A trophic state index for lakes[1]

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Abstract

A numerical trophic state index for lakes has been developed that incorporates most lakes in a scale of 0 to 100. Each major division (10, 20, 30, etc.) represents a doubling in algal biomass. The index number can be calculated from any of several parameters, including Secchi disk transparency, chlorophyll, and total phosphorus.

My purpose here is to present a new approach to the trophic classification of lakes. This new approach was developed because of frustration in communicating to the public both the current nature or status of lakes and their future condition after restoration when the traditional trophic classification system is used. The system presented here, termed a trophic state index (TSI), involves new methods both of defining trophic status and of determining that status in lakes.

All trophic classification is based on the division of the trophic continuum, however this is defined, into a series of classes termed trophic states. Traditional systems divide the continuum into three classes: oligotrophic, mesotrophic, and eutrophic. There is often no clear delineation of these divisions. Determinations of trophic state are made from examination of several diverse criteria, such as shape of the oxygen curve, species composition of the bottom fauna or of the phytoplankton, concentrations of nutrients, and various measures of biomass or production. Although each changes from oligotrophy to eutrophy, the changes do not occur at sharply defined places, nor do they all occur at the same place or at the same rate. Some lakes may be considered oligotrophic by one criterion and eutrophic by another; this problem is sometimes circumvented by classifying lakes that show characteristics of both oligotrophy and eutrophy as mesotrophic.

Two or three ill-defined trophic states cannot meet contemporary demands for a sensitive, unambiguous classification system. The addition of other trophic states, such as ultra-oligotrophic, meso-eutrophic, etc., could increase the discrimination of the index, but at present these additional divisions are no better defined than the first three and may actually add to the confusion by giving a false sense of accuracy and sensitivity.

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Current approaches

The large number of criteria that have been used to determine trophic status has contributed to the contention that the trophic concept is multidimensional, involving aspects of nutrient loading, nutrient concentration, productivity, faunal and floral quantity and quality, and even lake morphometry. As such, trophic status could not be evaluated by examining one or two parameters. Such reasoning may have fostered multiparameter indices (e.g. Brezonik and Shannon 1971; Michalski and Conroy 1972). A multiparameter index is limited in its usefulness because of the number of parameters that must be measured. In addition, the linear relationship assumed

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between the parameters in some of these indices does not hold as evidence presented below indicates.

Alternatives to the multidimensional trophic concept have been based on a single criterion, such as the rate of supply of either organic matter (Rodhe 1969) or nutrients (Beeton and Edmondson 1972) into a lake. Indices based on a single criterion potentially could be both unambiguous and sensitive to change. However, there is currently no consensus as to what should be the single criterion of trophic status, and it is doubtful that an index based on a single parameter would be widely accepted.

Basis for a new index

The ideal trophic state index (TSI) should incorporate the best of both the above approaches, retaining the expression of the diverse aspects of trophic state found in multiparameter indices yet still having the simplicity of a single parameter index. This can be done if the commonly used trophic criteria are interrelated. The evidence is that such is the case. Vollenweider (1969, 1976), Kirchner and Dillon (1975), and Larsen and Mercier (unpublished) have developed empirical equations to predict phosphorus concentration in lakes from knowledge of phosphorus loading. Sakamoto (1966) and Dillon and Rigler (1974) have shown a relationship between vernal phosphorus concentration and algal biomass, measured as chlorophyll *a* concentration. Lasenby (1975) used Secchi disk transparency to predict areal hypolimnetic oxygen deficits. If many of the commonly used trophic criteria could be related by a series of predictive equations, it would no longer be necessary to measure all possible trophic parameters to determine trophic status. A single trophic criterion, e.g. algal biomass, nutrient concentration, or nutrient loading, could be the basis for an index from which other trophic criteria could be estimated or predicted by means of the established relationships. Alternatively, measurements of any of the trophic criteria could be used to determine trophic status.

