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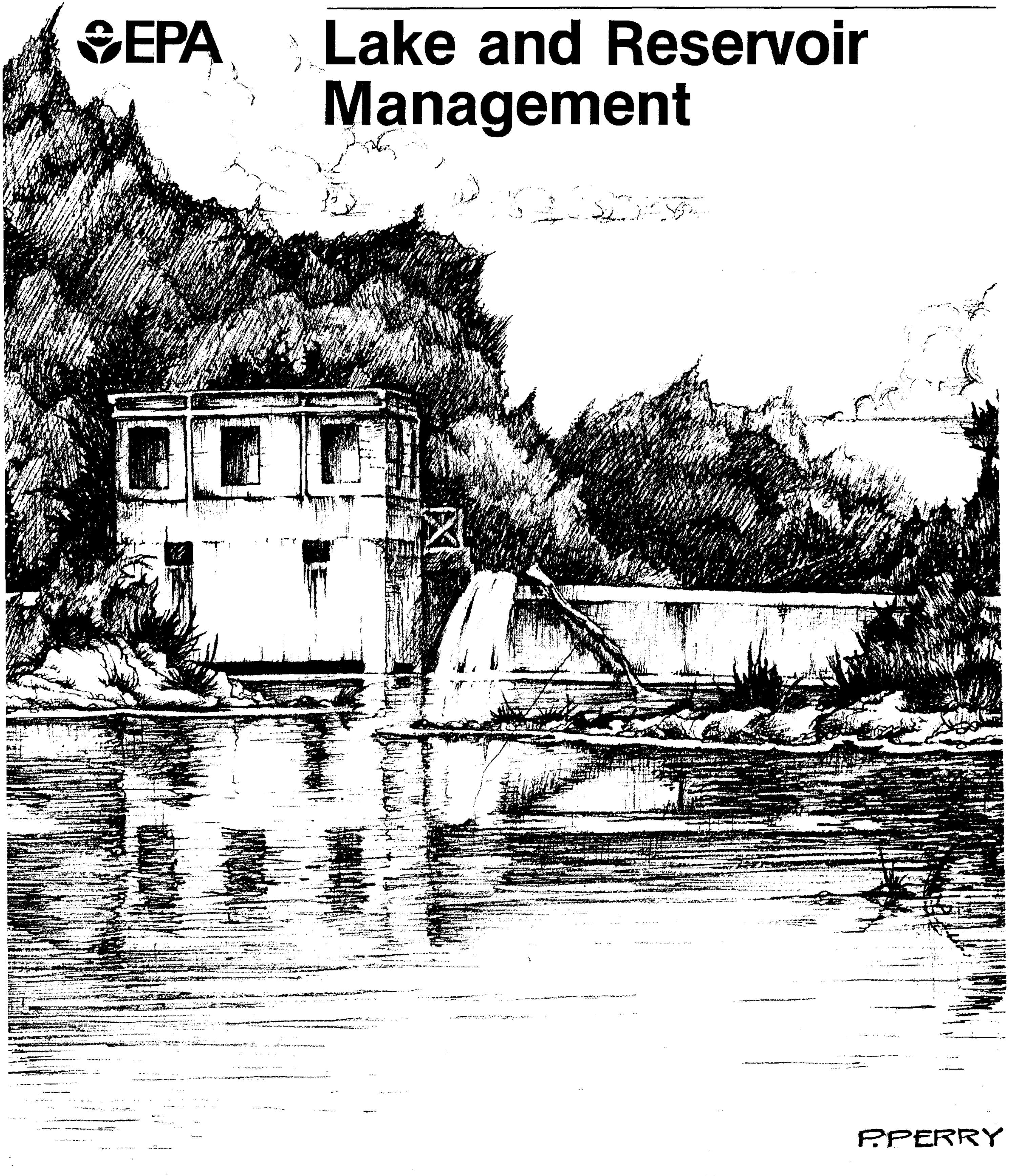

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TROPHIC STATE INDICES IN RESERVOIRS

