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QUANTIFICATION OF THE LAKE TROPHIC TYPOLOGIES OF NAUMANN (SURFACE QUALITY) AND THIENEMANN (OXYGEN) WITH SPECIAL REFERENCE TO THE GREAT LAKES

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ABSTRACT. Separate trophic scales and indices are developed for two of the most significant symptoms of eutrophication: surface water quality and hypolimnetic dissolved oxygen depletion. The scales are made comparable by expressing them in dimensionless form with a lower bound of zero and a mesotrophic range from 5 to 10. In this way, the two symptoms can be compared and their relative importance judged. This is done for the Great Lakes with the result that for both scales Lakes Superior, Huron, and Michigan are classified as oligotrophic. However, while central and eastern Lake Erie and Lake Ontario are classified as mesotrophic in terms of surface water quality, they range from eutrophic (central Lake Erie) to oligotrophic (Lake Ontario) on the oxygen scale. This is because, although these lakes are similar in surface water quality, their hypolimnion thicknesses range from approximately 4 m for central Erie to 70 m for Lake Ontario. Because of its shallowness, western Lake Erie does not have a persistent oxygen problem. In terms of surface quality it is classified as eutrophic.

We have attempted to relate the two scales by correlating surface primary production and areal depletion rate. The results indicate that for lakes of similar primary production, areal oxygen depletion is directly proportional to hypolimnion thickness.

INTRODUCTION

Einar Naumann and August Thienemann began work in the field of trophic typology and lake classification in the early part of the twentieth century (see Hutchinson 1973). Naumann characterized temperate lakes on the basis of their plant production and was in large part concerned with visual or aesthetic symptoms of eutrophication. Theinemann, on the other hand, emphasized the degree of hypolimnetic oxygen depletion in summer and the benthic organisms associated with eutrophication. Both systems were primarily qualitative and resulted in the division of the trophic continuum into classes, such as oligotrophy, mesotrophy, and eutrophy.

While the Naumann and Thienemann concepts of eutrophication are related, they are not equivalent (Lundbeck 1934). Most of the organic matter oxidized in the hypolimnion does in fact originate in the phytoplankton production of the surface waters of autotrophic lakes. However, the magnitude of the change in oxygen concentration of the deep water is inversely related to the thickness (or volume) of the hypolimnion. Thus, a morphometric effect that is independent of edaphic factors distinguishes the two concepts. Unfortunately, the belief that they are often directly correlated (Thienemann 1928) caused confusion in the area of trophic typology.

The concept of the areal hypolimnetic oxygen deficit was introduced (Ström 1931) in an attempt to clarify the matter. By the normalization of oxygen depletion to area rather than volume, the resulting rate can be interpreted as a measure of surface plant production and Thienemann's concept becomes comparable (and ancillary) to Naumann's definition of eutrophication. While the idea was most useful in clearing up a misconception, a secondary effect has been the general de-emphasis of oxygen concentration in trophic classification schemes (e.g. Shannon and Brezonik 1972, Carlson 1977). This is unfortunate because dissolved oxygen has profound biological and chemical significance to a lake. Therefore, the major premise

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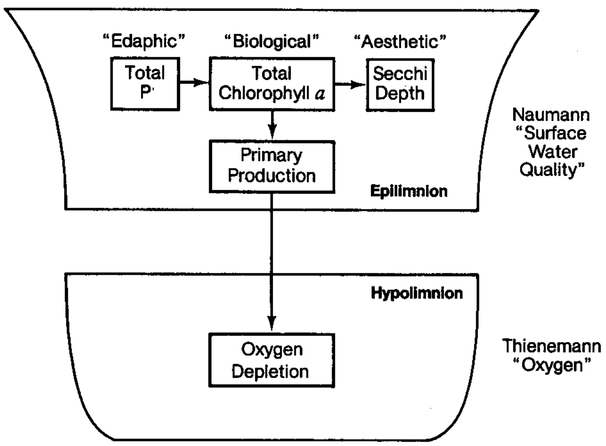

FIG. 1. Schematic of interrelations among variables in Naumann's and Thienemann's concepts of eutrophication.

of the present study is that oxygen deficit is a fundamental measure of lake trophic state that deserves to be studied and assessed for its own sake. This can be done by deriving two separate but related trophic schemes for the Great Lakes (Figure 1). The first, based on Naumann's concept, focuses on visual symptoms of eutrophication related to plant production in the lake's surface layer. The second, based on Thienemann's concept, focuses on the oxygen concentration in the deep waters. There is an attempt to express the two concepts on a common dimensionless scale in order to allow comparison of their relative importance in different parts of the Great Lakes. Although a quantitative approach is taken, the classical nomenclature is retained to assist communication, and while the analysis is devoted to the Great Lakes, the general approach should have relevance to smaller lakes.

