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

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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 1/m (in units of inverse Secchi depth, corrected for light absorption by chlorophyll) 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.

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 biochemical reactions (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, is also of potential importance in reservoirs, because of its role in restricting light penetration 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 15 feet. 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 a 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. A statistical summary of the data is given in Table 1.

ANALYSIS

Figure 1 depicts the relationship between total phosphorus and chlorophyll-a for 257 station-years with at least three sampling dates. For comparative purposes, regression lines calculated by Dillon and Rigler (1974), Hern et al. (1981), and the O.E.C.D. Eutrophication Program (Kerekes,1981). are shown, along with the regression line calculated 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 Dillon/Rigler and O.E.C.D. regressions, derived 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):

$$1/S = \alpha + \beta B \qquad (2)$$

where,

S = Secchi depth (m)

α = non-algal component (1/m)

β = 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 allocthonous 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, .025 m2/mg, has been selected so that the predicted Secchi depth at zero turbidity follows the upper edge of the distribution shown in Figure 2. Turbidities calculated from average transparencies and chlorophyll-a values using equation (2) are restricted to a minimum value of .08 1/m, which corresponds to a transparency of 12.5 meters in the absence of chlorophyll-a and other algal-related light extinction components.

Further analysis shows that both nitrogen and turbidity are related to chlorophyll in ways which may account for at least some of the varibility 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, as indicated by the correlation matrix in Table 2. The correlation between total phosphorus and turbidity is particularly important and may reflect effects of turbidity on the availablility of phosphorus to support algal growth.

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; and

(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 flexibility 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 formulated and tested, based upon the results of the data analysis.

After finding that response surface residuals were correlated with average temperature at low-turbidity stations, a linear temperature correction term has been added to the equation. This temperature correction essentially accounts for differences in the seasonal distribution of sampling dates. At low-turbidity stations (< .4 1/m), 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 (Walker, 1980a,b). For chlorophyll-a predictions at low-turbidity stations, the slope of this correction term is on the order of .02 /deg-C, which corresponds to a maximum temperature effect of .3 logarithmic units. Significant temperature effects have not been identified at high-turbidity stations, for which the temperature correction term is negligibly small.

Surface contours are displayed in Figures 3-7, 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 3. Within-station variablility in chlorophyll and nutrient concentrations imposes limitations on the variance which can be explained by the equations. This variablity leads to errors in the estimated mean concentrations for each station-year and accounts for some of the differences between the observed and predicted chlorophyll-a 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 3 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 1/m to divide the groups. The low-turbidity group includes roughly one third of the station-years. Analysis of residuals has indicated that .4 1/m is a reasonable cutpoint for the effects of turbidity on the chlorophyll/nutrient response surface. While some systematic turbidity effects remain within each group, these are small relative to the between-group differences.

Comparing Figures 3 and 4 indicates that 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 indicates a region in which chlorophyll levels are equally sensitive to nitrogen and phosphorus. This condition is approximately indicated by the the diagonal line in Figure 3, which represents a total N/P ratio of 20. This is considerably higher than the algal physiologic ratio (about 7), and agrees qualitatively with the results of Smith(1980), who found nitrogen effects on lake chlorophyll levels at N/P ratios up to 32. At a constant N/P ratio of 20, seven chlorophyll-a contour intervals are crossed over a phosphorus range of about 1.0 logarithmic units. This corresponds to a slope of 1.4 in the phosphorus/chlorophyll relationship, given adequate nitrogen and low turbidity. This slope agrees with many phosphorus/chlorophyll regressions derived from P-limited natural lakes (Dillon and Rigler, 1975, Jones and Bachman, 1976, Carlson, 1977, Walker, 1979). In the high-turbidity group (Figure 4), chlorophyll sensitivity to nutrients is low and nitrogen limitation effects less evident.

Figure 5 depicts the response of chlorophyll to turbidity and phosphorus for stations with inorganic N / ortho-P ratios exceeding 10. 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 chlorophyll/turbidity/phosphorus relationship estimated for stations with total N/P ratios exceeding 20 is not substantially different from that depicted in Figure 5, however. The model R-squared for this response surface is .71 (Table 3). 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, where the contours are more 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, Table 2). The decreasing response of chlorophyll to increasing turbidity seems most likely related to the effects of turbidity on phoshorus availablility 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. In order to permit analysis of nitrogen and turbidity effects simultaneously, residuals from the Dillon-Rigler phosphorus/chlorophyll regression have been tested against turbidity and nitrogen to phosphorus ratios. Residuals are calculated from:

