PREDICTION OF TOTAL NITROGEN IN LAKES AND RESERVOIRS

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ABSTRACT

The basic Vollenweider input-output model was adapted to predict total nitrogen concentrations in standing waters. Data from randomly selected group of lakes in the U.S. Environmental Protection Agency National Eutrophication Survey were used to develop the coefficients for the model, and data from a different group of lakes from the same survey were used for verification. The 95 percent confidence interval for predicting total nitrogen in a lake is from 41 to 255 percent of the calculated value for the best models. The same equations could be used equally well for natural lakes or artificial reservoirs.

Phosphorus and nitrogen have long been recognized as the two elements most likely to limit biological production in inland waters: thus, their cycles have been the subject of intensive research. An important advance was made by recognizing the importance of continuing nutrient inputs in the determination of trophic state (Vollenweider, 1968) and the development of input-output models for predicting nutrient concentrations on the basis of nutrient loading, lake morphometry, and hydraulic flushing rate (Vollenweider, 1969). Since that time, a number of empirical models have been developed to predict total phosphorus concentrations (Vollenweider, 1975; Kirchner and Dillon, 1975; Chapra, 1975; Jones and Bachmann, 1976; Larsen and Mercier, 1976; Reckhow, 1977, 1979; Canfield, 1979). Yet little effort has been expended on developing similar models for the other important element, nitrogen. The purpose of this study is to develop and test an input-output model for total nitrogen in natural and artificial lakes.

Unlike phosphorus with only one valence state in natural waters, nitrogen is found in four different states of oxidation. One of these, nitrogen gas, is relatively inert and is not included in the total nitrogen measurement; however, it can be incorporated into the cycle through biological fixation by blue-green algae or can be lost from the biological cycle through the action of denitrifying microorganisms on nitrates, thus reducing the total nitrogen concentration. By analogy with the general development of the phosphorus models (Vollenweider, 1969), the change in total nitrogen concentration per unit time equals the rate of loading of nitrogen from external sources per unit area divided by the sum of mean depth, plus internal loading from the sediments plus the rate of nitrogen fixation minus losses through the outlet minus losses to the sediments minus denitrification losses. Some of the parameters in this equation are easily measured or estimated (total nitrogen concentration, areal nitrogen loading, lake mean depth, and hydraulic flushing rate), but the rest are very difficult if not impossible to measure. These factors (internal loading, sedimentation losses, nitrogen fixation, and denitrification) are grouped together as attenuation losses and are expressed as:

attentuation losses = α TN
were
α = attenuation coefficient, yr^{-1}

TN = the concentration of total nitrogen in the lake, mg. m^{23}
The differential equation is given as:
$dTN/dt = L/z - TN - TN$ (1)
where
t = time
L = annual nitrogen loading per unit of lake surface area,
$mg{\cdot}m^{-2}yr^{-1}$
z = mean depth of lake, m
ρ = hydraulic flushing rate, yr^{-1}
The steady-state solution is:
$TN = L/(Z(\alpha + \rho))$ (2)

This is the same as the solution for the total phosphorus model (Vollenweider, 1975) with the exception that the sedimentation coefficient has been replaced with an attenuation coefficient.

DATA BASE

The basic data were obtained from the results of the U.S. Environmental Protection Agency National Eutrophication Survey. Data were tabulated for all lakes on annual areal total nitrogen loading rates, median total nitrogen concentrations, lake mean depths, hydraulic flushing rates, chlorophyll *a* concentrations, total phosphorus concentrations, and total phosphorus areal loading rates. The median total nitrogen concentration was taken to represent the steady-state total nitrogen concentration, agreeing with Reckhow (1977) that the median would be less affected by extreme measurements. Nitrogen attenuation coefficients for each lake were estimated from the data by assuming steady state and rearranging the terms in Equation 1:

$$\alpha = L/(TNZ) - \rho$$

All the errors in estimating the total nitrogen concentration, areal loading, lake mean depth, and hydraulic flushing rate are incorporated into the attenuation coefficient. Negative values for this coefficient might indicate a lake that has a net production of nitrogen through nitrogen fixation, is not in steady state, or where the errors of estimation may result in a negative value.