THE NAUMANN (SURFACE WATER QUALITY) SCALE

Whereas Naumann conceived of eutrophication as a complex of edaphic, biological, and aesthetic factors, he emphasized the latter. As Hutchinson (1973, p. 269) observed, "Naumann . . . gives the impression that he liked to draw limnological conclusions . . . merely by looking at lakes." While this was partially due to the observational capabilities contemporaneous with his studies, Naumann's emphasis on visual aspects is quite similar to the public's perception of eutrophication. For this reason, the surface water quality scale developed here is based on a variable that directly reflects a

TABLE 1. Surface water quality variables for the Great Lakes (1967 through 1975).

Lake	Total phosphorus [μgP/L]	Total chlorophyll *a* [μg/L]	Primary production [gC/(m^2 yr)]	Secchi depth [m]
Superior	4.6	0.7	50	9.2
Huron	5.5	1.2	83	8.2
Michigan	8.0	2.0	144	5.9
Western Erie	39.3	11.1	340	—
Central Erie	19.4	4.5	230	4.7
Eastern Erie	17.2	3.3	180	5.0
Ontario	21.0	5.4	184	2.6

lake's appearance—transparency measured by the depth of disappearance of the Secchi disc. Regression is then used to express the scale in terms of other variables that reflect edaphic and biological factors in a fashion similar to Carlson (1977). The variables include a causative variable (total phosphorus), a measure of phytoplankton biomass (total chlorophyll *a*, i.e., uncorrected for phaeopigments), and a variable reflecting photosynthesis (primary production).

Data

The data (Table 1) used here were generally collected from 1967 to 1975. Individual cruise data were averaged in a number of ways. Annual, whole-lake averages are used for total phosphorus since mathematical models (Chapra 1977) are available to relate this quantity to phosphorus loading information. Lake-wide, surface averages for the ice-free period are used for primary production since such values are available (Vollenweider, Munawar, and Stadelmann 1974) and they permit direct comparison with other attempts at trophic classification based on this variable (Rodhe 1958). Summer, off-shore averages are used for Secchi depth and surface chlorophyll *a* in an attempt to exclude influences that would interfere with the direct relationship between phytoplankton abundance and light extinction. Thus Secchi depth for western Lake Erie is excluded from the analysis because its shallow depth makes it especially prone to such influences. Summer (the summer stratified phase in Table 2) is used because the existence of a thermocline prevents the resuspension of bottom sediments that characterize non-stratified periods in shallow basins, such as central Lake Erie. Similarly, the highly variable nearshore zones are excluded because they are subject to intermittent upwellings, river discharges, and municipal pollution.

TABLE 2. Definition of periods of thermal stratification for the Great Lakes. The dates are approximate estimates of long-term average conditions.

	Stratification		
	Summer stratified phase		Autumnal cooling phase
Lake or basin	Onset of summer stratification	Accelerated deepening of thermocline	Fall overturn
Superior	1 August	30 September	15 November
Michigan	1 July	30 September	15 November
Huron	15 July	30 September	15 November
Central Erie	1 June	15 September	30 September
Eastern Erie	15 June	30 September	1 November
Ontario	1 July	30 September	15 November

Transformations

Before developing the trophic scale, Secchi depth and primary production must be transformed so that they are linearly proportional to the other variables.

Secchi depth—Secchi depth differs from the other variables in Table 1 in that it is inversely proportional to the degree of eutrophication. A useful basis for transforming Secchi depth to a direct proportionality with suspended matter is the Beer-Lambert law for light extinction in water

$$I_z = I_o e^{-\eta z}, \quad (1)$$

where I_z is the light intensity at depth z, I_0 is the intensity at the surface, and η is the extinction coefficient, regarded as a composite of a number of factors as follows (Åberg and Rodhe 1942):

$$\eta = \eta_w + \eta_p + \eta_c, \quad (2)$$

where η_w is due to extinction by water itself, η_p is due to suspended particles, and η_c is due to color from dissolved compounds. Equation (1) can be linearized and simplified by (a) taking its natural logarithm, (b) treating η_c and η_w as a single value, η_{cw}, (c) assuming that the Secchi depth corresponds to the level at which 90% of the surface light intensity has been dissipated (i.e., $I_z/I_0 = 0.10$) as suggested by Tyler (1968), and (d) assuming that η_p is linearly related to the concentration of chlorophyll *a*. From the application of these assumptions, equation (1) becomes

$$\frac{2.3}{S} = \alpha \text{ Chl } a + \eta_{cw}, \quad (3)$$

where S is the Secchi depth, α is a coefficient, and Chl *a* is chlorophyll *a* concentration.