$$R = \log_{10}(B) - 1.45 \log_{10}(P) + 1.14 \qquad (4)$$

where,

R = residual from Dillon-Rigler model

Figures 6 and 7 display the results using total N/P and inorganic N/P as indicators of limiting nutrient, respectively. Corresponding model R-squared values are .75 and .65. While the former model explains more variance, some of the error in the latter may be attributed to the relative inaccuracy and variablity of the inorganic nutrient measurements, especially at values approaching the lower limit of analytical detectability. The response surfaces are qualitatively similar, with N-limitation effects apparent at higher N/P ratios when the total concentrations are used (Figure 6) than when the inorganic fractions are used (Figure 7). The tops of the response surfaces, located at low turbidities and high N/P ratios, are fairly flat. These are the regions in which chlorophyll-a is most strongly related 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 neglible in relation to the 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 1/m. This represents the "top" of the response surface in Figure 7. 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 and the process repeated 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

$$\log_{10}(B) = -1.56 + 1.46 \log_{10}(P) + .022\ T \qquad (5)$$

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

$$\log_{10}(B) = -1.08 + 1.46 \log_{10}(P) \qquad (6)$$

With parameters estimated from 63 station-years with at least three sampling dates, the model has a gross standard error of .19 and explains 78% of the chlorophyll-a variance. An error analysis similar to those given in Table 3 indicates model standard error and model R-squared values of .08 and .95, respectively. Observations are plotted against predictions in Figure 8. The regression equation is nearly identical to those derived from P-limited northern lake data by Dillon 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 identical to that found in northern lakes.

Analyses of residuals from the above equation have indicated no significant effects of station type (upper pool, mid-pool, 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). There are some systematic effects of N/P ratio (both total and inorganic), but these are small in relation to the model standard error. Regional effects, principally higher residuals in the North Atlantic states, are also small and correlated with N/P ratios.

Table 4 classifies the station-years in the complete data set based upon limiting nutrient, turbidity level, and region, defined by Corps of Engineer Division. While the above analysis indicates that it is difficult to identify conditions under which only one factor is limiting, nutrient limitation is approximately assessed using an inorganic N / ortho P ratio of 10 and turbidity classifications are assigned using a cutpoint of .37 1/m. 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 station-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 phoshorus at stations with less than about .37 1/m non-algal turbidity and with inorganic N / ortho P ratios greater than 10. The relationship is indistinguishable from phoshorus/chlorophyll regressions derived from P-limited northern lake data, although small, systematic effects of nitrogen remain. 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 1
Statistical Summary of Data Base

Variable *	Units	Mean	Standard Deviation	Minimum	Maximum
Total Phosphorus	mg/m3	40.7	36.8	4.9	470
Ortho Phosphorus	mg/m3	12.9	12.4	2.2	221
Total Nitrogen	mg/m3	778	520	115	9311
Inorganic Nitrogen	mg/m3	292	298	20	7430
Total N/Total P	-	19.4	14.6	1.7	166
Inorganic N/Ortho P	-	22.6	24.3	.3	374
Secchi Depth	m	1.1	.86	.14	7.1
Non-Algal Turbidity	1/m	.61	.57	.08	6.4
Chlorophyll-a	mg/m3	8	6.7	.63	92.7
Station Total Depth	m	12.9	11.7	1.2	305
Reservoir Mean Depth	m	6.0	5.1	.3	60
Hyd. Residence Time	yrs	.14	.27	.0002	9.6
Overflow Rate	m/yr	44	75	.7	5970

* statistics based upon 525 station-years of data;
total nitrogen data available for 492 station-years;
means and standard deviations are geometric

Table 2
Correlation Matrix

	Variable	1	2	3	4	5	6	7
1	Chlorophyll-a	1.00						
2	Total Phosphorus	.55	1.00					
3	Total Nitrogen	.40	.56	1.00				
4	Non-Algal Turbidity	.16	.65	.46	1.00			
5	Total N/Total P	-.29	-.68	.23	-.43	1.00		
6	Inorganic N/Ortho P	-.13	-.32	.43	.03	.73	1.00	
7	Secchi Depth	-.51	-.81	-.54	-.89	.48	.09	1.00

* product-moment correlation coefficients computed using log-transformed data

Table 3
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 1/m
II = non-algal turbidity > .4 1/m
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)

Table 4
Regional Analysis of Factors Influencing Reservoir Chlorophyll Levels

	Station - Years					
Nutrient: *	N	N	P	P		Total
Turbidity:*	high	low	high	low	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	1C
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 1/m
regions based upon Corps of Engineer Divisions

