Canadian Water Resources Journal
Vol. 7, No. 1, 1982

AN EMPIRICAL ANALYSIS OF PHOSPHORUS, NITROGEN, AND TURBIDITY EFFECTS ON RESERVOIR CHLOROPHYLL-A LEVELS[1]

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ABSTRACT: As part of an effort to assess the feasibility of applying empirical eutrophication models to reservoirs, relationships among chlorophyll-a, phosphorus, nitrogen, and transparency are empirically examined. The data base is derived from 480 water quality monitoring stations located in 118 U.S. Army Corps of Engineer reservoirs distributed throughout the United States. Existing models assume a direct relationship between seasonally averaged total phosphorus and chlorophyll-a concentrations. It is difficult to identify sets of conditions under which chlorophyll is an exclusive function of total phosphorus in these reservoirs. The phosphorus/chlorophyll relationship derived from stations with average inorganic N / ortho P ratios greater than 10 and non-algal turbidities less than .37 m^{-1} (in units of inverse Secchi depth, corrected for light absorption by chlorophyll-related substances) is found to be similar to phosphorus/chlorophyll relationships derived from P-limited northern lakes. Nitrogen effects on chlorophyll-a are found to be significant in about 22% of the station-years examined, and turbidity effects, in about 69%. Modifications of existing empirical models to include nitrogen and turbidity as regulating factors are needed if they are to be valid and useful over the spectrum of physical and chemical environments found in reservoirs.

RESUME: L'eutrophisation est un processus qui influence plusieurs aspects de l'écologie et de la qualité de l'eau des réservoirs. Des études antérieures sur les données recueillies dans les lacs naturels ont démontré qu'une relation empirique existait entre les concentrations de substances nutritives, la morphométrie, l'hydrologie et les indicateurs de l'état trophique. Quoique ces modelès aient été utilisés pour la planification de la qualité de l'eau des lacs avec un succès mitigé, ils ne peuvent être utilisés à grande échelle pour planifier ou gérer des réservoirs à cause des différences existant entre les diverses caractéristiques des lacs et des réservoirs, caractéristiques qui ont un impact sur la concentration des substances nutritives, notamment l'hydrodynamique, la morphométrie et la sédimentation. Il semble cependant possible que l'approche des modèles puisse être adaptée pour être utilisée sur certains types de plans d'eau construits par l'homme à condition toutefois que ces modèles subissent certaines modifications.

Afin de tester ces méthodes de planification potentielles, on a créé une base de données décrivant 300 réservoirs exploités par le Corps des Ingénieurs de l'Armée Américaine. Cette base de données fournit des renseignements sur l'emplacement, la morphométrie, l'hydrologie, la sédimentation et la qualité de l'eau. Elle est actuellement utilisée pour tester systématiquement des modèles de deux types généraux: (1) la relation entre les indicateurs de l'état trophique observée dans les réservoirs (comprenant les substances nutritives, la chlorophylle-a, la transparence et le bilan d'oxygène dans l'hypolimnion); (2) les modèles qui comparent les apports externes du phosphore et d'autres facteurs déterminants, aux indicateurs mentionnés ci-dessus.

Des études préliminaires montrent l'étendue et l'importance des gradients spatiaux que l'on retrouve dans bon nombre de réservoirs et qui sont causés par l'advection. Les indicateurs de l'état trophique se comportent souvent de facon différente lorsque les données des différents postes de mesure d'un réservoir donné sont recueillies de l'amont vers l'aval. Ces tendances sont souvent la source de problèmes que l'on ne rencontre habituellement pas lors des analyses dans les lacs. Par exemple, la notion de la "moyenne" de la chlorophylle-a ou de la transparence n'a que très peu de signification lorsque les niveaux varient d'un facteur de 10 ou plus d'une extrémité d'un réservoir à l'autre. Lorsqu'on les transforme en coordonnées de temps de déplacement, les variations temporelles montrent des détails sur les taux et les directions des processus contrôlant la qualité de l'eau et la réponse trophique, comprenant la croissance des algues, l'origine des substances nutritives, la sédimentation et les processus d'adsorption/désorption.

Dans cette présentation, on donne plusieurs exemples de variations spatiales issues de différents types de réservoirs et on traite de la possibilité de les étendre à d'autres réservoirs, en fonction des caractéristiques qui contrôlent ces variations, notamment le temps de séjour de l'eau, la morphométrie et la sédimentation.

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[1] International Symposium on Reservoir Ecology and Management, Université Laval, Quebec, June, 1981.

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INTRODUCTION

The process of eutrophication influences many aspects of reservoir water quality and ecology. Previous studies of data from natural lakes have identified empirical relationships among nutrient loading, morphometry, hydrology, and trophic state indicators (Vollenweider, 1976, Dillon, 1974). While these models have been used in lake water quality planning with moderate success, their use in reservoir planning or management is tenuous because of lake/reservoir differences in many characteristics which influence responses to nutrient loadings, including hydrodynamics, morphometry, sedimentation, and region (Thornton et al., 1980, Walker, 1980b). It seems feasible, however, that with suitable modifications empirical modelling approaches could be adapted for use in certain types of man-made impoundments.