Carlson (1977) derived equation (3) in a similar fashion, but then set η_{cw} equal to zero by assuming that for many lakes it is small compared to the effect of particulate matter. This assumption results in a hyperbolic relationship with infinite Secchi depth in the absence of particulate matter. The present analysis does not neglect η_{cw}, but estimates it empirically from a linear regression of 2.3/S versus Chl *a*. The regression yields an intercept of 0.142/m that corresponds to a Secchi depth of about 16.2 m. This value is at the lower end of the range of the highest Secchi depths (or lowest extinction coefficients) reported for the Great Lakes; they range from approximately 15 to 20 m (Pinsak 1976). However, it would be expected that an average summer value for the entire offshore region of a lake would be somewhat lower than a maximum value at one point in time and space. Therefore, the value is assumed to be a reasonable estimate of the extinction of light due to particle-free Great Lakes water over the entire summer. Equation (3) can also be expressed as

$$\Psi = \frac{2.3}{S} - 0.142 = \alpha \text{ Chl } a, \quad (4)$$

where Ψ is transformed Secchi depth. Aside from making Secchi depth directly proportional to particulate matter, equation (4) is linear and has a zero intercept. The latter reflects the fact that the transformation corrects for light extinction due to color and water. Thus, Ψ should be solely dependent on plankton abundance, making it an appropriate basis for the trophic scale.

Primary production—While primary production is directly proportional to phytoplankton biomass, the relationship is non-linear and can be described as a saturating hyperbola (Vollenweider *et al.* 1974). The present analysis uses the following equation:

$$Pr = Pr_{max} (1 - e^{-\beta \text{ Chl } a}), \quad (5)$$

where Pr is primary production, Pr_{max} is a maximum value of primary production $\cong 420$ gC/(m^2 yr) for north temperate lakes (Vollenweider *et al.* 1974), and β is a coefficient. A logarithmic transform and algebra can be used to linearize equation (5) as

$$\Pi = \ln\left(\frac{420}{420 - Pr}\right) = \beta \text{ Chl } a, \quad (6)$$

where Π is transformed primary production.

TABLE 3. Correlation analysis of surface water quality variables.

	p	Chl *a*	Π	Ψ
a) Simple correlation coefficients				
p				
Chl *a*	0.99			
Π	0.97	0.97		
Ψ	0.83	0.90	0.62	
b) Significance levels of simple correlation coefficients (assuming normality)				
p				
Chl *a*	0.00			
Π	0.00	0.00		
Ψ	0.04	0.01	0.19	

Correlation Between Variables

Before the trophic scale is developed, the relationship between the four variables can be investigated by a multiple correlation analysis. The results, shown in Table 3, indicate strong correlations between the variables, implying that for the Great Lakes, edaphic, biological, and aesthetic criteria are related. The only nonsignificant correlation, between Ψ and Π, is due overwhelmingly (as determined by examination of the residuals) to the small Secchi depths and low primary production in Lake Ontario. The same anomaly becomes apparent when examining the trophic indices in a subsequent section.

Development of the Naumann Trophic Scale

The causal relationship between the variables is schematized in the upper layer of Figure 1. Using a linear regression with a zero intercept allows estimation of the functional relationships between variables. The zero intercept is based on the fact that, in the absence of any of the dependent variables, the independent variable would not be expected to be present. For example, if a lake were devoid of phosphorus, it would not be expected to contain chlorophyll. The regressions yield the following relationships

$$\text{Chl } a = 0.259 \text{ p}, \quad (7)$$

$$\Psi = 0.111 \text{ Chl } a, \text{ and} \quad (8)$$

$$\Pi = 0.148 \text{ Chl } a, \quad (9)$$

where p is total phosphorus concentration.

Equations (8) and (9) can also be expressed as

$$S = \frac{16.2}{1 + 0.783 \text{ Chl } a}, \text{ and} \quad (10)$$

$$Pr = 420\,(1 - e^{-0.148 \text{ Chl } a}). \quad (11)$$

The results and data are shown in Figure 2.

The trophic typology is then developed by setting bounds for each trophic state and using equations (7), (10), and (11) to determine corresponding values for each variable. Secchi depth is used as the basis for the scale due to its direct significance to man. A mesotrophic range of from 5 to 3 m (comparable to those suggested by Vallentyne *et al.* 1969, and Dillon and Rigler 1975) is used to calculate the trophic class ranges in Table 4. The ranges are generally consistent with other attempts to quantify trophic class boundaries, with the exception of primary production, where the lower level of mesotrophy is higher than the other estimates.

