oxygen depletion
rate on depth is depicted in Figure 8. The effects of the trophic
index have been removed according to (8). The positive depth
dependence in shallow lakes may reflect the combined effects of
(1) variations in epilimnion thickness as a function of mean
depth, (2) weak or intermittent stratification, (3) hypolimnetic
photosynthesis, and/or (4) initial (partially allochthonous)
concentrations of oxygen demanding substances in the hypo­
limnion at the onset of stratification. As indicated by the
dashed line in Figure 8, additional data are needed to estab­
lish the depth response in deep lakes more clearly. The
slightly negative depth dependence, if significant, might be
due to lower hypolimnetic temperatures in deeper lakes or to

| Table 2. Correlation Matrix of Regression Coefficients |
| --- | --- | --- | --- |
|  | \( a_1 \) | \( a_2 \) | \( a_3 \) |
| \( a_1 \) | 1.0 | | |
| \( a_2 \) | 0.27 | 1.0 | |
| \( a_3 \) | -0.23 | -0.99 | 1.0 |
greater exchange rates between the hypolimnion and epilimnion [Blanton, 1973]. The latter would cause more rapid thermocline erosion and possibly greater oxygen transfer into the hypolimnion during the stratified period. Future work should examine some of these possibilities with the aid of theoretical models of the type discussed above or elsewhere [Imboden, 1974]. Specific data on epilimnion and hypolimnion depths would be required for such an effort.

The residuals from (8) are not significantly related to other lake morphometric or hydrologic characteristics, including maximum depth, hydraulic residence time, or surface overflow rate. The equation overpredicts depletion rate by an average of about 10% in lakes with maximum depth/mean depth ratios less than 2.2. Six lakes in the data set are in this category; the effect is not considered strong enough to warrant additional complication of the model but is worthy of additional analysis using a refined data base.

Solving (8) for \( I \) yields an expression for a trophic state index based upon hypolimnetic oxygen depletion rate and lake mean depth:

\[
I_o = 175 + 49 \log_{10} \Delta HOD - 223 \log_{10} Z + 100(\log_{10} Z)^2 \tag{9}
\]

where \( I_o \) is the oxygen-based trophic state index. The equivalence between this version and that based upon chlorophyll-a, phosphorus, and transparency measurements (equation (5)) is demonstrated in Figure 9. The oxygen-based index \( I_o \) explains 89% of the variance in \( I \) with a residual standard error of 5.0 index units.

**USE IN PREDICTING OXYGEN STATUS**

Areal oxygen depletion rate, mean hypolimnion depth, and oxygen concentration at spring turnover are three important factors determining summer oxygen status. On the basis of a mass balance the following statistic seems to be a rational means of representing the combined influence of these factors,

\[
T_{DO} = OZ_m/\Delta HOD \tag{10}
\]

where

\( T_{DO} \) effective number of days of oxygen supply present in the hypolimnion at spring turnover, days;

\( O \) oxygen concentration at spring turnover, g/m³;

\( Z_m \) mean hypolimnion depth, m.

The above expression is exact only for the case of linear oxygen deficit development [Lasenby, 1975] and constant (average) hypolimnion depth. In such a case, comparing \( T_{DO} \) with the length of the stratified period should provide an indication of whether the hypolimnion is likely to become anaerobic before fall overturn. Because of the possible effects of nonlinearities in deficit development and variations in hypolimnion depth, testing of (10) as a predictor of oxygen status is required.

An independent set of data has been compiled to provide a basis for testing the \( T_{DO} \) statistic as a predictor of oxygen status. Reckhow [1977] used data primarily from the EPA's National Eutrophication Survey (NES) [EPA, 1975] and Snodgrass [1974] to classify a collection of northern temperate lakes and reservoirs according to stratification tendency and hypolimnetic oxygen status. The latter was indicated by one of four categories: (1) oxic, (2) possibly oxic, but uncertain, (3) possibly anoxic, but uncertain, and (4) anoxic. Categories 2 and 3 contained impoundments for which there were insufficient data to make reliable assessments of oxygen status during the late summer or early fall months. For the purposes of this analysis these two categories have been combined to form one 'uncertain' class. For each impoundment, Reckhow tabulated mean depth and median, summer total phosphorus measurements, which permit estimation of the trophic index and oxygen depletion rate according to (2) and (8), respectively.

Oxygen concentrations at spring overturn are required for estimating \( T_{DO} \) values according to (10). In the absence of specific data for each lake, an average \( O \), value of 12 g/m³ has been used [Norvell and Frink, 1975]. As discussed by Hutchinson [1957], this type of assumption may introduce errors in large, deep lakes with appreciable winter oxygen deficits or in lakes with long ice cover periods which heat rapidly and late in the spring.

