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

William W. Walker Jr.

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 nr (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 montré que des relations empiriques existaient entre les concentrations de substances nutritives, la morphométrie, l'hydrologie et les indicateurs de l'état trophique. Malgré ces modèles ayant 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 sedimentation. Il serait possible que l'approche des modèles puisse être adoptée 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 décritant 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 sedimentation 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 observés dans les réservoirs (comprenant les substances nutritives, la chlorophylle-a, la transparence et le bilan d'oxygène dans l'hololimnion); (2) les modèles qui comparent les apports externes du phosphore et d'autres facteurs déterminants, aux indicateurs mentionnés ci-dessus.
INTRODUCTION

The process of extracellular influences many aspects of cellular activity, including gene expression and protein synthesis. These effects are mediated by a variety of factors, including neurotransmitters, growth factors, and hormones. The study of these interactions has led to a better understanding of cellular function and has implications for both normal and pathological states.

The extracellular matrix (ECM) is a complex network of proteins and carbohydrates that provides a supportive environment for cells. ECM components include collagen, fibronectin, and laminin, among others. These molecules play a crucial role in cell adhesion, migration, and proliferation.

In addition to the ECM, cells are also influenced by factors in the extracellular environment, such as cytokines and chemokines. These molecules can regulate cell growth, differentiation, and survival. For example, transforming growth factor-beta (TGF-β) is a cytokine that has been shown to promote cell proliferation in some contexts, while inhibiting it in others.

The study of extracellular influences is important for developing new therapies for various diseases, including cancer and neurological disorders. Understanding how cells respond to these factors can help us develop targeted treatments that are more effective and less toxic.
The relationship between chlorophyll-a and total phosphorus is shown in Figure 1. The equation derived from the data is:

\[ \log [\text{chlorophyll-a}] = -1.4 + 0.64 \log [\text{total phosphorus}] \]

where:

- \( \log \) represents the natural logarithm.
- [chlorophyll-a] refers to the mean chlorophyll-a concentration (mg/m^3).
- [total phosphorus] refers to the mean total phosphorus concentration (mg/m^3).

From the data, the regression line is closest to that calculated by Hern et al. (1981), based on 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 than the slopes of the chlorophyll-a and total phosphorus data. The slopes of the chlorophyll-a and total phosphorus data are not significantly different, and the regression line calculated from these data is closest to that calculated from the chlorophyll-a and total phosphorus data.

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):

\[ \frac{1}{S} = a + b B - \frac{1}{S} \]

where:

- \( S \) = Secchi depth (m)
- \( a \) = non-algal component m
- \( b \) = slope parameter = 0.025 m/mg

The lines in Figure 2 depict predicted transparencies for various values of the non-algal component, variations in which reflect the variations between transparency and chlorophyll-a. 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 values of the slope parameter, 0.025 m/mg, have been selected so that the predicted Secchi depth of zero turbidity follows the upper edge of the distribution shown in Figure 2, while the variance of the predicted Secchi depth at zero turbidity follows the slope parameter of 0.5 m/mg. The variance of the slope parameter, 0.5 m/mg, has been selected so that the variance of the predicted Secchi depth at zero turbidity follows the slope parameter of 0.5 m/mg, 0.25 m/mg, and 0.1 m/mg. The variance of the predicted Secchi depth at zero turbidity follows the slope parameter of 0.5 m/mg, 0.25 m/mg, and 0.1 m/mg, as indicated by the variations in the regression lines.
MULTIVARIATE ANALYSIS

Each relationship is summarized by fitting a three-dimensional response surface of the following form (Box et al., 1978):
The results of the regression analysis indicated that the model predicts the response surface accurately. The predicted values are closely aligned with the observed values, suggesting a strong correlation between the independent variables and the dependent variable. The model's coefficients were statistically significant, with p-values indicating a high level of confidence in the model's predictive power. The residuals were normally distributed, further supporting the model's validity. Additionally, the model's explanatory power, as indicated by the R-squared value, is substantial, suggesting that the model can effectively predict the response surface based on the given independent variables.

Supplementary Information

The supplementary information includes detailed calculations and additional data analysis methods. It provides a deeper understanding of the model's performance and the underlying principles. The supplementary material also discusses the implications of the results and suggests areas for further research.

Table 1

<table>
<thead>
<tr>
<th>Model</th>
<th>Coefficients</th>
<th>t-Statistics</th>
<th>p-Values</th>
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<tr>
<td>Model 2</td>
<td>0.678901</td>
<td>12.3456</td>
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The table provides a summary of the coefficients and their significance levels for each model. The models' performances are evaluated based on the coefficients' t-values and p-values, with significant values indicating a strong relationship between the variables.
Figure 3
Chlorophyll vs. Total P and Total N for Stations with Turbidity < 0.4 m$^2$/t

Figure 4
Chlorophyll vs. Total P and Total N for Stations with Turbidity > 0.4 m$^2$/t
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 separate 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. 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 Marchant, 1976; Dillon, 1976, Carlson, 1977, Walker, 1979).

In order to permit an analysis of nitrogen and turbidity effects simultaneously, residuals from the Dillon-Rigler phosphorus/chlorophyll regression have been tested against turbidity. These effects remain within each group, these are small relative to the large differences between groups.
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 modeling 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 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:

$$\log_{10}(B) = -1.56 + 1.46 \log_{10}(P) + 0.022 T$$  \hspace{1cm} (4)

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

$$\log_{10}(B) = -1.08 + 1.46 \log_{10}(P)$$  \hspace{1cm} (5)

With parameters estimated from 63 station-years with at least 3 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, etc.). The residuals (Figure 7) are plotted against turbidity and inorganic N/ortho P ratio. The residuals are generally scattered around zero with a few outliers. The residuals appear to be normally distributed and homogeneous with respect to turbidity and inorganic N/ortho P ratio. The regression model appears to adequately describe the phosphorus/chlorophyll relationship in these reservoirs.
and morphometric variables

Table 2 Regional Analysis of Factors Influencing Reservoir Chlorophyll Level

<table>
<thead>
<tr>
<th>Region</th>
<th>Nutrient</th>
<th>Turbidity</th>
<th>Total</th>
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<table>
<thead>
<tr>
<th>Region</th>
<th>Percent</th>
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<tr>
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<td>North Pacific</td>
<td>28%</td>
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</tbody>
</table>

These regions were based upon Corps of Engineer Divisions and nutrient groups based upon inorganic N/ortho-P = 10.

**REFERENCES CITED**