The sample includes all the EPA-surveyed lakes with a complete set of data. In the first year of that survey, total nitrogen concentrations were not measured, thus reducing the size of the sample. The remaining 95 natural and 384 artificial lakes include a wide range of lake types with mean depths from 0.5 to 307 meters, total nitrogen concentrations from 125 to 7,185 mg m^{-3}, nitrogen loading from 1,500 to 14,900,000 mg $m^{-2}yr^{-1}$, and attenuation coefficients from -5 to 392 yr^{-1} (Table 1).

The lakes were randomly sorted into two data sets. One data set (model development) with 49 natural and 199 artificial lakes was used to develop the predictive models, and the other data set (model verification) with 46 natural and 185 artificial lakes was used to test the predictive abilities of the empirical models and establish confidence limits. Because the values of most parameters spanned several orders of magnitude and it was reasonable to assume that variances were proportional to means, all data were transformed to their natural logarithms before statistical analyses (unless stated otherwise.).

NITROGEN ATTENUATION COEFFICIENTS

Because the nitrogen attenuation coefficient cannot be directly measured, I investigated the possibility that it could be related to some other measurable variable. Correlations between the coefficient and several limnological variables are shown in Table 2. In general, stronger correlations were found for artificial than for natural lakes. The best correlations were obtained with various measures of water or nitrogen loading, with greater rates of input being associated with greater fractional losses of nitrogen from the lake water (Figure 1).

In addition, a nitrogen retention coefficent was calculated following the procedures that Dillon and Rigler (1974) used for phosphorus. The retention coefficient and its logarithms also were used in the same correlation matrix, but the resulting correlations were less strong than those found by using the attenuation coefficient. I also attempted to fit a nitrogen settling velocity following Chapra's (1975) work with phosphorus, but it also was less satisfactory.

The strongest correlations were found with the volumetric nitrogen loading, the areal nitrogen loading, and the hydraulic flushing rate: however, this does not prove a cause-and-effect relationship for any one variable. Indeed, these three variables are all intercorrelated (Table 3); any one of them could influence nitrogen attenuation, or there could be an important unmeasured variable that also is correlated with either nitrogen or water inputs.

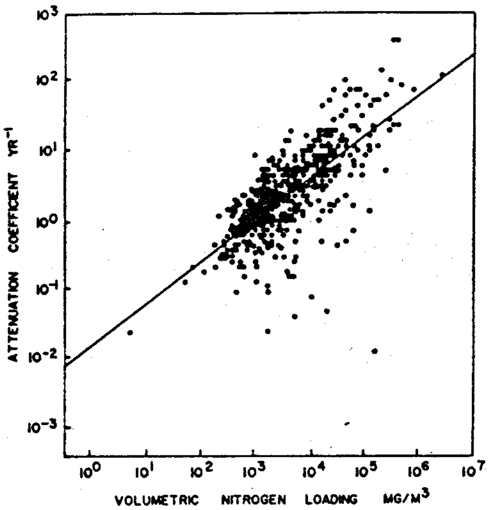

Figure 1. — Relationship between nitrogen attenuation coefficients and volumetric nitrogen loading for both natural and artificial lakes combined.

Table 1. — Mean values and related statistics for annual areal total nitrogen loading rates ($mg \cdot m^{-2}yr^{-1}$), total nitrogen concentrations ($mg \cdot m^{-3}$), mean depths (m), hydraulic flushing rates (yr^{-1}), and calculated attenuation coefficients (yr^{-1}), for 479 natural and artificial lakes included in this study.

Variable	Lake Type	No. in sample	Mean	Standard deviation	Range Minimum	Maximum
Areal nitrogen loading (L)	natural	95	60894.0	172457.0	1500.0	14900000
	artificial	384	139092.0	635435.0	1700.0	11155000
Total nitrogen (TN)	natural	95	1441.0	1223.0	125.0	6040
	artificial	384	1027.0	974.0	220.0	7185
Mean depth (z)	natural	95	11.0	32.4	0.5	307
	artificial	384	9.2	8.4	0.6	59
Hydraulic flushing rate (ρ)	natural	95	4.9	8.5	0.002	45
	artificial	384	14.4	40.4	0.019	365
Attentuation coefficient (α)	natural	95	4.8	14.3	-8.3	130
	artificial	384	8.7	31.3	-50.0	392

Table 2. — Correlation coefficients (r) between various limnological parameters and attenuation coefficients. Logarithmic transformations were used. All coefficients significant at the 5% level except those marked NS not significant).