I chose algal biomass as the key descriptor for such an index largely because algal blooms are of concern to the public. An index that is particularly sensitive to such concern would facilitate communication between the limnologist and the public.

Values for algal biomass itself are difficult to use in the index because biomass is a poorly defined term, usually in turn estimated by one or more parameters such as dry or wet weight, cell volume, particulate carbon, chlorophyll, or Secchi disk transparency. I constructed the index using the range of possible values for Secchi disk transparency. In addition to having values easily transformed into a convenient scale, Secchi disk transparency is one of the simplest and most often made limnological measurements. Its values are easily understood and appreciated.

The relationship between algal biomass and Secchi disk transparency is expressed by the equation for vertical extinction of light in water

$$I_z = I_0 e^{-(k_w + k_b)z}, \tag{1}$$

where $I_z =$ light intensity at the depth at which the Secchi disk disappears, $I_0 =$ intensity of light striking the water surface, $k_w =$ coefficient for attenuation of light by water and dissolved substances, $k_b =$ coefficient for attenuation of light by particulate matter, and $z =$ depth at which the Secchi disk disappears. The term k_b can be rewritten as αC, where α has the dimensions of $\mathrm{m^2\ mg^{-1}}$ and C is the concentration of particulate matter ($\mathrm{mg\ m^{-3}}$). Equation 1 can then be rewritten as

$$z = \left(\ln \frac{I_0}{I_z}\right)\left(\frac{1}{k_w + \alpha C}\right) \tag{2}$$

and rearranged to form the linear equation

$$\left(\frac{1}{z}\right)\left(\ln \frac{I_0}{I_z}\right) = k_w + \alpha C. \tag{3}$$

I_z is about 10% of I_0 (Hutchinson 1957; Tyler 1968) and can be considered to be a constant. Alpha may vary depending on the size and on the light-absorption and