Figure 1
Relationship Between Chlorophyll and Total Phosphorus

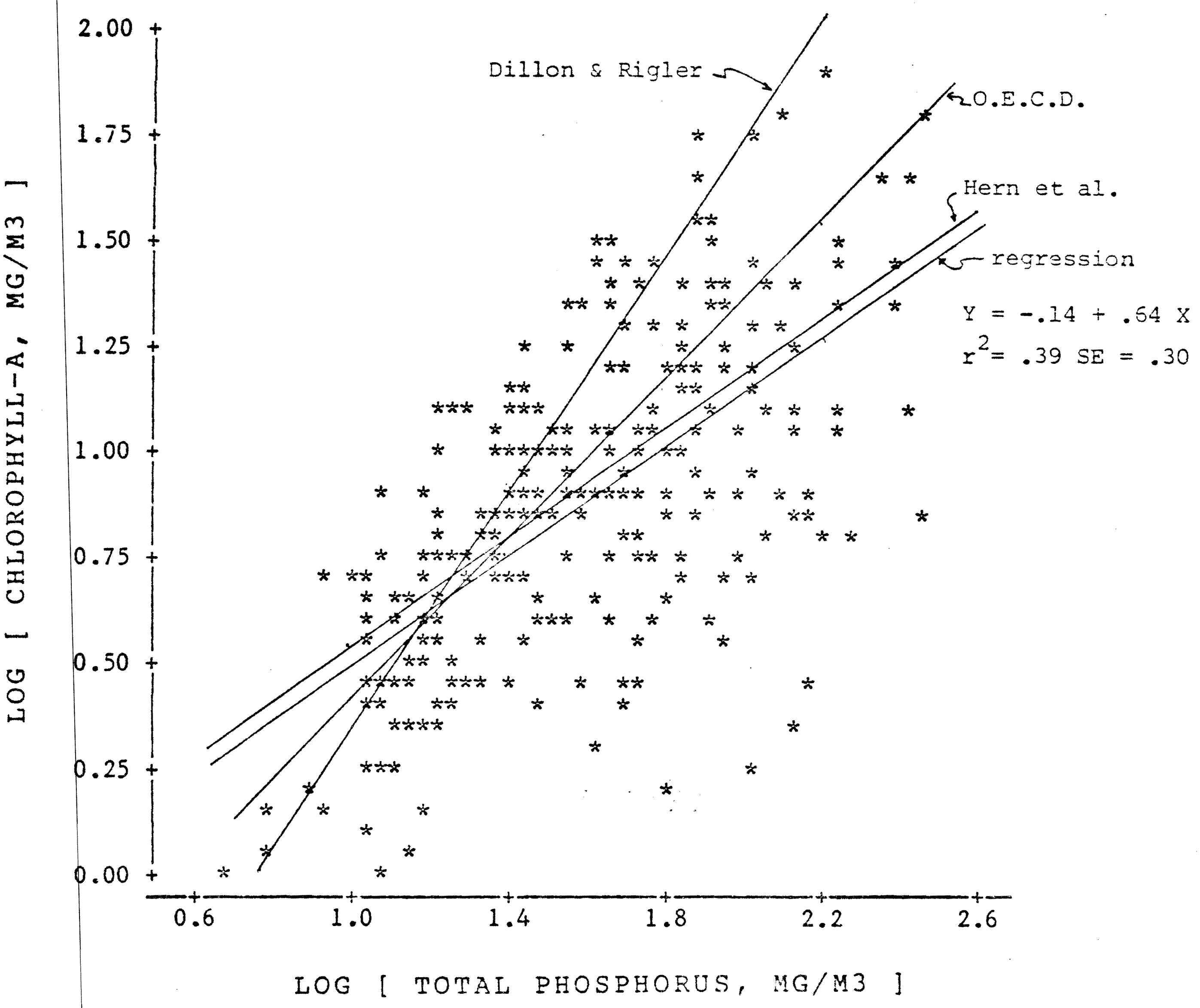

Figure 2
Relationship Between Transparency and Chlorophyll