To provide a means for testing these potential planning methods, a data base describing 299 reservoirs operated by the U.S. Army Corps of Engineers has been compiled (Walker, 1981). The data base includes information on location, morphometry, hydrology, sedimentation, and water quality in Corps of Engineer reservoirs with appreciable summer pools. Currently, the data base is being used for systematic testing of models in two general categories: (1) relationships among trophic state indicators measured within reservoirs (including nutrients, chlorophyll-a, transparency, and hypolimnetic oxygen deficit); and (2) models relating external nutrient loading and other controlling factors to the above indicators.

Preliminary studies have described spatial water quality gradients which occur in many reservoirs as a result of advection, sedimentation, and ecological processes (Thornton et al., 1980, Walker, 1980a). Trophic state indicators often exhibit trends when data from different monitoring stations are viewed in downstream order. These trends introduce complexities which are not generally found in analyses of lake systems. Analysis of within-reservoir variations requires consideration of spatial and temporal scales (i.e., time-of-travel), as well as the physical, chemical and biological relationships which regulate algal growth and standing crop at a given location.

Existing empirical models are based primarily upon the assumption of a direct relationship between total phosphorus and chlorophyll-a concentration, as demonstrated by Dillon and Rigler (1974) and others, for northern temperate lakes with total nitrogen to total phosphorus ratios exceeding 12. Studies by

Smith (1980) have indicated that lake chlorophyll concentrations can be predicted more accurately when both total phosphorus and total nitrogen concentrations are considered, even for total N/P ratios as high as 32. Turbidity, attributed to allocthonous suspended solids, and color are also of potential importance in reservoirs, because of their roles in restricting light penetratio and nutrient availability (Walker and Kuhner, 1978, Hern et al., 1981). This paper empirically analyzes the roles of phosphorus, nitrogen and turbidity as factors regulating chlorophyll levels in reservoirs. These relationships are fundamental to interpreting spatial water quality gradients and, more generally, to understanding the problems involved in adapting and applying nutrient loading models in reservoirs.

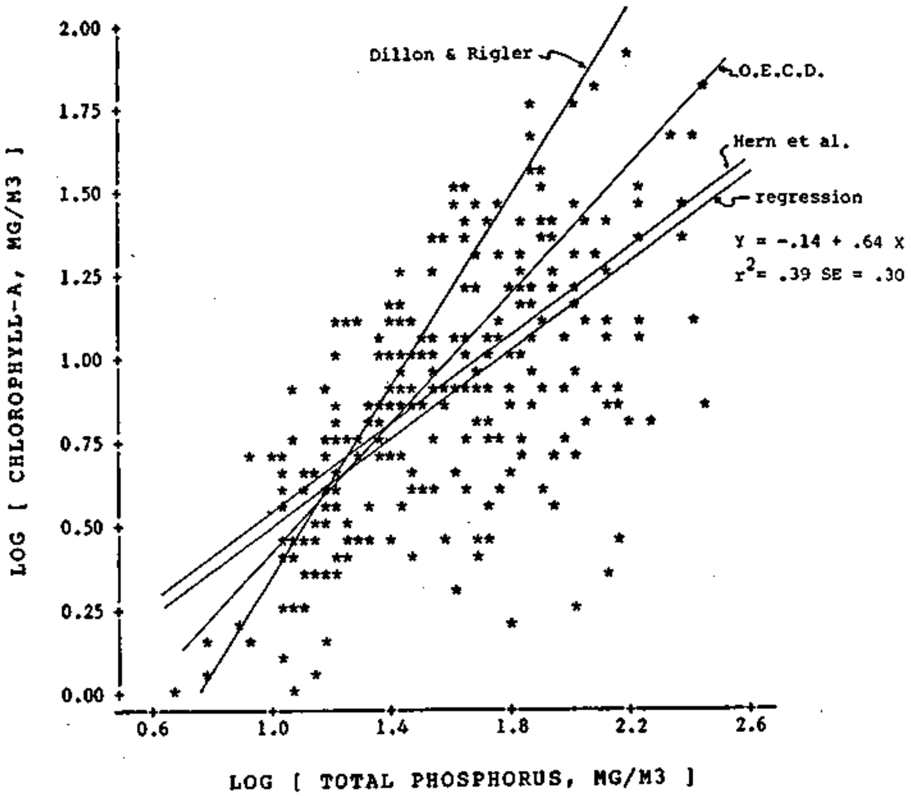
DATA BASE

The data base for this work consists of water quality data from 480 stations located in 118 reservoirs, derived from the U.S. Environmental Protection Agency's STORET system and from a separate data base maintained by the Ohio River Division of the Corps of Engineers. Nutrient, chlorophyll-a, and transparency measurements have been averaged by year at each station, including only measurements taken between April and October at depths less than 4.6 meters. Most (79%) of the station-years are from the U.S. Environmental Protection Agency's National Eutrophication Survey, which employed integrated sampling for chlorophyll-a over the euphotic zone. Station-years with fewer than two sampling dates for total phosphorus, chlorophyll-a, and transparency have been excluded. To provide a basis for error analysis, the standard errors of each station-year mean have also been estimated from the temporal variance and number of sampling dates. A separate list of 257 station-years with at least three sampling dates and with mean phosphorus, nitrogen chlorophyll, and transparency coefficients of variation less than .5 has been identified for use in model parameter estimation.

