Reports

Hypolimnetic Oxygen Deficits: Their Prediction and Interpretation

Abstract. *Rates of hypolimnetic oxygen depletion can be predicted from a knowledge of a lake's phosphorus retention, the average hypolimnetic temperature, and the mean thickness of the hypolimnion. Areal oxygen deficits cannot be used to index lake trophic status because areal calculations do not eliminate the influence of hypolimnetic morphometry.*

Limnology, the study of inland waters, has traditionally been primarily a descriptive science concerned with documenting population fluctuations in time or the interactions between species. Recent lake studies have documented the overexploitation of many commercial fish stocks, reductions in water quality caused by excessive anthropogenic nutrient enrichment, and the destruction of fish populations in some soft-water lakes by acid rain (*1*). These discoveries stimulated the development of empirical models which predict the impact of human activity, both present and future, upon the quality of lake water. Using existing empirical models, limnologists can predict sustainable fish harvest, algal biomass and clarity of surface waters, and the occurrence of blue-green algal blooms (*2*).

Oxygen is another important parameter in lakes. Although the surface waters of most lakes are well oxygenated, decomposition of organic matter in the deeper strata (hypolimnion) of a thermally stratified lake consumes significant amounts of oxygen. Hypolimnetic oxygen depletion appears to be accelerated by nutrient enrichment (*3*). Because anaerobiosis in the hypolimnion can release nutrients from the sediments, eliminate salmonid fisheries, and sometimes result in the production of hydrogen sulfide (*4, 5*), it would be desirable to be able to predict the relationship between nutrient loading to lakes and the minimum concentration of dissolved oxygen in the hypolimnion. We describe here a simple empirical method of accurately predicting the areal hypolimnetic oxygen deficit (AHOD), the first step toward the prediction of hypolimnetic oxygen concentrations.

Earlier in this century, limnologists concluded that, all other factors being equal, the morphometry of a lake would affect the decrease in dissolved oxygen in the hypolimnion. A lake with a thicker hypolimnion would suffer less from oxygen depletion than a lake with a thin hypolimnion. In an attempt to correct for differing morphometry of lakes, Hutchinson (*6*), Strom (*7*), and Thienemann (*8*) proposed that the oxygen deficit be expressed in areal terms. They reasoned that, if two lakes were equally productive but differed in hypolimnetic thickness, their oxygen deficits would be the same if expressed as the rate of oxygen depletion per square meter of surface area of the plane delimiting the upper boundary of the hypolimnion. From a study of only four lakes, Hutchinson seemed to demonstrate the promise of the AHOD in comparing the surface-water productivity and trophic status of lakes (*6*). However, subsequent studies (*9, 10*) failed to confirm his results. A simple proportionality between biomass in the epilimnion and AHOD does not appear to exist.

We have developed an alternative empirical model to predict AHOD as a function of phosphorus retention, the mean summer hypolimnetic temperature, and the mean thickness of the hypolimnion. Data for 12 lakes were gathered from the literature. We calculated the AHOD's using the method developed by Lasenby (*10*). On each sampling date, we calculated the mass of oxygen in the hypolimnion by summing the product of the average measured oxygen concentration in each stratum, G_i (in milligrams per cubic meter), multiplied by the volume of that stratum, V_i (in cubic meters). Dividing the total mass of oxygen by the surface area of the plane delimiting the upper boundary of the hypolimnion, H (in square meters), produced the mass of oxygen per square meter of hypolimnetic surface area, M (in milligrams per square meter)

$$M = \left(\sum_{i=1}^{n} V_i G_i \right) / H$$

These values were regressed against the sampling dates (in Julian days), during the period when hypolimnetic metabolism was not limited by low oxygen concentrations, to determine the average areal rate of oxygen depletion (AHOD). We included only those data sets where the AHOD was measured by type I least-squares linear regression analysis with sufficient accuracy to define greater than 65 percent of the variation in the mass of hypolimnetic oxygen during the period of calculation.