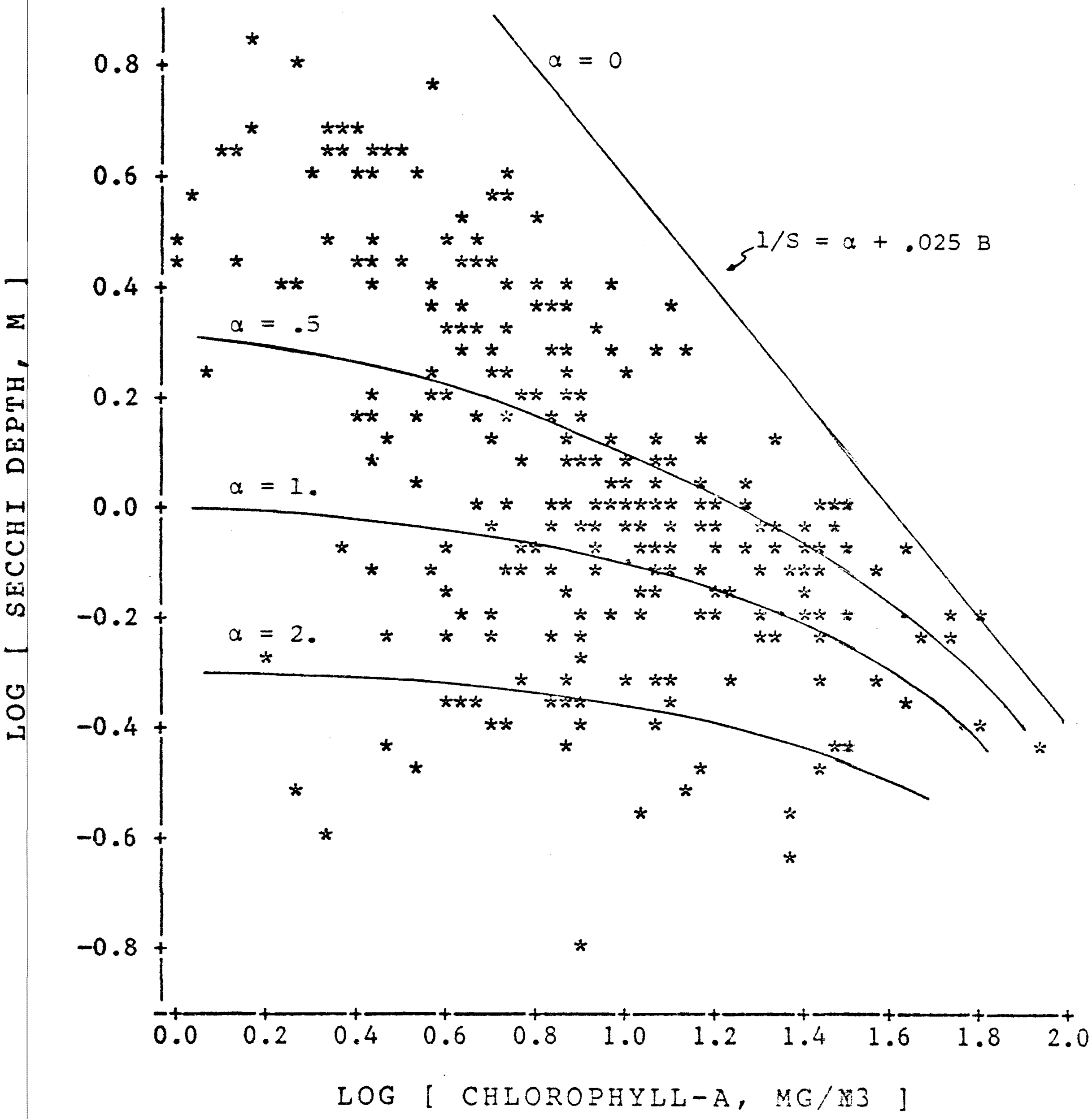

Figure 3
Chlorophyll vs. Total P and Total N for Stations with Turbidity < .4 1/m