As a final step, the four variables can be set to a common scale by normalizing to 10 all values at the upper bound of mesotrophy. The resulting trophic index for each variable is

$$TI_p = 0.461 \text{ p}, \quad (12)$$

$$TI_{\text{Chl } a} = 1.78 \text{ Chl } a, \quad (13)$$

$$TI_{Pr} = 12.0 \ln \frac{420}{420 - Pr}, \text{ and} \quad (14)$$

$$TI_s = \frac{36.8}{S} - 2.27, \quad (15)$$

where TI_i is the trophic index based on parameter i. A single surface water quality, or Naumann index (TI_N), then follows by a simple averaging of equations (12) through (15).

$$TI_N = 0.12 \text{ p} + 0.45 \text{ Chl } a + 3.0 \ln \frac{420}{420 - Pr} + \frac{9.2}{S} - 0.57 \quad (16)$$

Application to the Great Lakes

The present surface quality of the Great Lakes can be classified by inserting values from Table 1 into equations (12) through (16). The results (Table 5) show that, in terms of surface water quality, Lakes Superior, Huron, and Michigan are oligotrophic; central and eastern Lake Erie and Lake Ontario are mesotrophic; and western Lake Erie is eutrophic.

Since the trophic indices (equations 12 through 16) employ a common linear scale, Table 5 can also be used to compare the relative magnitude of the

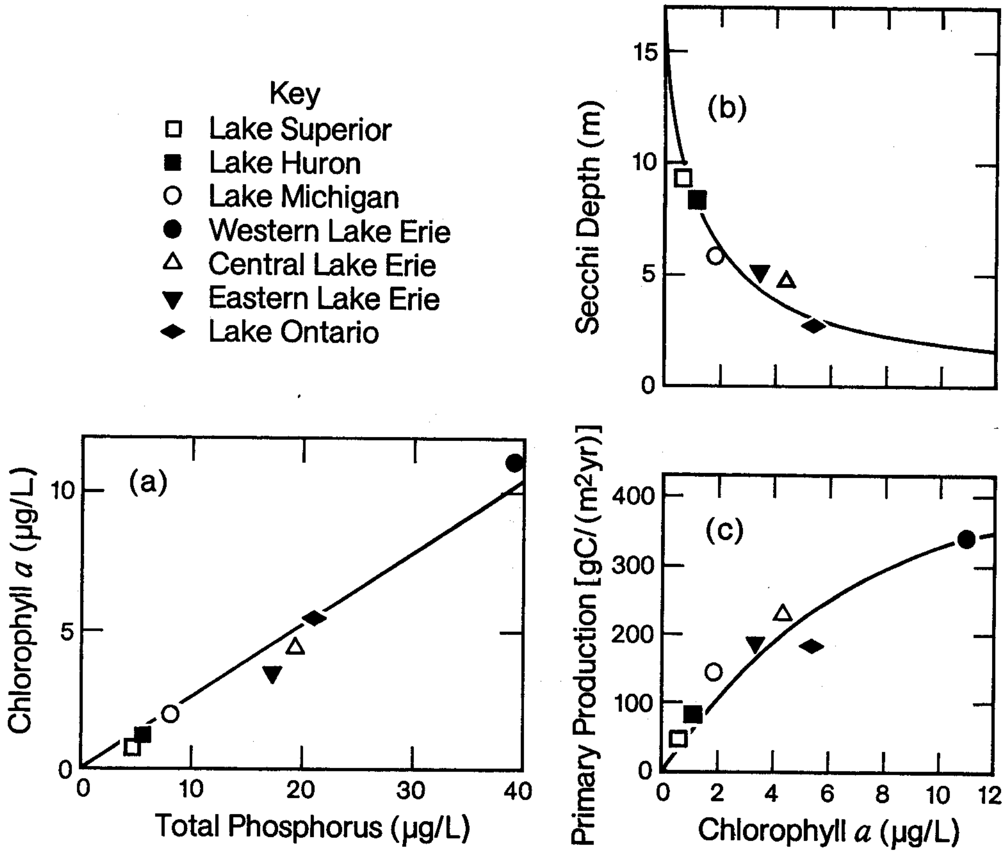

FIG. 2. Correlations of surface water quality variables (a) chlorophyll a *versus total phosphorus, (b) Secchi depth versus chlorophyll* a, *and (c) primary production versus chlorophyll* a.

surface quality variables within each lake. For example, Lake Ontario's transformed primary production seems to be inordinately low, whereas its transformed Secchi depth is high. The latter, which actually represents low water clarity, has been noted elsewhere (Dobson, Gilbertson, and Sly 1974) and may be due to calcium carbonate precipitation in late summer. This in turn may tend to reduce primary production due to light attenuation. Whatever the reason, the foregoing demonstrates an alternative use of the indices beyond classification—i.e., as a means for the identification of anomalies.

THE THIENEMANN (DISSOLVED OXYGEN) SCALE

Data

Thermal stratification—The dissolved oxygen content of a lake is strongly influenced by thermal stratification. While slight inverse stratification exists in some of the basins during winter and early spring, the critical period for dissolved oxygen occurs during summer and fall. This period may be divided into two distinct stages: a summer stratified phase and an autumnal cooling phase (see Mortimer 1975 for a more complete exposition of the seasonal cycle of heat distribution in a Great Lake).