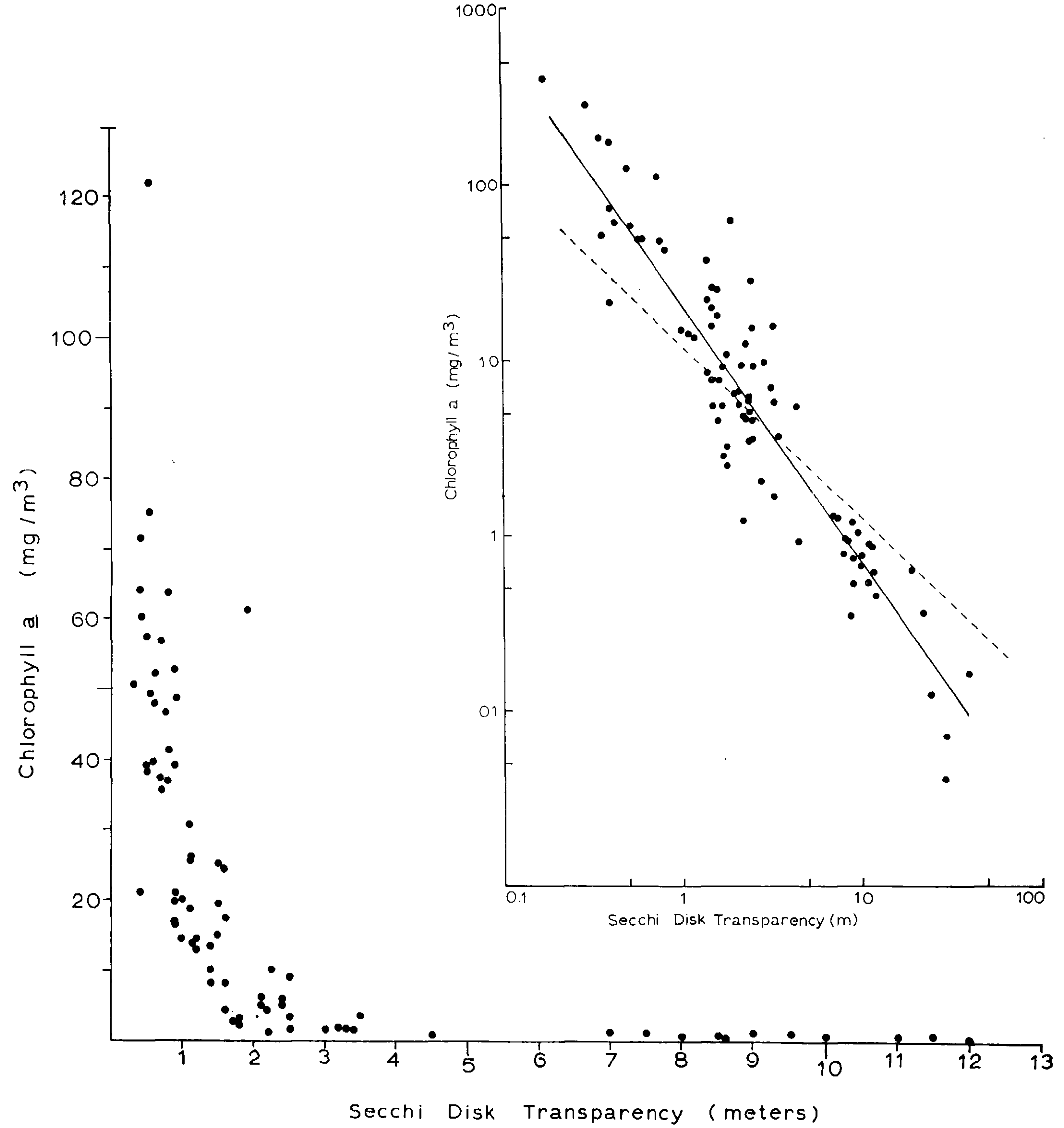

Fig. 1. Relationship between Secchi disk transparency and near-surface concentrations of chlorophyll *a*. Insert: log-log transformation of same data. Dashed line indicates slope of 1.0.

light-scattering properties of the particles, but intuitively one would expect the value, which is the reciprocal of the amount of particulate matter per square meter in the water column above the Secchi disk, not to vary as a function of algal concentration, and for this discussion it is considered a constant.

According to Eq. 3, Secchi disk transparency is inversely proportional to the sum of the absorbance of light by water and dissolved substances (k_w) and the concentration of particulate matter (C). In many lakes studied, k_w is apparently small in relation to C, and hyperbolic curves are obtained when Secchi disk transparency is plotted against parameters related to algal biomass, such as chlorophyll *a* (Fig. 1).

Construction of the index

I defined trophic states for the index using each doubling of algal biomass as the criterion for the division between each state, i.e. each time the concentration of algal biomass doubles from some base value, a new trophic state will be recognized. Because of the reciprocal relationship between biomass concentration and Secchi disk transparency, each doubling in biomass would result in halving transparency. By transforming Secchi disk values to the logarithm to the base 2, each biomass doubling would be represented by a whole integer at Secchi disk values of 1 m, 2 m, 4 m, 8 m, etc.

I felt that the zero point on the scale should be located at a Secchi disk (SD) value greater than any yet reported. The greatest value reported by Hutchinson (1957) is 41.6 m in Lake Masyuko, Japan. The next greatest integer on the $\log_2$ scale is at 64 m. A trophic state index (TSI) value of 0 at 64 m is obtained by subtracting the $\log_2$ of 64 from an indexing number of 6, giving a final TSI equation of

$$\mathrm{TSI} = 10(6 - \log_2 \mathrm{SD}). \qquad (4)$$

The value is multiplied by 10 to give the scale a range of 0 to 100 rather than 0 to 10. Two significant digits are all that can be reasonably expected. The completed scale begins at 0 at SD = 64 m, with 32 m being 10; 16 m, 20; 8 m, 30; etc. The theoretical limit is indefinite, but the practical limit is 100 or 110 (transparency values of 6.4 and 3.2 cm).