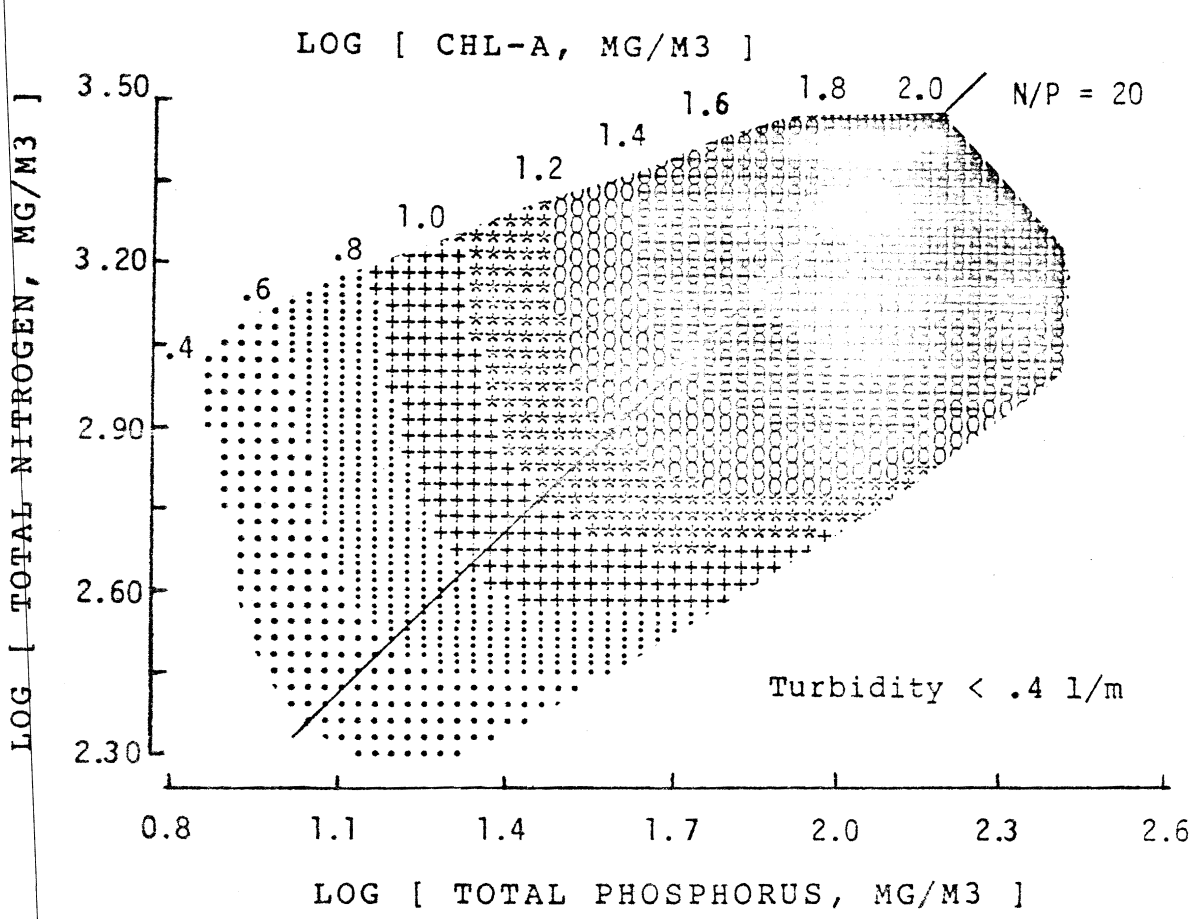

Figure 4
Chlorophyll vs. Total P and Total N for Stations with
Turbidity > .4 1/m