The summer stratified phase, which corresponds to Mortimer's (1975) "main warming" and "midsummer stratified" phases, is characterized by a stable thermocline that confines wind mixing to the epilimnion. During this time, the thermocline deepens at a very gradual rate and maintains a fairly constant and strong density gradient that essentially isolates hypolimnetic water from equilibration with the atmosphere. The autumnal cooling phase occurs when heat loss and strong winds that commence at the end of September cause the thermocline to deepen and weaken at an accelerated pace, culminating in overturn.

The duration and extent of these phases (Table 2) varies from lake to lake, depending on their latitude

TABLE 4. Ranges defining the three trophic classes applicable to offshore surface waters of the Great Lakes. Other schemes (italics) are presented for comparison.

	Low Oligotrophic Good	Medium Mesotrophic Fair	High Eutrophic Poor	Reference
Total phosphorus (μgP/L)	<11.0	11.0 to 21.7	>21.7	
	<9.9	*9.9 to 18.5*	*>18.5*	Dillon and Rigler (1975)
	5–10	*10 to 20*	*>20*	Wetzel (1975)
	<15	*15 to 30*	*>30*	Welch and Lindell (1978)
Total chlorophyll *a* (μg/L)	<2.9	2.9 to 5.6	>5.6	
	0.3 to 2.5	*1.0 to 15.0*	*5.0 to 140*	Sakamoto (1966)
	<4	*4 to 10*	*>10*	National Academy of Science (1973)
	4.3	*4.3 to 8.8*	*>8.8*	Dobson *et al.* (1974)
	<2	*2 to 5*	*>5*	Dillon and Rigler (1975)
	<3.7	*3.7 to 10*	*>10*	Welch and Lindell (1978)
Primary production (gC/(m^2 yr))	<145	145 to 240	>240	
	<25	*25 to 75*	*>75*	Rodhe (1958)
	<100	*100 to 200*	*>200*	Vollenweider *et al.* (1974)
	18 to 110	*90 to 365*	*>365*	Wetzel (1975)
Secchi depth (m)	>5	5 to 3	<3	
	>6	*6 to 3*	*<3*	Vallentyne *et al.* (1969)
	>5	*5 to 2*	*<2*	Dillon and Rigler (1975)
Naumann Index	<5	5 to 10	>10	

TABLE 5. Surface water quality indices for offshore waters of the Great Lakes: mean values for late 1960s and early 1970s. Values are expressed on a common scale on which mesotrophy is bounded by 5.0 and 10.0.

Lake or basin	Total phosphorus	Total chlorophyll *a*	Primary production	Secchi depth	Naumann index, TI_N
Superior	2.1	1.2	1.5	1.7	1.6
Huron	2.5	2.1	2.6	2.2	2.4
Michigan	3.7	3.6	5.0	4.0	4.1
Western Erie	18.1	19.7	19.9	—	19.2
Central Erie	9.0	8.0	9.5	5.6	8.0
Eastern Erie	7.9	5.9	6.7	5.1	6.4
Ontario	9.7	9.6	6.9	11.9	9.5

and size. A major difference that has an effect on oxygen depletion is the fact that shortly after the onset of autumnal cooling, the thermocline in the central basin of Lake Erie is driven through the bottom and the entire water column becomes well-mixed and aerated. For the other lakes, however, depletion continues in the deepest parts of the lake until overturn.

Development of the Thienemann Trophic Scale

While a subjective criterion was required to designate eutrophy in the Naumann sense, a more objective definition is possible for oxygen. There is no question that a level of approximately 10% saturation (~1 mg/L) represents a threshold for a variety of chemical and biological processes

TABLE 6. Great Lakes data relevant to oxygen depletion along with calculated value of the Thienemann index.

Lake or basin	Thickness of hypolimnion (m)	Volumetric oxygen depletion rate [mg/(L mo)]	Initial oxygen concentration (mg/L)	Duration of stratification (mo)	Thienemann index, TI_T
Superior	134	0.14	13	3.5	0.4
Huron	50	0.24	13	4.0	0.8
Central Erie	3.9	3.2	11	4.0	12.9
Eastern Erie	14.7	1.73	12	4.5	7.2
Ontario	71	0.33	13	4.5	1.3