The scale is intentionally designed to be numerical rather than nomenclatural. Because of the small number of categories usually allotted in nomenclatural systems, there is both a loss of information when lakes are lumped together and a lack of sensitivity to trophic changes. This problem is alleviated as more and more trophic state names are added, but the system soon becomes so encumbered that it loses its appeal. The scale presented here, a numerical classification with more than 100 trophic categories, avoids these problems. At the same time it retains the original meaning of the nomenclatural trophic system by using major divisions (10, 20, 30, etc.) that roughly correspond to existing concepts of trophic groupings.

Addition of other parameters

The regression of Secchi disk against chlorophyll *a* and total phosphorus was calculated from data readily available. The number of data points and the number of parameters used can be expanded. The data used came from Shapiro and Pfannkuch (unpublished), Schelske et al. (1972), Powers et al. (1972), Lawson (1972), Megard (unpublished), and Carlson (1975).

Chlorophyll *a* (Fig. 1) does not give a linear fit to the model predicted in Eq. 2. A nonlinear element in the relationship necessitated a log-log transformation of the data. The resulting equation is

$$\ln \mathrm{SD} = 2.04 - 0.68 \ln \mathrm{Chl} \qquad (5)$$
$$(r = 0.93, \quad n = 147),$$

where SD transparency is in meters and Chl *a* concentration is in milligrams per cubic meter taken near the surface. One possible explanation for this exponential relationship may be that as algal density increases, the algae become increasingly light limited. In response to lower light per unit cell, more chlorophyll may be produced (Steele 1962).

When all available data were included, the regression of total phosphorus (TP in mg m^{-3}) against the reciprocal of Secchi disk transparency yielded

$$\mathrm{SD} = 64.9/\mathrm{TP} \qquad (6)$$
$$(r = 0.89, \quad n = 61).$$

Total phosphorus should correlate best with transparency when phosphorus is the major factor limiting growth. Correlations may be poor during spring and fall overturn when algal production tends to be limited by temperature or light. Preliminary use of the above regression coefficients in the index suggested that the equation does predict the average seasonal relationship between total phosphorus and trans-

Table 1. Completed trophic state index and its associated parameters.

TSI	Secchi disk (m)	Surface phosphorus (mg/m^3)	Surface chlorophyll (mg/m^3)
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.34
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	20
70	0.5	96	56
80	0.25	192	154
90	0.12	384	427
100	0.062	768	1183

parency, but its predictions for phosphorus are too high in spring and fall and too low during summer. Because the equation is to be used in an index where agreement of correlated parameters is emphasized, I decided to use only summer values in the regression to provide the best agreement of total phosphorus with algal parameters during the season when sampling would normally be done.

There were not enough data available for phosphorus and transparency during July and August to produce a meaningful regression. Instead, chlorophyll was regressed against total phosphorus and the resulting equation combined with Eq. 4 to produce a phosphorus-transparency equation. The chlorophyll-total phosphorus for July and August data points yielded

$$\ln \mathrm{Chl} = 1.449 \ln \mathrm{TP} - 2.442 \qquad (7)$$

$(r = 0.846,\ n = 43)$.

This equation is similar to that derived by Dillon and Rigler (1974) for the relationship between vernal total phosphorus and summer chlorophyll:

$$\ln \mathrm{Chl} = 1.449 \ln \mathrm{TP} - 2.616. \qquad (8)$$

Combining 5 with 7 produced

$$\ln \mathrm{SD} = 3.876 - 0.98 \ln \mathrm{TP}, \qquad (9)$$

or approximately

$$\mathrm{SD} = 48(1/\mathrm{TP}). \qquad (10)$$

This equation was used in the index.