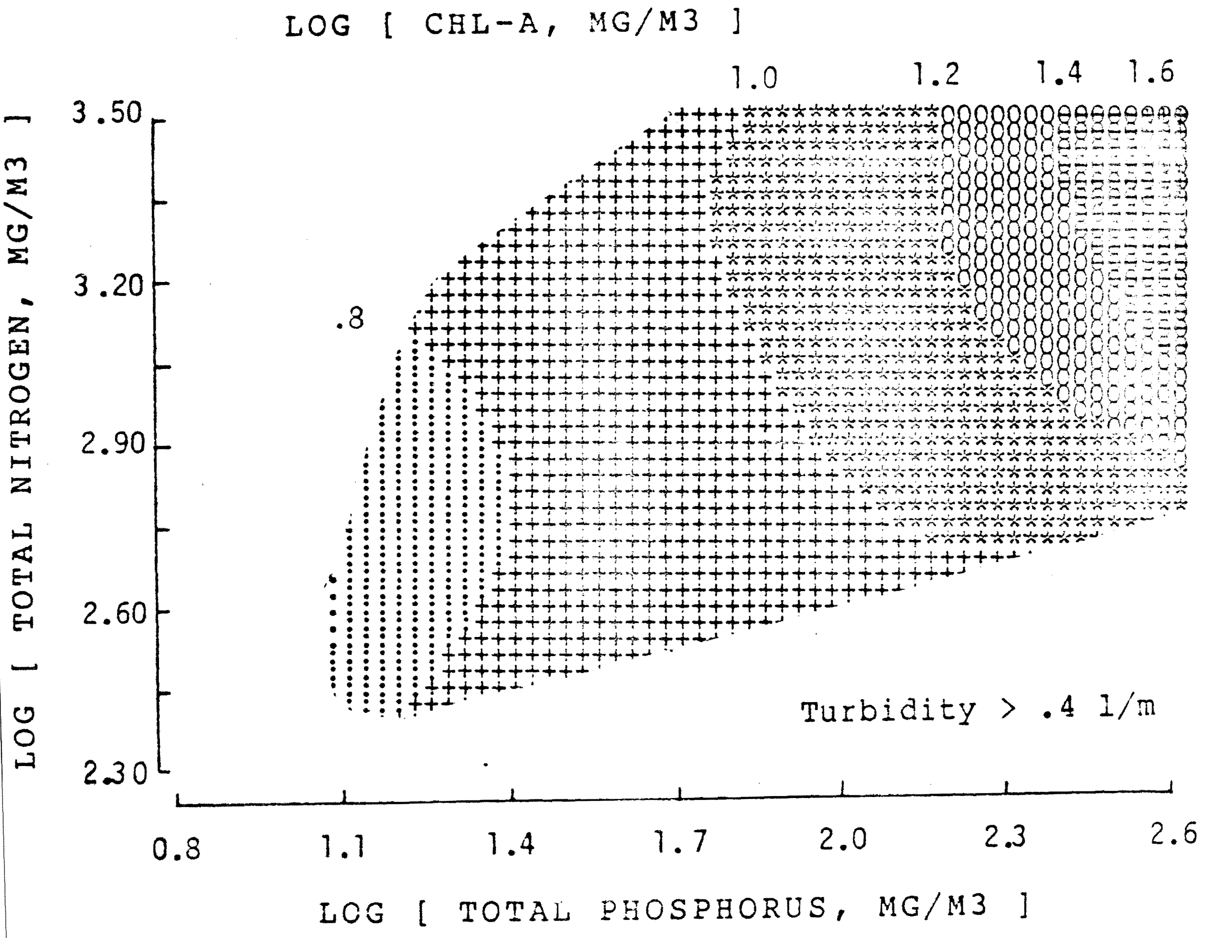

Figure 5
Chlorophyll vs. Total P and Turbidity for Stations with
Inorganic N / Ortho P > 10