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ABSTRACT

Trophic state index systems provide a framework for data summary, interpretation, and communication. Carlson's indices can be viewed as reexpressions of bivariate regression analyses derived from phosphorus-limited, northern, natural lakes. Several studies have shown that lakes or reservoirs which are nitrogen limited and/or have relatively high concentrations of non-algal turbidity tend to deviate in various ways from these regressions. These deviations are "problems" only if misinterpreted but limit the use of the index system for comparisons or rankings within certain regions and/or types of impoundments. Analysis of data from 65 Corps of Engineer impoundments indicates that a classification or index system which incorporates effects of nitrogen and non-algal turbidity would be of more general use in reservoirs. A principal components analysis is used to summarize impoundment response data into two composite variables which explain 93 percent of the variance in the original measurements. The first component is interpreted as a quantitative dimension which reflects the total amounts of nutrients and light extinction in the water column. The second is a qualitative dimension which reflects the partitioning of nutrients and light extinction between organic and inorganic forms. Basically, this system takes advantage of the fact that some of the deviations from a Carlson-type index system are systematic and contain information on the partitioning of nutrients and light extinction. If the objective is a concise summary of water quality data, information on both dimensions provides a more complete description of reservoir water quality than any single composite variable or index.

INTRODUCTION

Trophic state index systems provide a framework for summarizing, interpreting, and communicating water quality information. While the concept of a continuous index is more realistic than that of a discrete classification system, its use involves simplification and cannot serve as a complete substitute for analysis and interpretation of individual measurements. Of the practical and common water quality measurements chlorophyll *a* is the most direct indicator of algal standing crop. As discussed by Carlson (1983), given that there are estimates of mean chlorophyll *a* derived from adequate sampling programs, water bodies can be ranked and classified based on these measurements alone and there would be no need for more elaborate "index systems." This approach is limited, however, by (1) weaknesses in chlorophyll *a* as an indicator which can be attributed to variations in chlorophyll *a*/biomass ratios, and (2) practical difficulties in obtaining statistically reliable estimates of mean (or especially, maximum) chlorophyll *a* concentrations from limited monitoring data because of the relatively high temporal or spatial variability that may occur within a given water body and growing season. These problems suggest that interpretations should also be based upon other types of measurements related to trophic state, including transparency and nutrient concentrations. Complications arise when more than one variable is introduced because an underlying model must be assumed.

Carlson's (1977) index system and its descendants (Walker, 1979; Kratzner and Brezonik, 1981; Osgood, 1982) can be viewed as simple transformations of bivariate regression equations derived from populations of lakes. While the index system is "multivariate" in the sense that more than one type of measurement is considered, it is one-dimensional in the sense that it assumes a unique relationship between each measurement and a common scale. The underlying model is that phosphorus exclusively controls chlorophyll and transparency. When applied to data from a given lake, deviations among the various versions of the index will arise from combinations of (1) random sampling and analytical errors and (2) effects of deterministic factors which are not considered in the underlying model. As discussed by Walker (1979), and Kratzner and Brezonik (1981), and Osgood (1982), averaging the index versions helps to reduce the effects of random data errors and incorporates information from each type of measurement. If model errors (attributed to nitrogen limitation or turbidity, for example) are responsible for large deviations among the index versions, averaging can be misleading and results will be in error if phosphorus and/or transparency indices are used in the absence of chlorophyll *a* measurements. Osgood (1982) and Carlson (1983) present frameworks for interpreting systematic deviations among the indices in relation to various deterministic factors: this is one of the most useful applications for the index system because it places lake conditions into perspective and when considered along with other lake characteristics can provide insights into controlling factors other than phosphorus.

Significant deviations among Carlson-type indices have been shown when they are applied to data from some reservoirs (Carlson, 1980; Walker, 1980). Some of these deviations reflect systematic influences of non-algal turbidity on chlorophyll production and transparency at a given phosphorus level. Nitrogen limitation also causes systematic deviations when applied to lake or reservoir data (Carlson, 1980; Kratzner and Brezonik, 1981).

This paper describes a classification system for reservoirs which explicitly considers effects of turbidity and nitrogen, in addition to those considered in a Carlson-type system. This involves a basic change in model structure which goes beyond simple recalibration of the existing framework. The analysis is based upon surface-layer, growing-season means of chlorophyll *a*, transparency, organic nitrogen, and composite nutrient concentration derived from 65 Corps of Engineer impoundments (Walker, 1983).