Parameter	Natural Lakes	Aritifical Lakes	Both Combined
Volumetric nitrogen loading	0.60	0.78	0.74
Areal nitrogen loading	0.67	0.75	0.74
Hydraulic flushing rate	0.63	0.74	0.72
Areal water loading	0.61	0.66	0.65
Mean depth	-0.12	-0.30	-0.25
Ratio total nitrogen to total phosphorus	-0.25	-0.18	-0.20
Chlorophyll *a*	0.00 NS	-0.06 NS	-0.05 NS
Total nitrogen concentration	-0.14 NS	-0.04 NS	-0.01 NS

Table 3. — Correlations between the logarithms of chlorophyll *a* (CHLA), areal phosphorus loading rate (LP), areal nitrogen loading rate (L), volumetric nitrogen loading rate (L/Z), total nitrogen (TN), total phosphorus (TP), ratio of total nitrogen to total phosphorus (TN/TP), hydraulic flushing rate (ρ), and the ratio of the areal nitrogen loading rate to the areal phosphorus loading rate (L/LP).

	CHLA	LP	L	L/Z	TN	TP	TN/TP	ρ	L/LP
CHLA	1.00	0.07	0.05	0.33	0.67	0.69	-0.22	0.12	-0.25
LP		1.00	0.63	0.56	0.22	0.34	-0.22	0.53	-0.20
L			1.00	0.86	0.32	0.22	0.04	0.83	0.06
L/Z				1.00	0.56	0.47	-0.05	0.89	-0.02
TN					1.00	0.66	0.15	0.27	-0.08
TP						1.00	-0.64	0.26	-0.52
TN/TP							1.00	-0.08	0.61
ρ								1.00	-0.02
L/LP									1.00

Regression equations were developed with the model-development data set for the relationships between the nitrogen attenuation coefficients and the volumetric nitrogen loading, areal nitrogen loading, and hydraulic flushing rates. These were determined for natural and artificial lakes both separately and combined (Table 4). The attenuation coefficients were then substituted back into Equation 2 to yield the various predictive models for total nitrogen.

MODEL VERIFICATION

I tested the abilities of these models to predict the measured total nitrogen concentrations of the lakes in the model-verification data set. Correlation coefficients were calculated between measured and calculated total nitrogen concentrations, and empirical 95 percent confidence limits were determined for the calculated total nitrogen concentrations of each model by calculating the standard deviation of the mean difference between the logarithms of the measured and calculated total nitrogen concentrations. Average errors and average percentage errors also were calculated from the untransformed calculated and measured total nitrogen values. These four measures of precision were used to evaluate the respective models.

Table 4. — Comparison of calculated and measured total nitrogen concentrations for the model-verification data set with use of models based on volumetric nitrogen loading (L/Z), areal nitrogen loading (L), and hydraulic flushing rate (ρ). Error estimates include the average error (AE), percentage error (PE), and 95% confidence limits as percentages of the calculated total nitrogen value (CL).

Model	Correlation coefficient r	Error estimates		
		AE	PE	CL
Based on L/z				
natural lakes with				
$\ln \alpha = -0.345 + 0.505 \ln (L/z)$				
and artificial lakes with				
$\ln \alpha = -0.434 + 0.618 \ln (L/z)$	0.80	410	38	41-253
both with				
$\ln \alpha = -4.144 + 0.594 \ln (L/z)$	0.80	419	46	47-286
Based on L				
natural lakes with				
$\ln \alpha = -6.506 + 0.724 \ln L$ and				
artificial lakes with				
$\ln \alpha = -6.430 + 0.709 \ln L$	0.82	382	37	41-255
both with				
$\ln \alpha = -6.426 + 0.710 \ln L$	0.82	382	37	41-255
Based on ρ				
natural lakes with				
$\ln \alpha = -0.485 + 0.5861 \ln \rho$ and				
$\ln \alpha = -0.291 + 0.5821 \ln \rho$	0.76	513	59	36-325
both with				
$\ln \alpha = -0.367 + 0.5541 \ln \rho$	0.77	498	56	36-315