A relationship developed by Snodgrass [1974] has been used to estimate average thermocline depth:

\[
Z_r = 1.6Z^{0.77} \tag{11}
\]

![Fig. 8. Apparent effect of mean depth on oxygen depletion rate.](image)

![Fig. 9. Oxygen depletion rate index versus mean of indices based upon chlorophyll-a, phosphorus, and transparency.](image)
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where estimated as a single-term power function of total depth. The these quantities should be used in model applications. eliminate lakes and reservoirs which do not conform with the above assumptions concerning spring oxygen levels and hypo­

21 m has been assumed for Hallwillersee model testing with available data.

by the [EPA, Modifications made with reference to morphometric limits of the data base used to develop (8). Some additional insights into the relative importance of al­
gal production and impoundment morphometry in controlling oxygen status are derived from Figure 11, a plot of the phosphorus-based trophic state index against mean depth. Lakes and reservoirs classified by Reckhow as oxic or anoxic are distin­
guished by different symbols. The curves represent the solutions of (8), (10), (11), and (12) for a \( T_{DO} \) value of 200 days and for three typical values of \( Z_m/Z \). Figure 11 shows the ability of these functions to discriminate between oxic and anoxic lakes in two dimensions. Estimated \( T_{DO} \) values are less sensitive to \( Z_m/Z \) ratios in deeper lakes. The parabolic relationship indicates that oxygen status is most sensitive to phosphorus level in lakes with mean depths between 5 and 10 m. Below this range, areal oxygen depletion rates decrease with decreasing depth, as demonstrated in Figure 8. Above this range, areal depletion rates are relatively insensitive to depth, and an increasing supply of oxygen is available in the hypolimnion per unit area at the onset of stratification. This gives deeper lakes greater tolerance to algal production (or phosphorus) from a dissolved oxygen aspect. Reckhow [1978] also noted the importance of mean depth as a factor determining the response of lake oxygen status to phosphorus loading on the basis of a discriminant analysis.

**DISCUSSION**

The relationships identified and tested above provide a link between phosphorus management and dissolved oxygen criteria for lakes. In combination with a phosphorus mass balance model they can be used to assess the impacts of phosphorus loadings on hypolimnetic dissolved oxygen. Applications should be restricted to thermally stratified, phosphorus-limited, natural lakes in the northern temperate zone with mean depths between 3 and 33 m. These relationships are not applicable to lakes with high levels of allochthonous suspended solids, which may restrict light penetration, reduce phosphorus availability, and exert oxygen demand [Walker and Kühner, 1978]. While Figure 11 indicates that the seven reservoirs with available data are correctly classified by the model, it should
be noted that the data base used to develop the oxygen depletion rate model consists exclusively of natural lakes. The dissolved oxygen dynamics of reservoirs may be significantly different from those of natural lakes owing to differences in morphometry and hydrodynamics. In addition, allochthonous sources of oxygen demand may be more important in reservoirs than in natural lakes. For these reasons, additional analysis needs to be done to determine whether modifications are necessary for reservoirs.

In reducing the Connecticut lake data provided by Norvell and Frink [1975], only those sampling dates with phosphorus, transparency, and chlorophyll-a measurements have been included, resulting in an average of only 2.1 sampling dates at one station per lake. This provides a benchmark for assessing data adequacy in applications and demonstrates the feasibility of using the approach with limited amounts of information, as is often the case in lake management situations. While this level of information may be adequate for preliminary analyses or for screening lake problems at a regional level, more intensive monitoring efforts are required to provide a basis for management strategy design and implementation.

The magnitudes of potential errors should be considered in applying these relationships. Table 3 compares the standard errors involved in estimating any of the four versions of the trophic state index on the basis of any one of the remaining three. These standard errors range from 5.0 to 7.5 index units. By comparison, the standard errors of phosphorus mass balance models typically used to predict lake phosphorus concentrations from phosphorus loadings, hydrologic factors, and morphometric factors are on the order of 0.2, on a base 10 logarithmic scale [Reckhow, 1977; Walker, 1977]. On the basis of (2) a standard error of 0.2 in the logarithm of lake total phosphorus concentration corresponds to a standard error of 9.2 in estimating the phosphorus-based trophic state index from the above external factors. On the basis of a comparison of error variance there appears to be more uncertainty involved in predicting lake phosphorus concentrations from external factors than in summarizing relationships among within-lake measures of trophic state (phosphorus, chlorophyll-a, transparency, and oxygen depletion rate). As discussed above, these errors result from combinations of model and data errors. The relatively poor performance of phosphorus mass balance models may be due, in part, to the relatively poor quality of phosphorus loading estimates, which are often more difficult to quantify than within-lake conditions owing to the temporal and spatial variability of flows and phosphorus concentrations in tributary streams and point sources.

The feasibility of improving upon these types of relationships depends strongly upon the quality of the data used in model development and testing. The data base used above has been derived from a number of studies employing different spatial and temporal sampling frequencies, analytical methods, and data reduction methods. Uniformity in these aspects would permit more direct comparison of lake characteristics. This may lead to the development of models which are more theoretically based and better understood from an error analysis point of view than those presented above.

**Conclusions**

Using a simple, empirical framework, this paper has demonstrated the feasibility of relating measures of epilimnetic algal standing crop to hypolimnetic oxygen depletion. The influence of lake morphometry on these relationships has been identified and quantified.

**References**


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