Composite nutrient concentration is computed from total phosphorus and total nitrogen concentrations and has been designed as a measure of nutrient supply that is independent of whether phosphorus or nitrogen is limiting (Walker, 1983):

$$Xpn = [P^{-2} + ((N - 150)/12)^{-2}]^{-.5}$$

where,

Xpn = composite nutrient concentration (mg/m3)
P = total phosphorus (mg/m3)
N = total nitrogen (mg/m3)

At high N/P ratios, the expression is independent of nitrogen and approaches the total phosphorus concentration. At low N/P ratios, it is independent of phosphorus and approaches (N – 150)/12. The parameters used in computing the composite nutrient concentration are based upon partitioning models which relate organic nitrogen and particulate phosphorus concentrations to chlorophyll *a* and nonalgal turbidity (Walker, 1983). The nitrogen intercept (150 mg/m^3) reflects an average organic nitrogen component which is uncorrelated with chlorophyll *a* or turbidity. The intercept is needed to stabilize the ratio of organic N to particulate phosphorus (12) over the range of observed chlorophyll *a* values. Use of composite nutrient concentration as a trophic state index is an alternative to the scheme proposed by Kratzner and Brezonik (1981) involving the minimum of Carlson-type phosphorus and nitrogen indices.

Relationships among the previous measurements are shown in Figure 1, using different symbols to distinguish reservoirs with chlorophyll transparency products above and below 10 mg/m^2. This value divides the data set roughly in half. As discussed in more detail later, this product is proportional to light-limited productivity and to the fraction of light extinction attributed to chlorophyll and chlorophyll-related substances. The symbol distributions suggest that each of the bivariate relationships is influenced to some extent by the chlorophyll–transparency product. The chlorophyll versus nutrient plot indicates that reservoirs in which chlorophyll accounts for a major portion of light extinction also show a higher response to nutrient concentrations. Some of this influence is spurious because the chlorophyll value determines the vertical scale and partially determines the symbol. The organic nitrogen versus composite nutrient plot is free of spurious correlation, however, and shows a similar symbol distribution, particularly at high nutrient concentrations.

One measure of the performance of an index system is the extent to which it explains variance and covariance among the original measurements. This, in turn, reflects the generality of the underlying model and the amount of "lost" information when the index summarizes water quality conditions (Reckhow, 1981). Table 1 summarizes the performance of various one-dimensional and two-dimensional index systems applied to CE reservoir data.

The one-dimensional systems are similar in concept to Carlson's (1977) and explain between 62.9 percent and 77.3 percent of the total variance in all four measurements. Principal components analyses have been found useful in previous developments of regional trophic state indices for lakes (Shannon and Brezonik, 1972) (Boland, 1976) and other types of classification problems (Harris, 1975). The first principal component (PC-1) defined in Table 1 captures 82.2 percent of the source variance. While PC-1 is analogous to an "average Carlson index", two reservoirs can have similar PC-1 values but very different chlorophyll *a* concentrations, as described below. Thus, it is risky to define PC-1 as a "trophic state index."

Two-dimensional index systems explain significantly higher percentages of the source variance. A system based upon the first two principal components explains 95.5 percent (Fig. 2). The second component accounts for 13.3 percent (or 75 percent of that remaining after consideration of PC-1) and is controlled largely by variations in the product of chlorophyll and transparency, since the signs and magnitudes of these terms are nearly identical. Because of the correlations discussed later, the classification system can be simplified by treating the composite nutrient concentration as the first dimension and the chlorophyll-transparency product as the second. The revised system (Fig. 3) captures 91.6 percent of the variance in the individual measurements.

Correlations between the principal components and impoundment characteristics are listed in Table 2, along with a series of multiple regression equations which help to provide physical interpretations. While PC-1 is strongly correlated with each of the individual measurements, PC-2 is strongly correlated with composite variables, such as the chlorophyll-transparency product (r = .99) and the ratio of chlorophyll *a* to limiting nutrient concentration (r = .87).

The first principal component can be interpreted as a *quantitative* factor which reflects total concentrations and, particularly, the total nutrient supply (Xpn). The second component can be interpreted as a *qualitative* factor which reflects the partitioning of light extinction and nutrients between algal and nonalgal components. Based upon kinetic theories of algal growth, the chlorophyll-Secchi product is also proportional to the areal primary production rate in a mixed, totally-absorbing surface layer under light-limited conditions (Oskam, 1973). The revised classification system permits isolation of the composite nutrient concentration along one dimension, which

Table 1.—Peformance of various index systems.