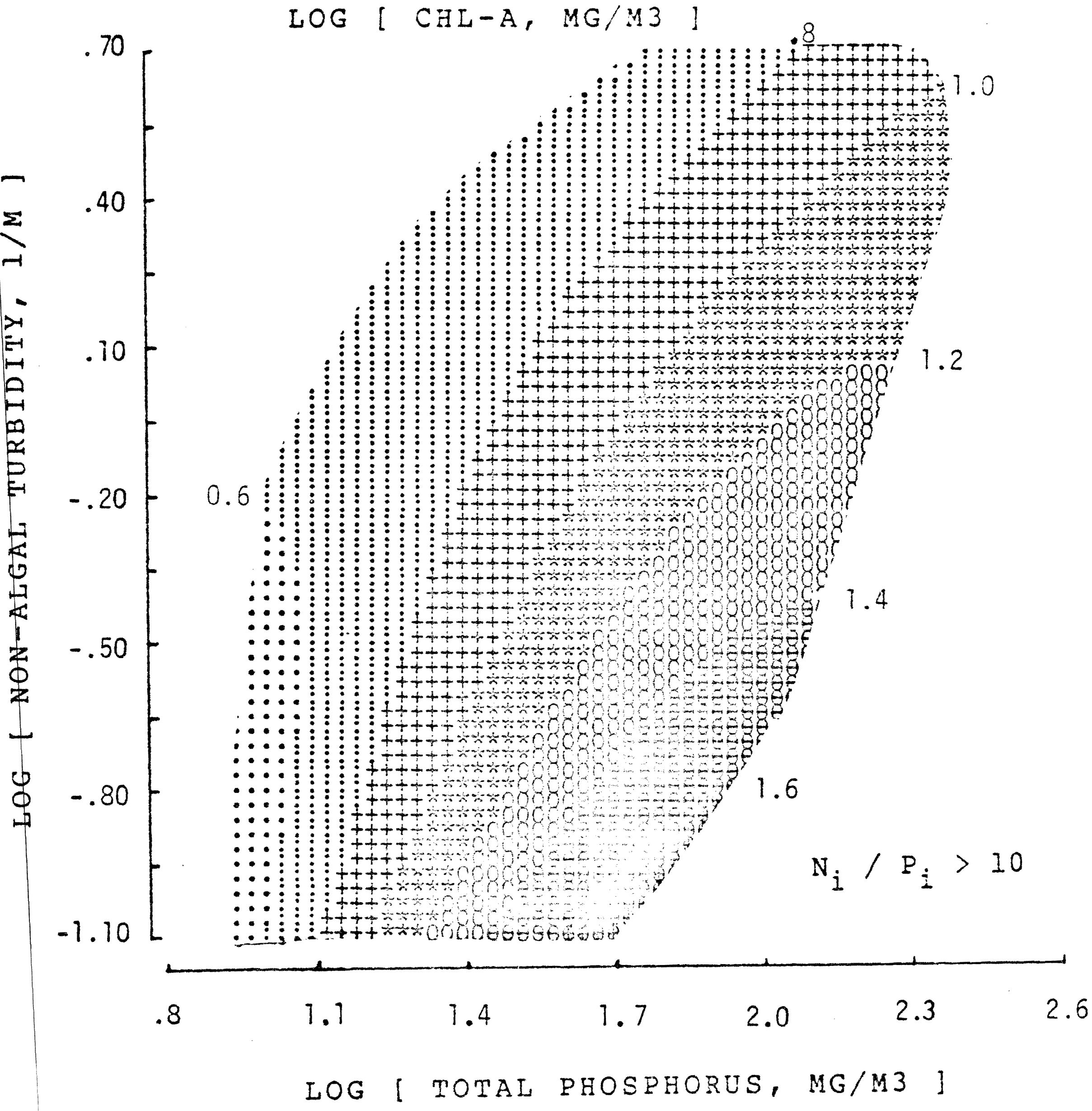

Figure 6
Dillon-Rigler Residual vs. Turbidity and Total N / Total P

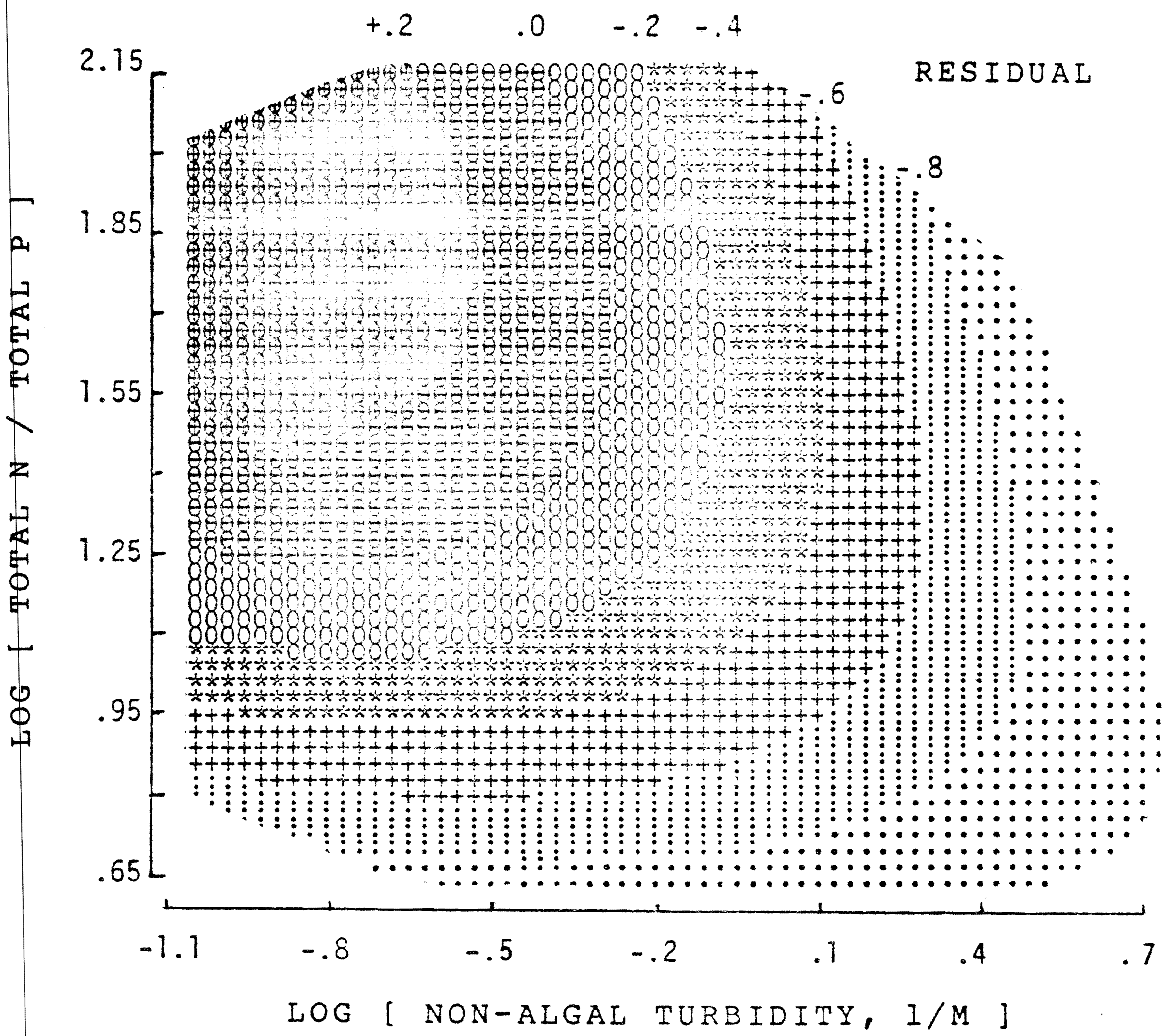

Figure 7