BIVARIATE ANALYSIS

Figure 1 depicts the relationship between total phosphorus and chlorophyll-a for station-years with at least three sampling dates. For comparative purposes, regression lines calculated by Dillon and Rigler (1974), Hern et al. (1981) and Vollenweider and Kerekes (1980) are shown, along with the regression line calculated

Figure 1
Relationship Between Chlorophyll and Total Phosphorus



from the data:

$$\log_{10}(B) = -.14 + .64 \log_{10}(P) \quad (1)$$

where,

B = mean chlorophyll-a (mg/m^3)

P = mean total phosphorus (mg/m^3)

The equation explains 39% of the variance in the chlorophyll-a data with a residual standard error of .30 logarithmic units. It is apparent that the phosphorus/chlorophyll relationship is not stable across data sets (as indicated by the variations in the regression lines) and that the regression line calculated from these data would be of limited use for planning purposes. The regression line is closest to that calculated by Hern et al. (1981), based upon U.S.E.P.A. National Eutrophication Survey data from over 700 lakes and reservoirs, some of which are included in the data base analyzed here. The slopes of the other regressions, derived primarily from natural lakes, are greater.

The relationship between transparency and chlorophyll-a is shown in Figure 2. The following model is used to separate light extinction into two components, one related and the other unrelated to chlorophyll (Walker and Kuhner, 1978, Lorenzen, 1980):

$$1/S = a + b\,B \quad (2)$$

where,

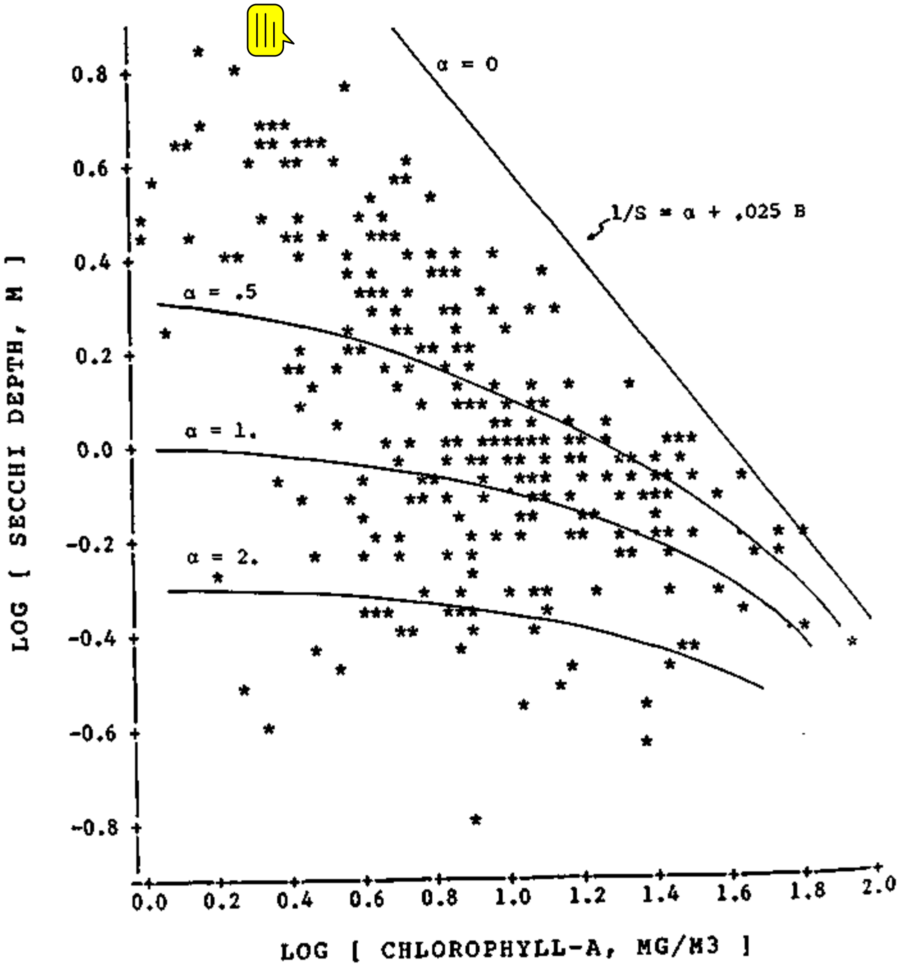
S = Secchi depth (m)

a = non-algal component m^{-1}

b = slope parameter = .025 m^2/mg

The lines in Figure 2 depict predicted transparencies for various values of the non-algal component, variations in which reflect variations in allochtonous suspended solids and color. For simplicity, this component is referred to as "turbidity" in the remainder of the paper. Because of turbidity variations, chlorophyll-a is a poor predictor of transparency and vice-versa. The value of the slope parameter, 0.25 m^2/mg, has been selected so that the predicted Secchi depth at zero turbidity follows the upper edge of the distribution shown in Figure 2. While the slope may vary somewhat with algal species and environmental

Figure 2
Relationship Between Transparency and Chlorophyll



conditions, the second term in equation (2) accounts for the average effect of chlorophyll and algal-related substances on transparency, including algal biomass and detritus. Turbidities calculated from average transparencies and chlorophyll-a values using equation (2) are restricted to a minimum value of .08 m^{-1}, which corresponds to a transparency of 12.5 meters in the absence of chlorophyll-a and other algal-related light extinction components.