The trophic state index can now be computed from Secchi disk transparency, chlorophyll, or total phosphorus. The computational forms of the equations are

$$\mathrm{TSI(SD)} = 10\left(6 - \frac{\ln \mathrm{SD}}{\ln 2}\right), \qquad (11)$$

$$\mathrm{TSI(Chl)} = 10\left(6 - \frac{2.04 - 0.68 \ln \mathrm{Chl}}{\ln 2}\right), \qquad (12)$$

and

$$\mathrm{TSI(TP)} = 10\left(6 - \frac{\ln \frac{48}{\mathrm{TP}}}{\ln 2}\right). \qquad (13)$$

The completed scale and its associated parameters are shown in Table 1.

Using the index

Seasonal TSI values for several Minnesota lakes are plotted in Fig. 2. The TSI values for total phosphorus tended to fluctuate less than those for the biological parameters, which approached the values based on phosphorus during July and especially August and September. The extreme fluctuations in the TSI based on biological parameters in May and June may result from springtime crashes in algal populations. In Lake Harriet, the chlorophyll and Secchi disk TSI values remained below the phosphorus TSI throughout summer. This divergence of the biological TSI values from the phosphorus TSI cannot yet be explained, but it does emphasize one of the strongest advantages of individually determined trophic indices. All parameters when transformed to the trophic scale should have the same value. Any divergence from this value by one or more parameters demands investigation. For example, is it really true that Lake Harriet is P limited, since it seems to be producing less biomass than the phosphorus levels would suggest? Thus, the TSI scale not only classifies the lake but can serve as an internal check on assumptions about the relationships among various components of the lake ecosystem.

To use the index for classifying lakes requires that a single number be generated that adequately reflects the trophic status of the lake. It should be emphasized that the number generated is only an *index* of

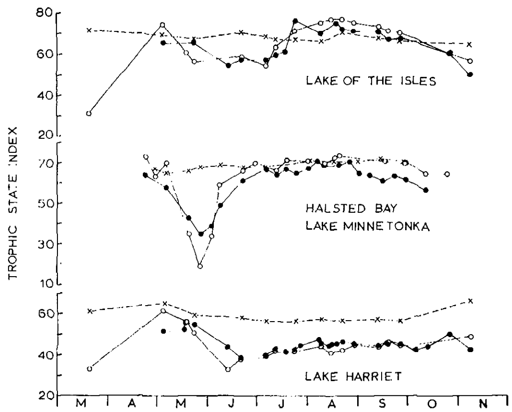

Fig. 2. Seasonal variation in trophic state indices calculated from Secchi disk transparency (●), chlorophyll *a* (○), and total phosphorus (×) for three Minnesota lakes in 1972.

the trophic status of a lake and does not define the trophic status. In other words, chlorophyll or total phosphorus are not considered as the basis of a definition of trophic state but only as indicators of a more broadly defined concept. The best indicator of trophic status may vary from lake to lake and also seasonally, so the best index to use should be chosen on pragmatic grounds.

Secchi disk transparency might be expected to give erroneous values in lakes containing high amounts of nonalgal particulate matter, in highly colored lakes (those with a high k_w), and in extremely clear lakes where k_w again is an important factor in light extinction. The advantage of using the Secchi disk is that it is an extremely simple and cheap measurement and usually provides a TSI value similar to that obtained for chlorophyll.

Chlorophyll *a* values are apparently free from interference, especially if the values are corrected for pheophytin. It may be that the number derived from chlorophyll is best for estimating algal biomass in most lakes and that priority should be given for its use as a trophic state indicator.

Accurate index values from total phosphorus depend on the assumptions that phosphorus is the major limiting factor for algal growth and that the concentrations of all forms of phosphorus present are a function of algal biomass. The former assumption does not seem to hold during spring, fall, or winter (Fig. 2) nor is the latter the case in lakes having high orthophosphorus values (such as some lakes receiving domestic sewage) or in highly colored lakes where some forms of phosphorus may be tied up with humic acids (Moyer and Thomas 1970). The advantage of the phosphorus index is that it is relatively stable throughout the year and, because of this, can supply a meaningful value during seasons when algal biomass is far below its potential maximum.