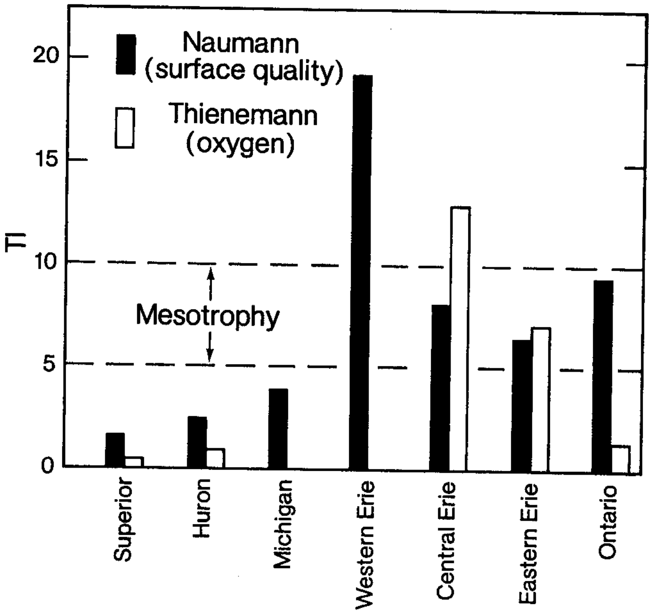

FIG. 3. Comparison of Naumann and Thienemann indices for the Great Lakes. Thienemann indices are not included for Lake Michigan and western Lake Erie owing to a lack of data and to nonstratified conditions, respectively.

(Mortimer 1941, 1942, Hutchinson 1957). A lake is therefore assumed to be eutrophic in the Thienemann sense if its hypolimnetic oxygen content falls below this level by the end of the stratified period. If, as was done with the Naumann index, the lower level of eutrophy is set at 10.0, the Thienemann index, TI_T, can be expressed as

$$TI_T = \frac{10}{[0.9 \text{ depleted}]} [\text{Fraction depleted}] = 11.1 \left[\frac{D_v t_s}{c_i}\right] \quad (17)$$

where D_v is the volumetric oxygen depletion rate, t_s is the duration of the stratified period, and c_i is the oxygen concentration of the hypolimnion at the onset of stratification.

A trophic index of 5.0, which represented the upper level of oligotrophy in the Naumann index, is equivalent to approximately 50% saturation (or ~ 6 mg/L). This conforms to attempts to define oligo-mesotrophy based on fish (Davis 1975) and on oxygen and benthic fauna (Kitagawa 1978). Thus, the mesotrophic range for both scales (5 to 10) is consistent.

Application to the Great Lakes

Equation (17) can now be used to classify the basins of the Great Lakes with respect to oxygen (Table 6). Lakes Superior, Huron, and Ontario are oligotrophic, eastern Lake Erie is mesotrophic, and central Lake Erie is eutrophic. Insufficient data were available to classify Lake Michigan, but because of its low productivity and great depth it is undoubtedly oligotrophic with respect to oxygen.

THE RELATIONSHIP BETWEEN OXYGEN AND SURFACE QUALITY

Lake Classification

Comparisons for the Great Lakes—Since the Naumann and Thienemann indices have been set to a common scale, a direct comparison of dissolved oxygen and surface quality is possible. As can be seen in Figure 3, Lakes Superior, Huron, and Ontario have lower Thienemann than Naumann indices due to the large oxygen reserves in their hypolimnia. Conversely, shallow central Lake Erie has a greater oxygen problem. Intermediate-depth eastern Lake Erie represents a case where the two aspects are similar.

The effect of depth is especially apparent when comparing the indices for central and eastern Lake Erie and Lake Ontario. Although in the Naumann sense the three basins are all mesotrophic, in the Thienemann sense they range from eutrophy for shallow central Lake Erie to oligotrophy for deep Lake Ontario.

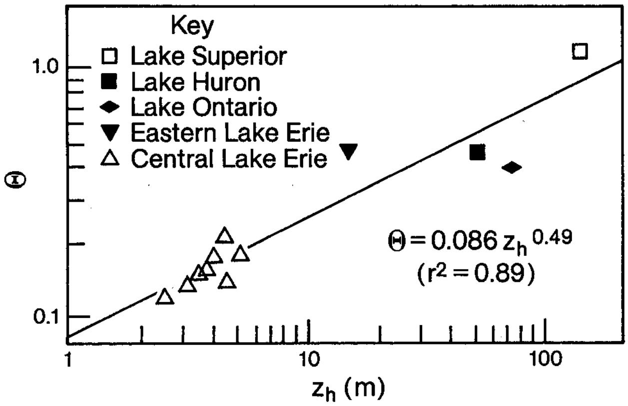

FIG. 4. Plot of ratio of surface production to bottom oxidation, Θ, versus mean thickness of the hypolimnion for the Great Lakes.

Classification and management objectives—There are three possibilities for classifying lakes using the indices: (1) average them, (2) classify the lake in terms of the maximum index, or (3) use both. We prefer the last since it retains the most information. For management purposes, however, we feel that the maximum index should form the basis for determining remedial measures. Thus, central Lake Erie should be managed to alleviate its oxygen problem whereas Lake Ontario's rehabilitation program should be in terms of surface water quality. In fact, this is what was done in defining water quality criteria for these lakes as part of the 1978 Great Lakes Water Quality Agreement between the United States and Canada (Thomas, Robertson, and Sonzogni 1980).