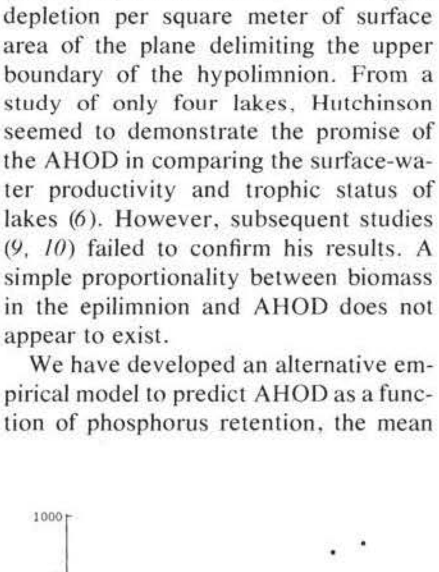

Fig. 1. Relationship between the areal hypolimnetic oxygen deficit (AHOD) and phosphorus retention (R_p) in the study lakes.

Hutchinson's conceptual model of the AHOD (*6*) implies that the fraction of surface-water productivity sedimented into the hypolimnion is constant in all lakes. Data presented by Rich and Wetzel (*11*) and Lastein (*12*) for Lawrence Lake and Lake Esrom suggest that this assumption is false. The sediment trap catch in Lake Esrom was approximately 47 percent of the annual areal pelagic ^{14}C productivity; a similar comparison in Lawrence Lake yielded only 20 percent. To eliminate this erroneous assumption from the AHOD model, we must compare the AHOD to the rate of sedimentation. Because sedimentation is difficult to measure, it has been estimated in phosphorus models by retention. Areal phosphorus retention, R_p (in milligrams per square meter per year), can be calculated for any lake, from the mass balance model tested by Dillon and Rigler (*13*) in which

$$R_p = P\,Q\,R/[A(1 - R)]$$

where A is the lake surface area (in square meters), Q is the water discharge through the outflow (in cubic meters per year), and P is the phosphorus concentration in the lake (in milligrams per cubic meter). The fraction of the input mass

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of phosphorus retained by the lake (R) was defined by an empirical relation to the lake's areal water load (*14*), which, if not measured, was calculated from meteorological data and the lake's catchment defined by topographic maps.

Figure 1 shows that R_p is highly correlated with AHOD and accounts for 55 percent of the variation in AHOD. Of other variables tested, we found that the mean volume-weighted temperature of the hypolimnion, $\overline{T}_H$ (in degrees Celsius), and the mean thickness of the hypolimnion, $\overline{Z}_H$ (in meters), were most effective in reducing the residual variation. A least-squares multiple regression analysis (Table 1) showed that AHOD can be predicted from

$$\text{AHOD} = -277 + 0.5R_p + 5.0\overline{T}_H{}^{1.74} + 150\ln(\overline{Z}_H)$$

To test the ability of this model to predict AHOD's, we applied the model to a second set of lakes for which the necessary data were acquired after the model was constructed. The measured and predicted AHOD's are highly correlated (Fig. 2).

Of the three variables found to be useful in predicting AHOD's, the only surprising parameter was $\overline{Z}_H$. Because temperature affects all biological processes, we would expect higher temperatures to increase system respiration in the range of hypolimnetic temperatures included in this analysis (4.5° to 12°C). It is more surprising that Stewart (*15*) is the only limnologist that we know of who investigated Thienemann's postulated relationship between AHOD and temperature, which was proposed more than half a century ago. We did not observe a stronger temperature effect because hypolimnetic temperature and thickness were very strongly correlated in this small sample of lakes (Table 1).

This AHOD model and our preliminary testing emphasize the influence of a lake's hydrology upon its AHOD. Since most phosphorus in lake water is associated with plankton and is carried to the sediments in fecal pellets or dead organisms, there must be a strong correlation between the amount of decomposable organic matter and the phosphorus sedimented into the hypolimnion. However, lakes with high areal water loads retain very little of their phosphorus load or organic production (*16*).