	Percent of Variance Explained				
Index	Chl-a	Xpn	Org-N	Secchi	Total
	One-Dimensional Indices				
Chl-a	100.0	59.8	71.5	31.4	67.0
Xpn	59.8	100.0	77.1	72.8	77.3
Org-N	71.5	77.1	100.0	45.0	70.0
Secchi	31.4	72.8	45.0	100.0	62.9
PC-1	78.3	93.7	84.5	72.6	82.2
	Two-Dimensional Indices				
PC-1 & PC-2	97.9	95.5	87.2	96.5	95.5
Xpn & B*S	90.1	100.0	84.1	87.5	91.6

all statistics on log scales
PC-1, PC-2 = principal components of covariance matrix:
PC-1 = .554 log(B) + .359 log(Norg) + .583 log (Xpn) – log(S)
PC-2 = .689 log(B) + .162 log(Norg) – .205 log(Xpn) + .676 log(S)
B = chlorophyll *a* (mg/m3)
Norg = organic nitrogen (mg/m3)
Xpn = composite nutrient concentration (mg/m3)
S = Secchi depth (m)

can be interpreted as a causal factor rather than a system response (Carlson, 1983). Information on both dimensions provides a more complete picture of variations in chlorophyll, transparency, and organic nitrogen concentrations than can be derived from any of the one-dimensional systems.

The vectors shown in Figures 2 and 3 depict directions of increasing response measurements, based upon the multiple regressions presented in Table 2. These regressions should not be applied outside of the ranges of data shown in the figures. The two-dimensional aspect of the classification system is reflected by the divergence of the vectors. Projects with the highest chlorophyll *a* concentrations tend to be located in the upper right corner of the plots, where nutrient supply and light-limited productivity are both relatively high. Of the other three measurements, the organic nitrogen vector is most similar to the chlorophyll *a* vector. This reflects the fact that organic nitrogen concentrations are only weakly correlated with nonalgal turbidity levels.

Figure 4 verifies the chlorophyll distribution by using different symbols to depict variations in chlorophyll concentration. Observed chlorophyll *a* contours are shown in relation to those predicted by the multiple regression equation in Table 2. The plot shows