An Attempt at Closure Using Primary Production

The ideal link between the two indices (and therefore the two concepts) should be primary production, which ostensibly measures carbon reduction at the surface, and areal oxygen depletion, which measures carbon oxidation at the bottom (Figure 1). While there are many reasons why this ideal is flawed (not the least of which is the question of what is actually being determined by ^{14}C tracers to measure productivity), it can serve as a preliminary basis for the closure of the two concepts. If the oxidation of phytoplankton protoplasm is represented as

$$C_{106}H_{263}O_{110}N_{16}P_1 + 138\ O_2 \tag{18}$$

(Stumm and Morgan 1970),

it can be calculated that 3.47 grams of oxygen would be required to oxidize a gram of carbon. From this and other conversion factors, a dimensionless quantity representing the fraction of the surface production that is oxidized in the bottom waters can be calculated as

$$\Theta = 3.46\ \frac{D_a}{Pr}, \tag{19}$$

where 3.46 is a conversion factor = (12 mo/yr) ($gC/3.47\ gO_2$), Θ is the oxidation-reduction ratio, and D_a is the areal oxygen depletion rate [$gO_2/(m^2$ mo)] calculated as

$$D_a = D_v\ z_h, \tag{20}$$

where z_h is the mean thickness of the hypolimnion (m).

The fact that the application of equation (19) to the Great Lakes yields some unlikely results (i.e., Θ for Lake Superior > 1) suggests that the calculation is not a precise measure.

Nevertheless, Figure 4 suggests, somewhat surprisingly, that Θ increases with the thickness of hypolimnion. In other words, the oxidation of organic matter becomes more efficient in deeper lakes. Welch, Dillon, and Sreedharan (1976) observed a similar correlation between winter oxygen consumption and the mean depth of 16 small lakes in Ontario. Cornett and Rigler (1979) presented empirical results along the same lines for summer D_a in small lakes. Such results introduce a complication into the notion that areal hypolimnetic oxygen depletion can be interpreted directly as a measure of surface primary production. One explanation for this effect is that primary production might be underestimated as the lakes become deeper as in Hutchinson's (1938) observation that, for deep clear lakes, production could occur below the thermocline.

Another possibility is that a higher proportion of primary production in Lakes Superior and Huron is grazed and converted to fecal pellets than in central and eastern Lake Erie. As a consequence, a higher proportion of the primary production in Lakes Superior and Huron settles into the hypolimnion for subsequent oxidation, whether it occurs in the water column or in the sediments. This may also be true in the general case because, especially since summer average values are used, a higher proportion of primary production in eutrophic lakes consists of phytoplankton types (e.g. blue-greens) that are not ingested and/or assimilated as efficiently as other phytoplankton types (e.g. diatoms).

However, the fact that the relationship holds for year-to-year variations in one lake (central Lake Erie) suggests an alternative hypothesis: oxidation might be more efficient in the water column than in the sediments. One possible mechanism to explain this is the burial of a portion of the organic matter in the shallower lakes, thus rendering it inaccessible for oxidation.

Whatever the reason, the analysis can be carried further by applying linear regression to Figure 4, which results in

$$\Theta = 0.086\ z_h^{0.49} \tag{21}$$

Equation (21) can be combined with equations (14), (17), and (19) to determine that Great Lakes with hypolimnetic thicknesses less than 5 m (or with total mean depths less than 20 m for an average epilimnetic thickness of 15 m) would be more critical from an oxygen than from a surface quality perspective. This result and Figure 4 are certainly approximate, but are meant as a first attempt at a closure of Naumann's and Thienemann's concepts and to make the point that below a certain hypolimnetic thickness a stratified lake will be oxygen determined rather than surface quality determined.

DISCUSSION

As with any statistical approach, the foregoing exercise has been intended to explain the maximum amount of natural variability on the basis of the simplest theoretical structure or model. Lest this simplicity lead to casual interpretation and application, we would like to stress the following ideas that must be considered for a balanced concept of trophic analysis.

Residual Variability

There is no question that statistical approaches have contributed useful tools and theoretical structures for the analysis of lake trophic state (e.g., Vollenweider 1968, Vollenweider and Dillon 1974, Dillon and Rigler 1975, etc.). However, as with all idealizations, there is a residual error not explained by the model (Chapra and Reckhow 1979). Two major components of this residual error that are relevant to the present discussion are biological variability and time/space scale variability.

Biological variability and "biomanipulation"—Recently, Shapiro (1978) noted the wide residual variability of simple eutrophication models and ascribed it to the vagaries of nature and in particular to biological variations between lakes. In other words, while simple models may yield sound estimates of the most likely value, factors not included in the model (such as the make-up of the biological community) can cause significant divergence from the most likely value for any particular lake. This has been dramatically demonstrated in Lake Washington, where recent changes in zooplankton grazing have increased water transparency during a period when phosphorus levels have remained relatively constant (Edmondson 1978). Shapiro (1978) made a persuasive argument for directing research toward understanding the processes that contribute to such biovariability with the hope of applying this knowledge to lake rehabilitation. While a discussion of the biomanipulation of lakes is beyond the present context and probably premature, it should be considered as a possible future option for the improvement of Great Lakes water quality.