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

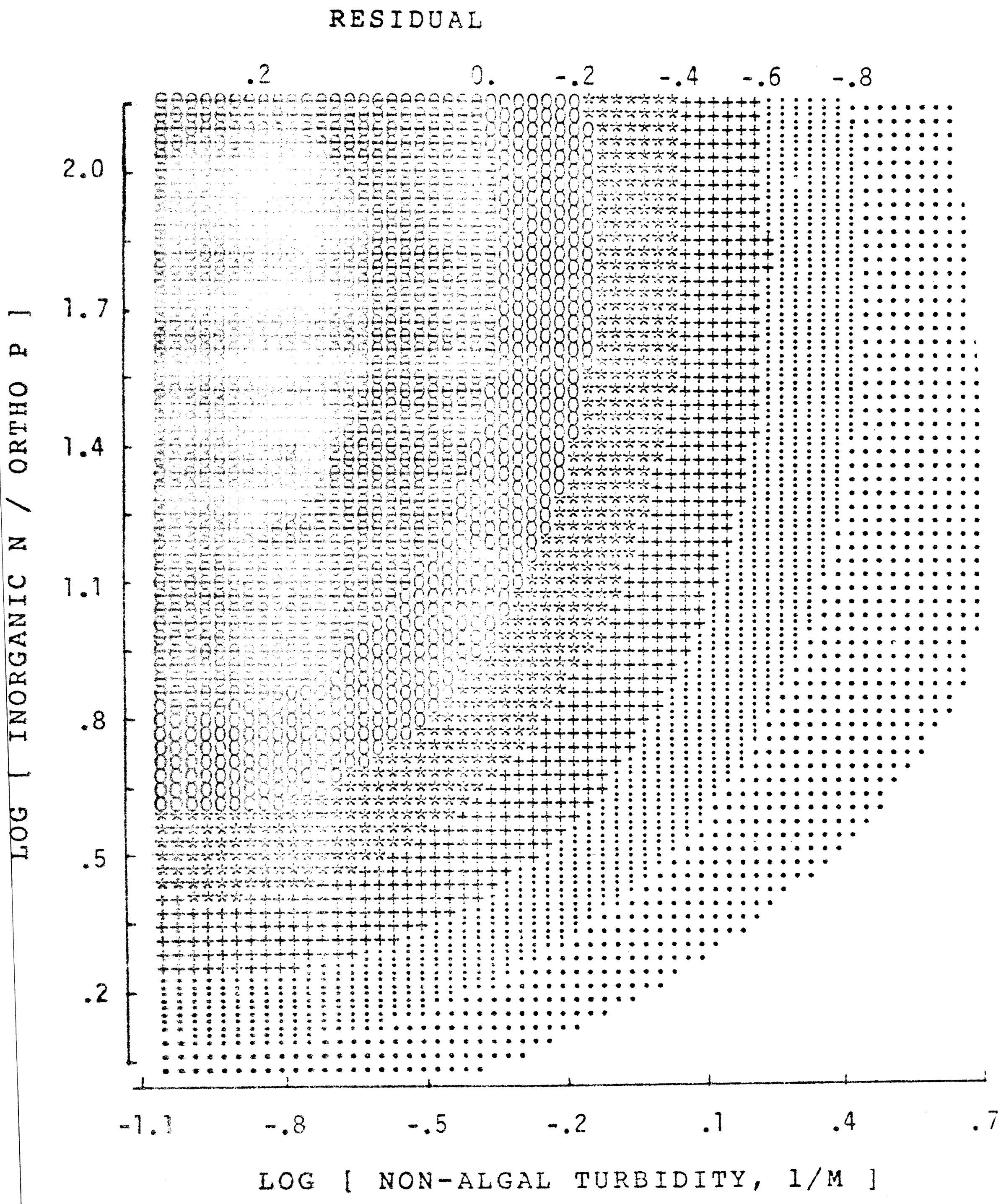

Figure 8
Chlorophyll-a vs. Total Phosphorus for Stations with Inorganic N / Ortho P > 10 and Turbidity < .37 1/m