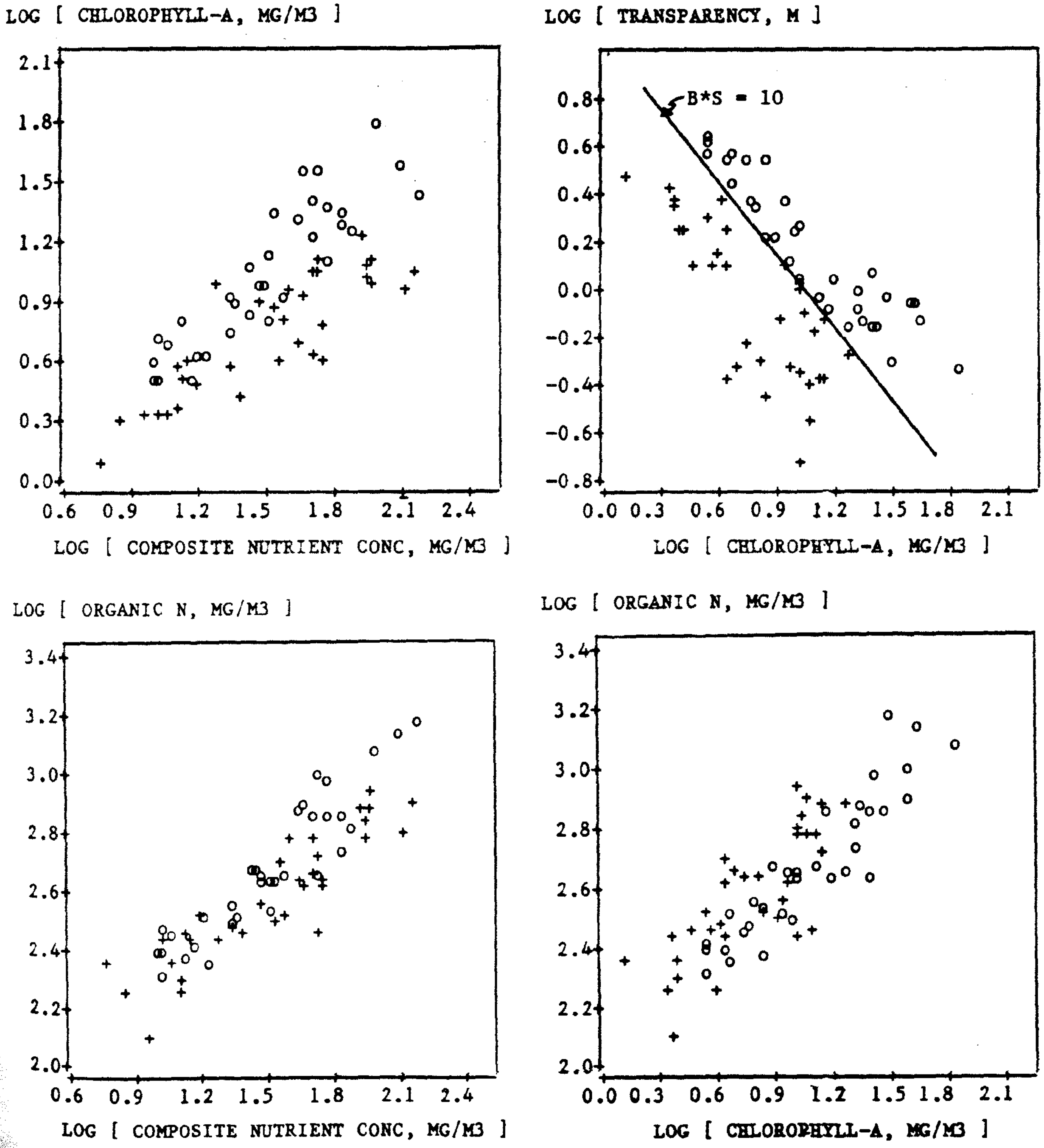

Figure 1.—Relationships among reservoir trophic state indicators[1].

[1] (o) $B*S > 10$ mg/m^2, "chlorophyll-dominated"; (+) $B*S < 10$ mg/m^2, "turbidity-dominated"; B = chlorophyll *a* (mg/m^3); S = Secchi (m).

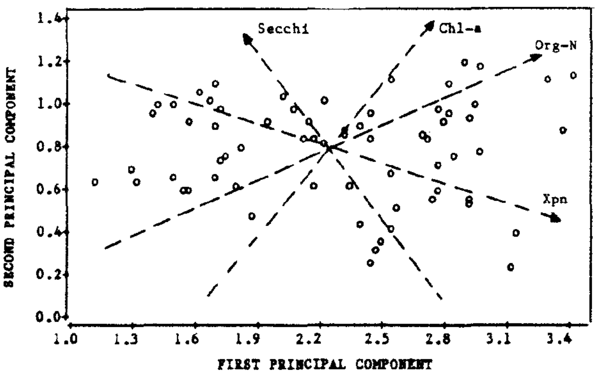

Figure 2.—CE reservoirs distributed on PC-2 versus PC-1 Axes[1].

[1] Arrows show directions of increasing chlorphyll *a*, transparency, organic nitrogen, and composite nutrient concentrations, based upon multiple regression equations in Table 2.

that, at a given nutrient level, chlorophyll *a* concentrations can vary systematically by as much as eightfold ~~(.9 log units), depending upon the second component~~. Since chlorophyll concentrations must be known in order to compute the second dimension, Figure 4 and the regression equation are useful only for data interpretation. A theoretically-based model for predicting chlorophyll as a function of phosphorus, nitrogen, nonalgal turbidity, depth, and predictive flushing rate has been developed for use in a predictive mode (Walker, 1983).

Figure 5 compares the distributions of 65 CE reservoirs, 15 TVA reservoirs (Higgins and Kim, 1981), and 73 natural lakes sampled by the EPA National Eutrophication Survey (U.S. Environ. Prot. Agency, 1978). Because total nitrogen concentrations are required for computation of composite nutrient concentrations, but were not measured by the EPA/NES in north-central and northeastern States, the lakes data are primarily from middle and southern latitudes of the United States. While a wide range of nutrient concentrations is apparent for each group, the distribution of chlorophyll-transparency products tends to be higher for the lakes. A clear distinction between TVA

Table 2.—Impoundment characteristics versus two-dimensional index systems.