For the models based on volumetric loading, areal loading, and flushing rate, similar results (Table 4) were obtained whether separate equations were used for natural and artificial lakes or a single equation was used for both. This indicates that the same coefficients can be used in nitrogen models for both natural and artificial lakes. This contrasts with phosphorus models in which different coefficients for the respective lake types lead to a greater degree of precision (Canfield, 1979).

The best results were obtained for the models based on volumetric nitrogen loading (Figure 2) or areal nitrogen loading although the model based on flushing rate also gave acceptable results. It was originally thought that a simple nitrogen model would give poorer results than a phosphorus model because of the greater complexity of the nitrogen cycle. This was not found, for by comparison, the best available model for predicting total phosphorus (Canfield, 1979) had an average percentage error of 44 percent and 95 percent confidence limits of 31 to 288 percent when applied to a similar set of lakes. My best nitrogen models have a 37 percent percentage error and 95 percent confidence limits of 41 to 255 percent.

NITROGEN, PHOSPHORUS, AND CHLOROPHYLL *a*

Stronger correlations (Table 5) were found between total nitrogen and chlorophyll *a* in natural lakes than in artificial lakes. This agrees with similar findings by Canfield (1979) for the total phosphorus-chlorophyll *a* relationship and presumably results from a greater chance of light limitation in artificial lakes because of greater concentrations of inorganic particulate materials.

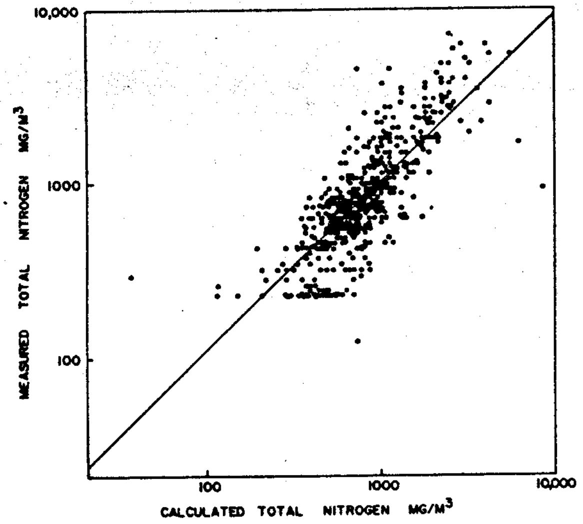

Figure 2. — Relationship between measured total nitrogen and total nitrogen calculated with separate regressions for natural and artificial lakes on the basis of volumetric nitrogen loading (Table 4). The best-fit linear regression line is shown.

Table 5. — Correlations (r) between logarithms of chlorophyll *a* and total nitrogen and total phosphorus for natural and artificial lakes.

	Natural lakes	Artificial lakes
Total phosphorus	0.84	0.59
Total nitrogen	0.81	0.59

The relatively high correlation (r = 0.81) between total nitrogen and chlorophyll *a* was unexpected, because most of the lakes were thought to be phosphorus-limited on the basis of the ratios of total nitrogen to total phosphorus (Table 6). Vallentyne (1974) reported that aquatic plants characteristically have ratios of nitrogen to phosphorus of about 7, considerably smaller than the average ratio of 23.7 in the sample lakes. Most likely, the high correlation is because of the fact that total nitrogen and total phosphorus concentrations in lakes are highly correlated with each other (Table 3), so that they both would be correlated with chlorophyll even though phosphorus may have been the limiting nutrient in most instances.

Other similarities were noted between the behavior of nitrogen and phosphorus in the lakes in this sample. In general, the lakes were sinks for both elements with similar loss rates for both as indicated by the finding that the average ratios of nitrogen to phosphorus within the lakes were not significantly different from the ratios in the inputs (Table 6). There were no large shifts in the ratio indicating differential losses or substantial effects of nitrogen fixation by blue-green algae.