In instances where the biological TSI values diverge from that predicted by the phosphorus index, it is not satisfactory to average the different values, as the resulting value would neither represent the trophic state predicted by the nutrient concentration nor the biological condition estimated from biological criteria. I suggest that for purposes of classification priority be given to the biological parameters, especially the chlorophyll index, during summer, and perhaps to the phosphorus values in spring, fall, and winter, when the algae may be limited by factors other than phosphorus. These priorities would result in about the same index value during any season of the year.

Some period should be identified during which samples should be taken for lake classification. It might be argued that samples should be taken throughout a calendar year to include all variations in trophic status, but this would require the switching of index parameters during the year, as mentioned above, and the large number of samples required might limit the usefulness of the index.

Basing the index on samples taken during spring or fall turnover would provide a phosphorus index based on mean phosphorus concentration, a measurement used in most predictive loading models. However, some disadvantages of limiting sampling to overturn periods are the brief or even nonexistent overturn in some lakes and the possibility of a lessened agreement with the biological parameters. In addition, mean phosphorus concentrations could be calculated at any time if appropriate morphometric data were available. An alternative might be to take epilimnetic samples during summer stratification, when there should be the best agreement between all of the index parameters. This would allow confidence in comparisons between studies that used different parameters. This period would also coincide, in temperate lakes, with peak recreational usage, increasing the utility of the index in communicating the meaning of the classification to the general public.

A calculation of TSI values from the yearly data for Lake Washington (Fig. 3), supplied by W. T. Edmondson, also illustrates the utility of the scale. In 1957, the lake was receiving 57% of its phosphorus from sewage effluent, and there was a noticeable deterioration in water quality. Sewage diversion began in 1963, and by 1968, 99% of the sewage had been diverted from the lake (Edmondson 1970). Although the data plotted in Fig. 3 show the increase and decrease in nutrients and resulting biological changes, the rates of change differ considerably for each parameter. Chlorophyll *a* seems to be only slightly affected until 1961, whereas Secchi disk transparency shows a drastic decrease between 1950 and 1955. Conversely, after sewage diversion in 1963, chlorophyll *a* shows a dramatic decrease, while there is a 3-year lag before Secchi disk transparency changes noticeably. These discrepancies in rates of response are the result of the inverse relationship between chlorophyll concentration and transparency. Secchi disk transparency is very sensitive to biomass changes at low concentrations, but is insensitive at high concentrations. If only chlorophyll had been measured during the 1950s, it might have seemed that significant changes in the lake did not occur until after 1961. When chlorophyll values are converted to TSI, however, they can be seen to be responding rapidly to enrichment, and the changes parallel those in the TSI values based on transparency. The TSI values predicted by total phosphorus closely parallel the biological TSI values, adding strength to the argument that phosphorus was the key nutrient in determining the biological trophic state of Lake Washington.

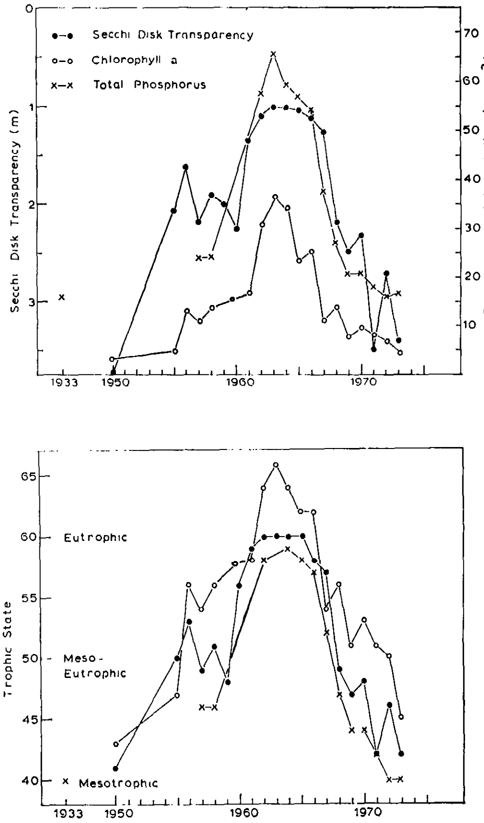

Fig. 3. Top: Yearly changes in average summer values of three parameters in Lake Washington, Seattle, Washington. Below: Data transformed into trophic state index values.