Product-Moment Correlation Coefficients:

	Index System					
	I		II			
Variable	**PC-1**	**PC-2**	**Xpn**	**B*S**	**Mean**	**Std. Dev.**
Chlorophyll *a*	.885	.443	.774	.564	.89	.37
Organic nitrogen	.919	.167	.878	.280	2.63	.23
Secchi depth	−.852	.490	−.853	.368	.05	.32
Composite nutrient	.968	−.137	1.000	.017	1.47	.35
Nonalgal turbidity	.610	−.756	.670	−.662	−.22	.38
Chl-*a* * Secchi	.144	986	.017	1.000	.94	.33
Chl-*a*/Xpn	−.070	.870	−.285	.827	−.58	.24
Mean	2.27	.77	.89	1.47		
Standard deviation	.58	.24	.37	.35		

Multiple Regression Equations:

		Coefficients			
System I	**Intercept**	**PC-1**	**PC-2**	**R²**	**SE²**
Chl-*a*	−.899	.554	.689	.979	.0028
Org-N	1.691	.359	.162	.872	.0069
Xpn	.304	.583	−.205	.955	.0057
Secchi	.605	−.474	.676	.965	.0038
Turbidity	−.176	.393	−1.208	.944	.0081
Chl-*a* * Secchi	−.295	.080	1.365	.993	.0008
Chl-*a* / Xpn	−1.203	−.028	.894	.761	.0144

		Coefficients			
System II	**Intercept**	**Xpn**	**B*S**	**R²**	**SE²**
Chl-*a*	−.858	.794	.617	.901	.0136
Org-N	1.623	.567	.185	.841	.0085
Xpn	.000	1.000	.000	1.000	.0000
Secchi	.858	−.794	.382	.875	.0136
Turbidity	−.556	.729	−.777	.903	.0141
Chl-*a* * Secchi	.000	.000	1.000	1.000	.0000
Chl-*a* / Xpn	−.859	−.206	.618	.774	.0136

all statistics computed on log scales

tributary and mainstem impoundments is also apparent. Turbidity and flushing rate are more important as controlling factors in the latter.

Analysis of additional data from Vermont (Walker, 1982) and Minnesota (Osgood, 1982) indicates that chlorophyll-transparency products in northern lakes tend to exceed 10 mg/m2 and most are outside of the range in which light-limitation effects are likely to be important. At high values, variations in chlorophyll-transparency products are probably related more to effects of different algal species (Osgood, 1982) and mixing regimes (metalimnetic algal populations) on the chlorophyll-Secchi relationship than to variations in nonalgal turbidity. A strong correlation between nutrient partitioning (chlorophyll/nutrient) and light partitioning (chlorophyll × transparency) would not be expected in this range.

In summary, a two-dimensional classification system that describes nutrient supply and potential light-limited productivity provides a more complete summary of reservoir water quality than is possible with a one-dimensional system. A principal components analysis yields quantitative and qualitative dimensions which account for 95.5 percent of the variance in four measurements. The second component (chlorophyll-transparency product) explains 75 percent of the variance remaining after consideration of the first component and 75 percent of the deviations from a Carlson-type index system based upon chlorophyll and calibrated to reservoir data (91.6 percent versus 67.0 percent). Because of the importance of the second dimension, rankings of reservoirs based upon chlorophyll would not necessarily correspond to rankings based upon transparency or upon nutrients. These factors should be considered in interpreting water quality data and in applying empirical eutrophication models to reservoirs.

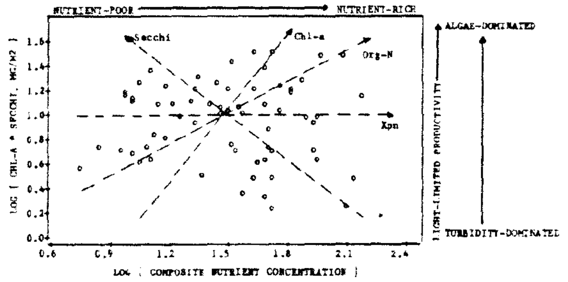

Figure 3.—CE reservoirs distributed on B*S versus Xpn Axes[1].