MULTIVARIATE ANALYSIS

Further analysis shows that both nitrogen and turbidity are related to chlorophyll in ways which may account for at least some of the variability in the phosphorus/chlorophyll correlations. This is a problem in four dimensions which is difficult to analyze using the bivariate plotting strategy traditionally used in studying phosphorus/chlorophyll relationships. It is also complicated by collinearity in the factors. The approach taken below is to reduce the problem to three dimensions using three alternative techniques:

(1) Dividing the data set into groups based upon turbidity and studying the response of chlorophyll to phosphorus and nitrogen separately within each group;

(2) Studying the response of chlorophyll to phosphorus and turbidity at stations which are classified as phosphorus limited, based upon inorganic N/ortho-P ratios.

(3) Combining two dimensions by calculating the residual from the Dillon-Rigler (1974) phosphorus/chlorophyll regression equation and studying its relationship with turbidity and N/P ratios.

Each relationship is summarized by fitting a three-dimensional response surface of the following form (Box _et al._, 1978):

$$Z = K_0 + K_1 X + K_2 X^2 + K_3 X^3 + K_4 Y + K_5 Y^2 + K_6 Y^3 + K_7 X Y + K_8 X^2 Y + K_9 X Y^2 + K_{10} T \qquad (3)$$

where,

K_i = empirical parameters
Z = predicted variable
X = first independent variable

Y = second independent variable

T = mean temperature (degrees-C)

Base-10 logarithmic transformations are used for the X,Y, and Z variables in each case. The cubic polynomials and interaction terms provide fexibility for fitting a wide variety of possible response surface topographies, provided that no sharp discontinuities exist. The response surface methodology provides a convenient means of summarizing the data in each group. It is used here more as an analytical tool than as a formal model. More concise and theoretically consistent models could be formulated and tested, based upon the results of the data analysis.

Preliminary analyses indicated that response surface residuals were correlated with average temperature at low-turbidity stations. A linear temperature correction term has been included in the equation to account for differences in the seasonal distribution of sampling dates. At low-turbidity stations ($< .4\ m^{-1}$), average temperatures on chlorophyll and nutrient sampling dates ranged from 14 to 30 degrees C. Low temperatures primarily reflect dominance of spring and or fall sampling dates over summer dates. Significant seasonal effects on chlorophyll-a concentrations have been identified previously (Walker, 1980a,b) For chlorophyll-a predictions at low-turbidity stations, the slope of the correction term is on the order of .02/deg-C, which corresponds to a maximum temperature effect of .3 logarithmic units. The term is negligible at high-turbidity stations.

Surface contours are displayed in Figures 3-6, using uniform scales and a contour shading interval of .2 logarithmic units. Each surface has been trimmed to reflect data ranges and adjusted to an average temperature of 22 degrees C. Response surface statistics are summarized in Table 1. Within-station variability leads to errors in the estimated mean concentrations for each station-year and accounts for some of the differences between the observed and predicted concentrations (Walker, 1980a,b). Based upon total residual variance and the calculated standard error of each station-year mean, model and data error components have been estimated and listed in Table 1 for each response surface.

Figures 3 and 4 display chlorophyll responses to nitrogen and phosphorus for low-turbidity and high-turbidity stations, respectively, using a turbidity value of $.4\ m^{-1}$ to divide the groups. Analysis of residuals has indicated that $.4\ m^{-1}$ is a reasonable cutpoint for the effects of turbidity on the chlorophyll/nutrient response surface. While some systematic turbidity

Table 1

Summary of Response Surface Statistics

Statistic	Note	Model				
Predicted Variable	a	—Chlorophyll-a—			-Dillon/Rigler- Residual	
X Variable		P	P	P	Turb.	Turb.
Y Variable		N	N	Turb.	N/P	Ni/Pi
Data Group	b	I	II	III	all	all
Figure		3	4	5	6	7
Number of Station-Years		159	331	403	490	488
F Ratio	c	30.8	9.6	28.4	91.1	74.8
Model Deg. of Freedom		10	10	10	10	10
Error Deg. of Freedom		148	320	392	479	477
Gross R-Squared		.675	.223	.420	.655	.611
Total Mean Squared Error		.0524	.0770	.0596	.0768	.0870
Data Error Component		.0322	.0416	.0379	.0525	.0525
Model Error Component		.0202	.0354	.0217	.0243	.0345
Chlorophyll Variance		.1513	.0967	.0999	.1239	.1239
Data Error Comp.		.0240	.0268	.0253	.0258	.0258
Corrected Variance	d	.1273	.0699	.0746	.0981	.0981
Model R-Squared	e	.841	.494	.709	.752	.648

a - Dillon-Rigler Residual = log(B) - 1.45 log(P) + 1.14

b - Data Groups I = non-algal turbidity $< .4\ m^{-1}$
II = non-algal turbidity $> .4\ m^{-1}$
III = inorganic N / ortho P > 10

c - F Ratio = model mean square / error mean square;
all F ratios significant at $p < .0001$

d - total variance - data error component

e - 1 - (model error)/(corrected chlorophyll-a variance)