We did not expect to observe that, all other factors being equal, a lake with a thick hypolimnion would have a higher AHOD than a lake with a thin hypolimnion. In fact, this is inconsistent with the original objective and assumptions that Hutchinson used to justify the use of the AHOD. The objective of expressing the rate of hypolimnetic oxygen depletion on an areal basis was to eliminate the effects of hypolimnetic morphometry. Hutchinson thought he eliminated morphometric influences by assuming that the same percentage of the organic matter loaded into the hypolimnion was respired in hypolimnia of differing thickness. We cannot persist in assuming that a constant fraction of sedimenting organic matter is respired in the hypolimnion. One obvious way of interpreting the effects of $\overline{Z}_H$ is to postulate that respiration by the sediments is limited, perhaps by diffusion of oxygen, and that deep lakes respire more efficiently than shallow lakes because more of their hypolimnetic respiration is associated with decomposition of organic matter in the thicker water column. More attention must be directed toward this phenomenon and to the question of whether the hypolimnetic oxygen deficit is, in fact, determined solely by respiration.

Table 1. Results of the multiple regression analysis including a simple correlation matrix (top half of table), partial regression coefficient (prc), Student t value of the partial regression coefficient (T) and probability (P), and total amount of variation explained by stepwise addition of variables to regression by order in which they are listed (R^2). Other variables and units are as in the text.

Parameter	AHOD	R_p	$\ln(\overline{Z}_H)$	$\overline{T}_H{}^{1.74}$
AHOD	1.00	0.74	0.62	−0.10
R_p		1.00	0.34	0.07
$\ln(\overline{Z}_H)$			1.00	−0.69
$\overline{T}_H{}^{1.74}$				1.00
prc		0.50	150	5.03
T		3.14	3.38	1.83
P		$< .01$	$<.01$	0.08
R^2		0.54	0.69	0.75

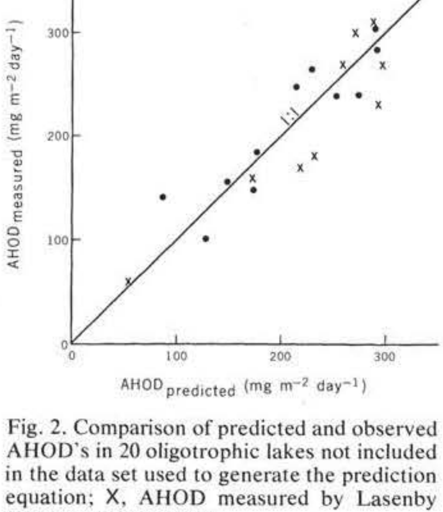

Fig. 2. Comparison of predicted and observed AHOD's in 20 oligotrophic lakes not included in the data set used to generate the prediction equation; X, AHOD measured by Lasenby (*10*); ●, present study.

In addition, this model demonstrates that Hutchinson's (*17*) and Mortimer's (*5*) method of classifying lakes into trophic categories according to AHOD's cannot be used unless a factor is included to compensate for the thickness of the hypolimnion. If AHOD's are used as the criteria, lakes with thick hypolimnia may be classified as eutrophic solely because of their morphometry and not because of their productivity. Current indices of trophic status as indicated by AHOD are biased and cannot be used to compare lakes of differing morphometry.

Now that it is possible to predict the rate of oxygen consumption in a restricted range of lakes, this model should be tested under conditions not found in the original data set. Measurements of AHOD in highly eutrophic lakes and in lakes with changing trophic status will be particularly useful and will strengthen our confidence in this predictive equation.

R. JACK CORNETT
FRANK H. RIGLER
Department of Biology,
McGill University, Montreal,
Quebec, Canada H3A 1B1

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