[1] Arrows show directions of increasing chlorophyll a, transparency, organic nitrogen, and composite nutrient concentrations, based upon multiple regression equations in Table 2.

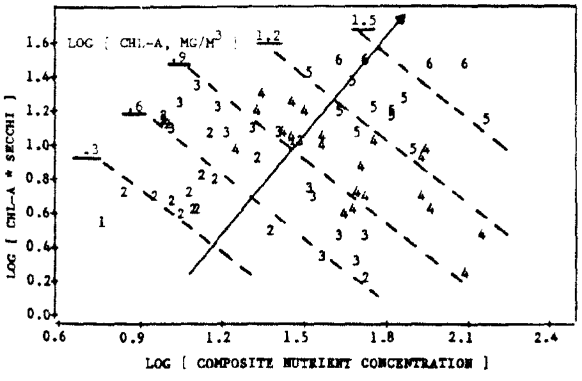

Figure 4.—Distribution of chlorophyll a values on B*S versus Xpn Axes[1].

[1] Symbol	Maximum log 10 (Chl a, mg/m³)
1	.3
2	.6
3	.9
4	1.2
5	1.5
6	> 1.5

Dashed lines show chlorophyll a contours predicted from multiple regression equation in Table 2.

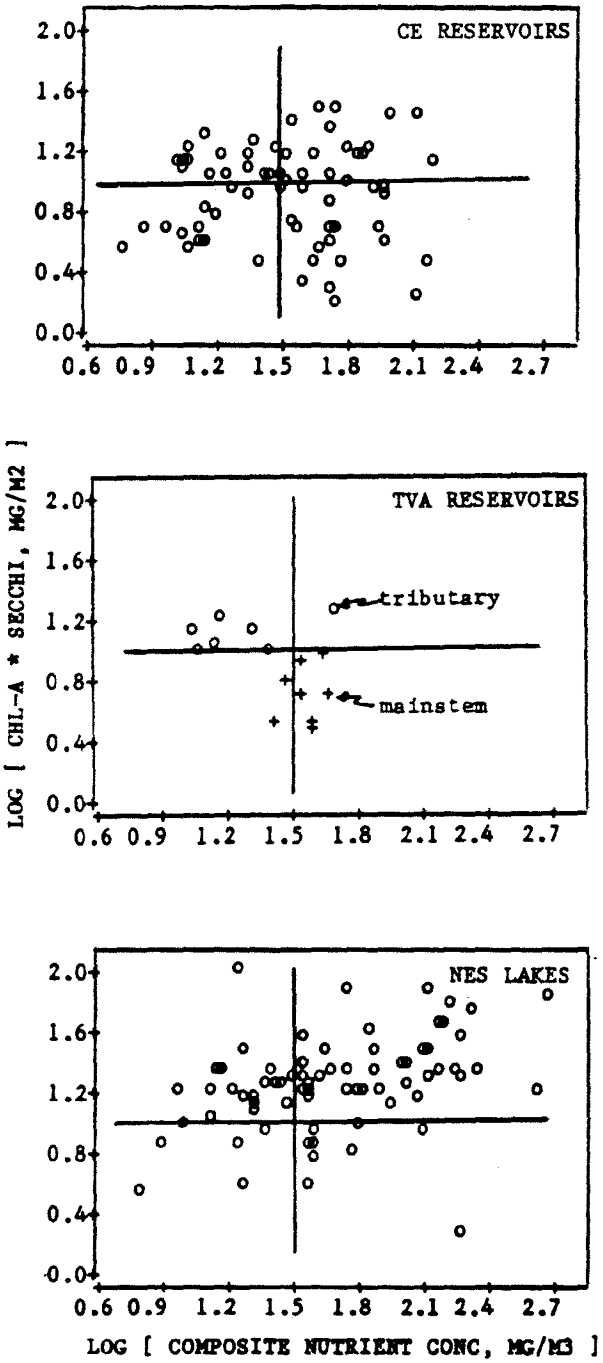

Figure 5.—Distribution of CE reservoirs, TVA reservoirs and EPA/NES lakes on B*S versus Xpn Axes[1].

[1] Horizontal and vertical lines indicate approximate mean values for Corps of Engineer reservoirs.

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