Figure 3
Chlorophyll vs. Total P and Total N for Stations with
Turbidity < .4 m^{-1}

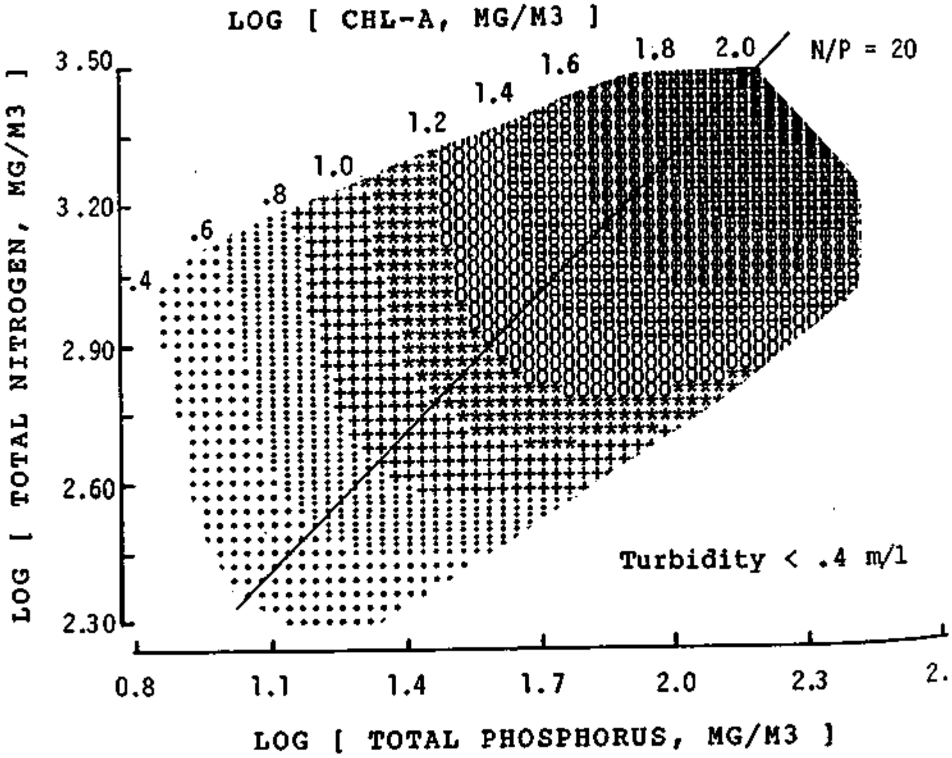
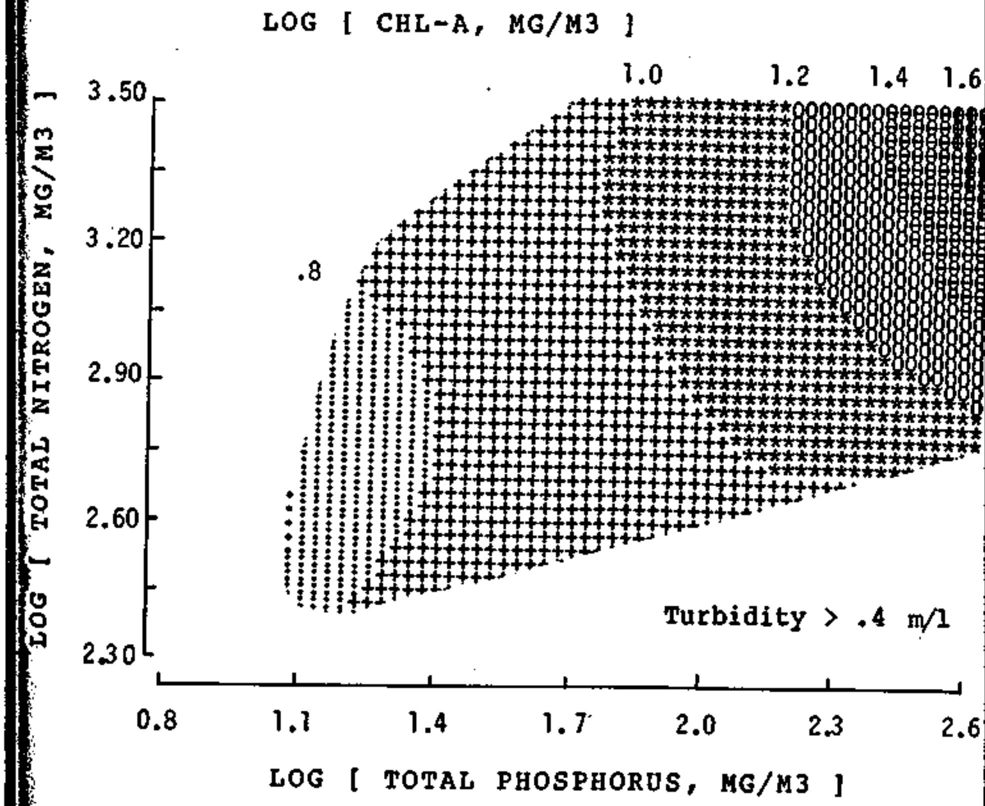


Figure 4
Chlorophyll vs. Total P and Total N for Stations with
Turbidity > .4 m^{-1}



effects remain within each group, these are small relative to the between-group differences.