Discussion

The trophic index presented here has several advantages over previous attempts at trophic classification.

The scale is numerical rather than nomenclatural, allowing a large number of individual lake classes rather than three to five distinct ones. This allows sensitivity in describing trophic changes. The major trophic divisions have a logical basis, namely the doubling of concentrations of surface algal biomass, which should make the trophic state classification more acceptable theoretically.

Although the scale itself is constructed from a single parameter, the mathematical correlation with other parameters allows some latitude in selecting the best one for a given situation. The use of correlated parameters also allows trophic comparisons between lakes where different types of data were collected in different studies. Calculation of the index for more than one parameter for a given lake also serves as an internal check both on methodology and on assumptions as to relationships between parameters.

The data used can be minimal or extensive, depending on the level of accuracy desired and the resources available. Secchi disk values alone can give a trophic state classification, information that can be collected even by nonscientists in public-participation programs at little expense (Shapiro et al. 1975). If the survey is more extensive, data on chlorophyll and total phosphorus can provide supplementary or alternative index values. The index number gives both the public and the limnologist a reasonably accurate impression of a lake's water quality. For the layman, the number may have little meaning at first, but it can readily be transformed into Secchi transparency, which is easily understood. By analogy, the Richter scale has meaning for people other than seismologists. For the limnologist the index can be an aid in communication between himself and other scientists. With only the TSI value, a reasonable estimate can be made of the Secchi disk transparency, chlorophyll, and total phosphorus.

The index can be used as a predictive tool in lake-management programs. If the mean total phosphorus after nutrient abatement can be predicted with loading-rate equations such as those of Vollenweider (1969, 1976), then a new TSI can easily be calculated and the biological conditions of the lake estimated. This should prove of value to groups interested in determining how much nutrient abatement is necessary to reach a desired trophic condition.

The index can be used for regional classification of all surface waters, including streams and rivers. Any body of water could be classified using the total phosphorus index, which is essentially a predictor of potential algal biomass. Hutchinson (1969) suggested that lakes and their drainage basins should be considered as trophic systems, where a eutrophic system is one in which the potential concentration of nutrients is high. The index allows the classification of that potential concentration for a watershed or region, at least on the basis of phosphorus. Such a classification could develop an awareness of regional patterns in trophic potential, and could then also allow regional trophic standards to be the basis of rational management.

Finally, a trophic state index is not the same as a water quality index. The term quality implies a subjective judgment that is best kept separate from the concept of trophic state. A major point of confusion with the existing terminology is that eutrophic is often equated with poor water quality. Excellent, or poor, water quality depends on the use of that water and the local attitudes of the people. The definition of trophic state and its index should remain neutral to such subjective judgments, remaining a framework within which various evaluations of water quality can be made. The TSI can be a valuable tool for lake management, but it is also a valid scientific tool for investigations where an objective standard of trophic state is necessary. I hope that the index can serve as a standard of trophic measurement against which comparisons can be made between the many chemical and biological components of the lake system that are related to trophic status. The result could be a more complete and dynamic picture of how these components relate to one another and to the lake ecosystem as a whole.

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Announcement

Pacific Section, American Society of Limnology and Oceanography, Inc.

The Pacific Section will meet 12–16 June 1977 at San Francisco State University, San Francisco, California. A symposium on "The San Francisco Bay" is scheduled for 13 June. Symposia on "Coastal upwelling" and "Ecology of western streams and rivers" are planned for 15 June.