The only major difference was found in those lakes (27 of 479) where negative nitrogen attenuation coefficients indicated that more nitrogen was being produced in the lake than was being lost. It may be significant that the average N:P ratio in the inputs to those 27 lakes (17.4) is significantly different from the ratio (24.5) in the other 452 lakes with positive attenuation coefficients, but the N:P ratios within the two groups (23.9 and 23.7, respectively) are not different. This could illustrate the proposal by Schindler (1977) that lakes with small ratios of N:P in their inputs will have enhanced rates of nitrogen fixation, with a subsequent elevation of the N:P ratio within the lakes themselves.

Table 6. — Frequency distributions of the ratios of total nitrogen (TN) to total phosphorus (TP) within the lakes in the sample and the ratios of the annual surface loading of total nitrogen (L) to the annual surface loading of total phosphorus (LP). The differences between the averages of the two ratios are not statistically significant.

Ratio TN:TP	% of lakes with a smaller ratio	Ratio L:LP	% of lakes with a smaller ratio
2	0.6	2	0.2
4	1.9	4	2.9
6	7.0	6	9.2
8	12.1	8	15.8
10	19.8	10	23.2
12	27.4	12	30.5
14	34.9	14	39.4
16	42.3	16	47.3
18	49.6	18	54.3
20	56.8	20	58.2
30	79.1	30	77.5
40	89.1	40	86.2
60	96.6	60	95.2
80	99.4	80	98.1
Average = 23.7			Average = 24.1
Std. Dev. = 20.9			Std. Dev. = 27.5

Lastly, the nitrogen attenuation coefficient and the analogous phosphorus sedimentation coefficient are both strongly correlated with the loading rates of the respective elements as well as with the water loading rates (Canfield, 1979), leading to similar forms for their respective prediction equations. The reasons for this are poorly understood. The strong affinity of phosphorus for particulate materials has been used as an explanation for its behavior (Canfield, 1979), but this does not seem likely for nitrogen. Clearly more work is needed to understand the factors controlling nitrogen concentrations in lakes.

REFERENCES

Canfield, D. F. 1979. Prediction of total phosphorus concentrations and trophic states in natural and artificial lakes: The importance of phosphorus sedimentation. Ph.D dissertation. Iowa State University, Ames.

Chapra, S. C. 1975. Comment on "An empirical method of estimating the retention of phosphorus in lakes" by W. B. Kirchner and P. J. Dillon. Water Resour. Res. 11:1033.

Dillon, P. J., and F. H. Rigler. 1974. The phosphorus-chlorophyll relationship in lakes. Limnol. Oceanogr. 19:767.

Jones, J. R., and R. W. Bachmann. 1976. Prediction of phosphorus and chlorophyll levels in lakes. Jour. Water Pollut. Control Fed. 48:2176.

Kirchner, W. B., and P. J. Dillon. 1975. An empirical method of estimating the retention of phosphorus in lakes. Water Resour. Res. 11:182.

Larsen, D. P., and H. T. Mercier. 1976. Phosphorus retention capacity of lakes. Jour. Fish. Res. Board Can. 33:1742.

Reckhow, K. H. 1977. Phosphorus models for lake management. Ph.D. dissertation, Harvard University.

———. 1979. Uncertainty applied to Vollenweider's phosphorus criterion. Jour. Water Pollut. Control Fed. 51:2123.

Schindler, D. W. 1977. The evolution of phosphorus limitation in lakes. Science 195:260.

Vallentyne, J. R. 1974. The algal bowl: lakes and man. Fish. Res. Board Can. Misc. Publ. 22.

Vollenweider, R. A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Organ. Econ. Coop. Dev. Tech. Rep. DAS/CS1/68.27.

———. 1969. Possibilities and limits of elementary models concerning the budget of substances in lakes (in German). Arch. Hydrobiol. 66:1.

———. 1975. Input-output models with special reference to the phosphorus loading concept in limnology. Schweizerische Zeitschrift fur Hydrologie. 37:53.

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