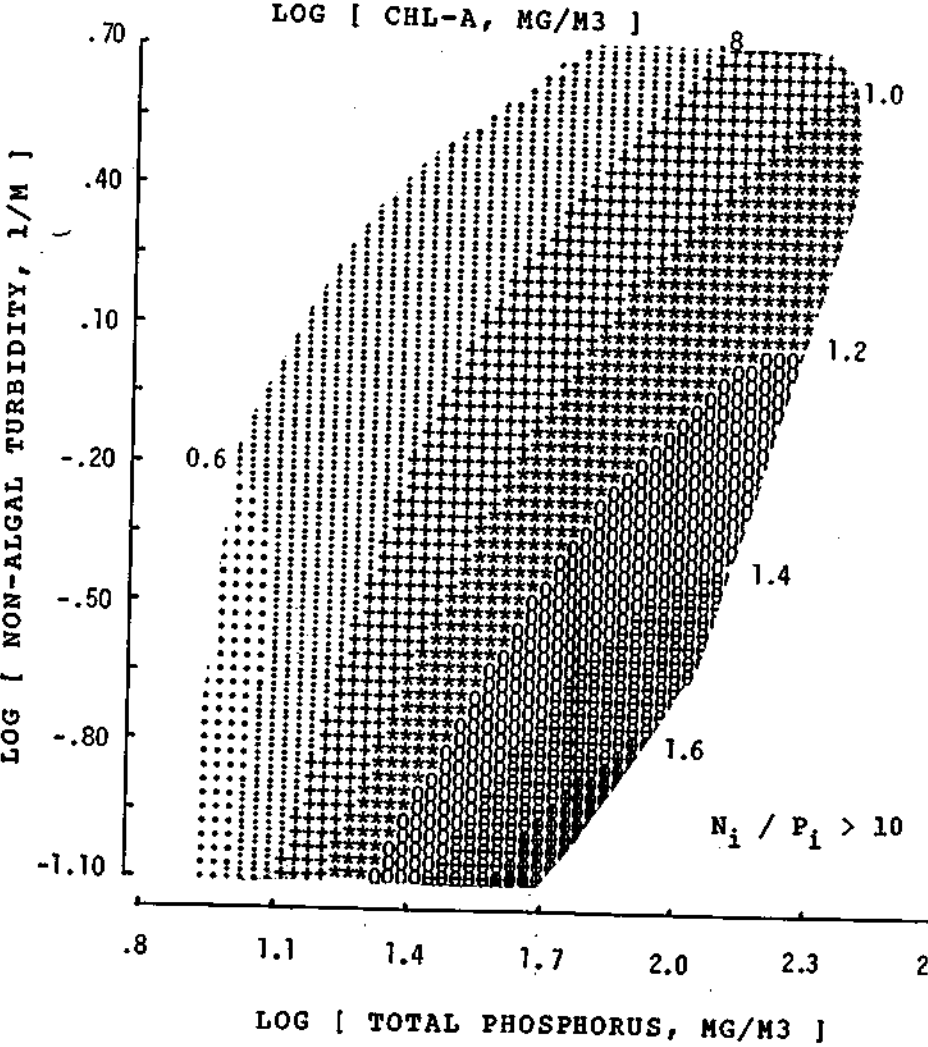
Chlorophyll levels are much more sensitive to nutrient concentrations at low-turbidity stations. Model R-Squared values are .84 and .49 for the low-turbidity and high-turbidity stations, respectively. In Figure 3, regions of phosphorus- and nitrogen-limitation are indicated by vertical and horizontal contours, respectively. A contour angle of 45 degrees reflect equal sensitivity to nitrogen and phosphorus and occurs at a total N/P ratio of about 20 (Figure 3). This is considerably higher than the algal physiologic ratio (about 7), and agrees qualitatively with the results of Smith (1980). In the high turbidity group (Figure 4), chlorophyll sensitivity to nutrients is low and effects of nitrogen limitation are less evident.