In the same vein, our present emphasis on aesthetics and oxygen has omitted other symptoms of eutrophication related to biological changes within a lake. For example, Schindler (1977) speculated that as a lake is enriched with phosphorus it reaches a point at which it becomes nitrogen-limited. At this point the biota of the lake can change (i.e. nitrogen-fixing blue-green algae can gain ascendancy) to compensate for this shortage. Such a threshold might form the basis of a biologically-based trophic scale that uses nitrogen-to-phosphorus ratios.

Finally, all of the foregoing has assumed that increased productivity is necessarily "bad." Yet a case can be made that some lakes might "improve" by increases in their productivity: i.e., increased fish production in barren lakes such as Lake Superior.

Space and time scales—Another characteristic of simple approaches is that they employ macroscopic scales (i.e. whole lake or mean seasonal averages) to describe trophic state. Thus, variability on finer time and space scales is not considered. For example, Fee (1976) showed a considerable depth-dependent structure of chlorophyll *a*, and similar variations can be demonstrated temporally (algal blooms). Future research might be directed toward ascertaining whether important features of the finer scale structure might be included as measures of trophic state.

Nomenclature

An alternative reason for developing the trophic scale is to give a more objective and tangible meaning to some commonly measured variables associated with lake eutrophication. Managers and limnologists are often at a loss to place a "value" on a particular concentration of a variable such as chlorophyll *a* or dissolved oxygen. By relating them, we hope that a more meaningful discussion of the trophic state of the Great Lakes will result. In the same context, three sets of synonyms for the lake types are included in Table 4. First, there is a set of terms for the layman: low, medium, and high. A second set of terms is the classical limnological terminology: oligotrophic, mesotrophic, and eutrophic. Third, there are some terms of value judgement also to be used in a quantitative way: good, fair, and poor. These latter terms are suggested to define practical values associated with the trophic status of surface and bottom waters and to provide a basis for quantitative goals for trophic management of the Great Lakes. For instance, the upper limit of the "good" range might be chosen as a goal. Similar value judgement terms were introduced by Vollenweider (1968). He designated specific external loadings of nitrogen and phosphorus as "permissible" and "dangerous." In so doing, he provided decisionmakers with an extremely useful tool for the management of lake eutrophication.

Apples and Oranges (Or The Problem of Incommensurate Measures of Eutrophication)

By setting the Naumann and Thienemann trophic indices to a common scale, we have contrived an equivalence of biological and human values. In essence, we have made the catastrophic modification of an environment (i.e. the complete depletion of oxygen) equal in value to a subjective appraisal of what humans would consider ugly. While there would no doubt be debate over even the possibility of such an equivalence, we feel that it must be attempted in order to further rationalize the management of lake eutrophication. Furthermore, what seems far worse to us is the design of lake restoration programs based on surface quality (and therefore aesthetic considerations) alone. For systems with thin hypolimnia, this could result in a reasonably clear lake cosmetically covering over a biological and chemical disaster.

A more substantial criticism of our "apples and oranges" approach would be our choice of Secchi depth as our basis for the Naumann scale and our somewhat arbitrary choice of 3 to 5 m as the bounds for mesotrophy as measured by this variable. The former criticism would be based on the fact that in some lakes color and turbidity could have a significant impact on water clarity and, thus, obviate the direct relationships between Secchi depth and algal biomass (see Lorenzen 1980, Megard *et al.* 1980). This does not seem to be a major problem in the offshore waters of the Great Lakes, but would need to be addressed before applying the present approach to nearshore areas and to other lakes. The latter criticism—the choice of bounds for mesotrophy— is somewhat more difficult. We somehow have to answer the question: at what point does a lake's color and transparency become ugly? The question is further compounded by the fact that the answer might differ on a regional basis. A possible quantitative approach to the problem is suggested by the hyperbolic shape of the Secchi depth-chlorophyll relationship (Figure 2b). As chlorophyll increases, the Secchi depth levels off to a point where relatively large fluctuations in biomass would cause minimal changes in transparency. This point of diminishing returns might be an objective criterion or threshold for eutrophy in the Naumann sense.

In conclusion, the major purpose of this paper has been to reintroduce oxygen concentration as a trophic state indicator and to provide a quantitative framework for the theories of Naumann and Thienemann. In addition, we have attempted to draw some broad conclusions related to Great Lakes eutrophication and to demonstrate some advantages of the quantitative approach, i.e., the intercomparison of incommensurate qualities, and the identification of anomalies. It is hoped that the study will contribute to our ability to draw "limnological conclusions [by more than] merely . . . looking at lakes."

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