Figure 5 depicts the response of chlorophyll to turbidity and phosphorus for stations with inorganic N / ortho-P ratios exceeding 10 (R-Squared=.71). This criterion has been used to distinguish N-limited from P-limited stations because, as demonstrated above, use of a single total N/P ratio to assess limiting nutrient may not be valid over the range of turbidities studied. The slopes of the contours indicate that it is difficult to separage the effects of phosphorus from those of turbidity or to identify a set of conditions under which only one of the factors is controlling. Turbidity seems to have less effect at lower phosphorus concentrations, where the contours are more nearly vertical. Highest chlorophyll-a levels are found at stations with high phosphorus and low turbidity. Some of the apparent turbidity effect may result from the fact that the turbidity values are not estimated independently of chlorophyll-a (see equation (2)); however, turbidity is more strongly correlated with transparency (r=-.89) than with chlorophyll-a (r=.16).

The decreasing response of chlorophyll to increasing turbidity is most likely related to the effects of turbidity on phosphorus availability and/or light penetration. Both Figures 3 and 5 indicate that the slope of chlorophyll with respect to phosphorus is about 1.4 at high N/P ratios and low turbidity. This slope agrees with phosphorus/chlorophyll regressions derived from P-limited natural lakes (Dillon and Rigler, 1975, Jones and Bachman, 1976, Carlson, 1977, Walker, 1979).

In order to permit analysis of nitrogen and turbidity effects simultaneously, residuals from the Dillon-Rigler phosphorus/chlorophyll regression(see Table 1) have been tested against turbidity

Figure 5
Chlorophyll vs. Total P and Turbidity for Stations with Inorganic N / Ortho P > 10



and nitrogen to phosphorus ratio. Figure 6 displays the response surface using an inorganic N/P as the indicator of limiting nutrient; results using total N/P are qualitatively similar. The top of the response surface, located at low turbidity and high N/P ratio, is fairly flat. This is the region in which chlorophyll-a is most strongly correlated to phosphorus. The effects of nitrogen limitation (indicated by horizontal contours) become obscure at high turbidity levels. Response surfaces calculated for the chlorophyll/phosphorus ratio (Hern et al., 1981) are similar in shape.

The response surfaces described above provide some guidance for assessing the effects of nitrogen and turbidity on phosphorus/chlorophyll relationships. To determine the conditions under which these effects are negligible in relation to errors inherent in the empirical modelling approach, a series of phosphorus/chlorophyll regressions have been done, starting with a group of stations with inorganic N/P ratios exceeding 16 and turbidity levels less than .2 m^{-1} (the "top" of the response surface in Figure 6). This model has been applied to all the data and residuals plotted against turbidity, inorganic N/P ratio and total N/P ratio. The bounds of the data set have been expanded until significant deviations (about .2 logarithmic units) from the fit are evident in the residuals just outside of the range of the data set. The following regression model summarizes the phosphorus/chlorophyll relationship for station-years with turbidities less than .37 m^{-1} and inorganic N/P ratios greater than 10:

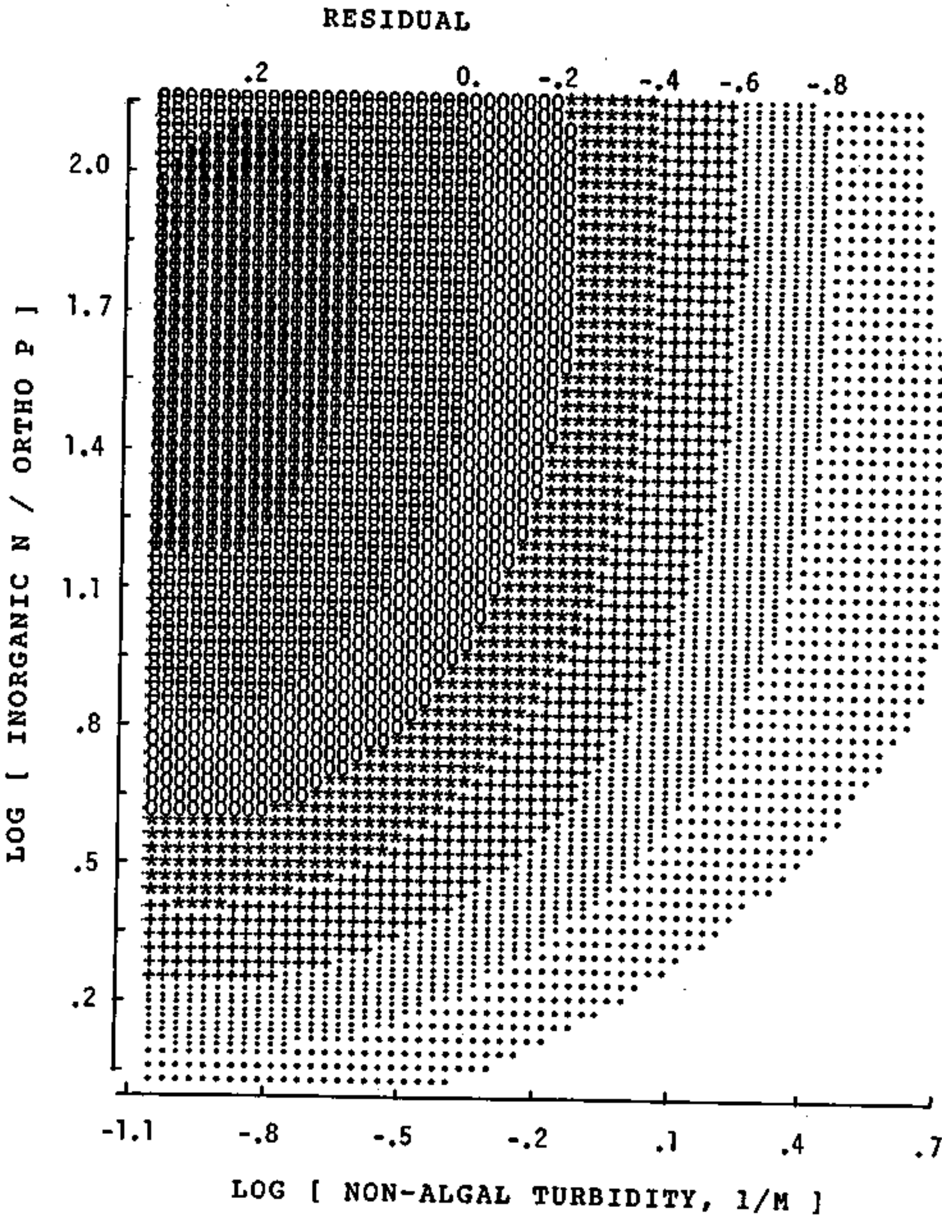
$$\log_{10}(B) = -1.56 + 1.46 \log_{10}(P) + .022\ T \qquad (4)$$

At an average station temperature of 22 degrees C, this becomes:

$$\log_{10}(B) = -1.08 + 1.46 \log_{10}(P) \qquad (5)$$

With parameters estimated from 63 station-years with at least three sampling dates, the model has a standard error of .19 and explains 78% of the observed chlorophyll-a variance. The regression equation is nearly identical to those derived from P-limited northern lake data by Killon and Rigler (1974) (slope = 1.45, intercept = -1.14), Jones and Bachman (1976) (slope = 1.46, intercept = -1.09), and Carlson (1977) (slope = 1.45, intercept = -1.06). Thus, when data from turbid and/or N-limited reservoirs are excluded, the phosphorus.chlorophyll relationship in these reservoirs is indistinguishable from that found in northern lakes. Analyses of residuals from the above equation have indicated no significant effects of station type (upper pool, mid-pool,

Figure 6
Dillon/Rigler Residual vs. Turbidity and Inorganic N / Ortho P



near-dam), station total depth (range 2.9 - 60 m), reservoir mean depth (range 3.2 - 23 m), hydraulic residence time (range .06 - 6.3 years), or surface overflow rate (range 2 - 305 m/year).

REGIONAL VARIATIONS

Table 2 classifies the station-years in the complete data set based upon limiting nutrient, turbidity level, and region, defined by Corps of Engineer Division. Nutrient limitation is approximately assessed using an inorganic N/ortho P ratio of 10 and turbidity classifications are assigned using a cutpoint of .37 m^{-1}. Regional patterns suggest an east-west trend from phosphorus- to nitrogen-limitation and greater percentages of high-turbidity stations in the Ohio River, Lower Mississippi, Southwest, and Missouri River Divisions. Additional data from the New England, North Atlantic, North Pacific, and South Pacific Divisions are needed to provide a better basis for assessing regional effects. The low-turbidity, phosphorus-limited stations account for 24% of the total stations-years in the data set. While the response surfaces presented above provide some perspectives on turbidity and nitrogen effects, more complex models are needed for empirical chlorophyll-a prediction in the remaining 76% of the stations, which are influenced by nitrogen and/or turbidity.

CONCLUSIONS

The data analyses presented above indicate that chlorophyll-a levels can be directly related to total phosphorus at stations with less than about .37 m^{-1} non-algal turbidity and with inorganic N/ortho P ratios greater than 10. The relationship is indistinguishable from phosphorus/chlorophyll regressions derived from P-limited northern lake data. The potential limiting effects of nitrogen and turbidity must be considered in applying empirical eutrophication models to reservoirs. Significant nitrogen effects are apparent in 22% of the station-years analyzed above and significant turbidity effects, in 69%. Mass-balance models are needed for these variables, as well as phosphorus, in order to permit prediction of reservoir chlorophyll levels and transparencies as functions of external loadings, hydrologic variables, and morphometric variables.

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Table 2

Regional Analysis of Factors Influencing Reservoir Chlorophyll Leve

	Station - Years					
Nutrient: * Turbidity:*	N high	N low	P high	P low	Total	Total Reservoirs
North Atlantic	0	0	3	7	10	4
South Atlantic	6	0	43	29	78	13
Ohio River	20	2	107	31	160	37
North Central	3	11	3	6	23	6
Lower Mississippi	1	2	29	9	41	10
South West	35	4	59	31	129	29
Missouri River	10	2	36	11	59	15
North Pacific	2	9	0	0	11	3
South Pacific	0	7	0	0	7	1
Total	77	37	280	124	518	118
Percent	15%	7%	54%	24%	100%	-

* nutrient groups based upon inorganic N / ortho-P = 10
turbidity groups based upon non-algal turbidity = .37 m^{-1}
regions based upon Corps of Engineer Divisions

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