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Development of Lake Assessment Methods Based Upon the Aquatic Ecoregion Concept

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ABSTRACT

The development of practical lake management strategies in Minnesota has been greatly facilitated by using the aquatic ecoregion approach and standard assessment methodologies (models). Previous studies have shown the significance of the aquatic ecoregion in determining lake water quality patterns, water quality attainability, and development of nutrient criteria (Heiskary et al. 1987; Heiskary and Walker, 1988). This paper focuses upon the use of ecoregion data for modeling purposes. The Minnesota Lake Eutrophication Analysis Procedure (MINLEAP) is a computer program designed to predict eutrophication indices in Minnesota lakes based upon area watershed, depth, and ecoregion. Ecoregion is used to predict runoff and average stream phosphorus concentration. The program formulates water and phosphorus balances and uses a network of empirical models to predict lake phosphorus, chlorophyll a, and transparency values. The program is intended primarily as a screening tool for estimating lake conditions with minimal input data and for identifying "problem" lakes. Included in the program output are: (1) statistical comparisons of observed and predicted phosphorus, chlorophyll a, and transparency values; (2) uncertainty estimates; and (3) estimates of chlorophyll a interval frequencies (nuisance frequencies), for observed and predicted conditions. These expressions of lake condition may be calibrated to citizen preferences using observer surveys (Heiskary and Walker, 1988) to define swimmable and nonswimmable conditions in a locally meaningful manner. The model should be used to approximate lake water quality expectations acknowledging that individual lakes may deviate greatly from regionally defined patterns.

Introduction

There are over 12,000 lakes greater than 10 hectares (25 acres) in Minnesota, 98 percent of which are principally distributed among four of Minnesota's seven ecoregions (Fig. 1). Lake types vary from relatively shallow, fertile lakes in the south to relatively deep, mesotrophic or oligotrophic lakes in the north (Moyle, 1956; Omernik, 1987; Omernik and Gallant, 1988; Heiskary et al. 1987). Statewide lake management efforts have focused on the development of regional phosphorus criteria (Heiskary and Walker, 1988). These efforts are intended to improve the state's ability to manage the water quality of its lake resources and to provide a framework for setting lake restoration/protection goals. Most recently, lake management goals have been defined by ecoregion based upon phosphorus criteria, the lake's most sensitive uses, and water quality attainability (Heiskary and Wilson, 1988).

The aquatic ecoregion framework has been used to describe lake water quality patterns, citizen perceptions of physical appearance and recreational suitability, stream characteristics, fisheries management, and appropriate phosphorus criteria for Minnesota lakes (Heiskary et al. 1987; Heiskary and Wilson, 1988). These ecoregion-based analyses have facilitated preparing summary documents for 305b reports to Congress, state assessments for Clean Lakes Program participation as authorized by Section 314 of the Water Quality Act of 1987, and assessments for state lake resource managers.

In setting goals for individual lakes, initial steps involve monitoring to characterize existing lake water quality and determining whether monitored condi-

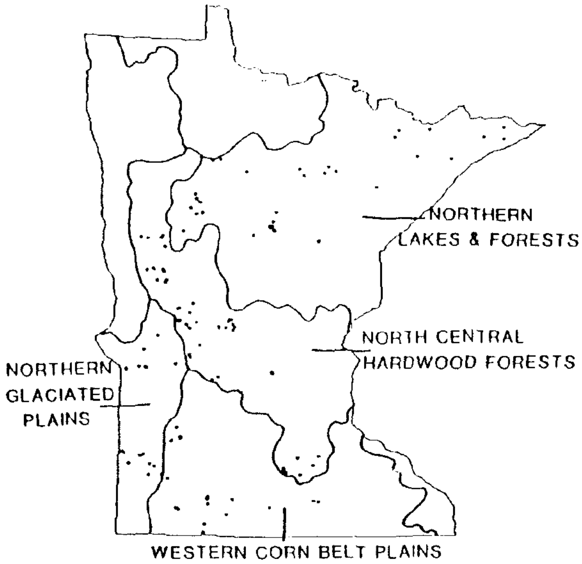


Figure 1.—Minnesota's lake ecoregions and spatial distribution of representative lakes. These lakes comprise the "ecoregion data base."

tions are typical, given the lake setting and morphometry. The Minnesota Lake Eutrophication Analysis Procedure (MINLEAP) is a computer program developed to assist in these efforts. MINLEAP predicts eutrophication indicators based upon ecoregion, watershed area, and lake morphometry. It is a descendent of the Lake Eutrophication Analysis Procedure (LEAP), a program developed to assist statewide lake management efforts in Vermont (Walker, 1982b,c). MINLEAP formulates lake water and phosphorus balances and employs a linkage of empirical models to predict lake phosphorus, chlorophyll *a*, and transparency values. The program is intended primarily as a **screening tool** for estimating lake conditions with minimal input data and for identifying "problem" lakes (those with unusually high measured phosphorus concentrations, given their location, morphometry, and hydrology). The development and application of MINLEAP are described below.

Data Base Development

MINLEAP has been developed from an ecoregion data set collected by Minnesota Pollution Control Agency (MPCA) staff in a statewide lake sampling program conducted during the summers of 1985, 1986, and 1987. Results described in this paper are based upon data from 90 reference lakes distributed among four ecoregions: Northern Lakes and Forests, North Central Hardwood Forests, Western Corn Belt Plains, and Northern Glaciated Plains (Fig. 1). These lakes were selected as to represent minimally impacted lakes (those without known point sources, largely urban watersheds, and/or feedlots). Land uses for these lakes are typical of their respective ecoregions. Factors such as maximum depth, surface area, and fishery management classification were also considered in the lake selection process.

Water quality data were collected three to four times each summer during 1985, 1986, or 1987. Generally, two mid-lake epilimnetic sites were sampled for the trophic variables using a 2 m PVC tube 3.6 cm in diameter (integrated samplers). Chlorophyll samples were chilled and kept in the dark immediately after collection and then filtered through a 4.5 cm diameter glass fiber filter within four hours of collection and kept frozen and in the dark until analyzed. Chlorophyll samples were analyzed within 10 days of sampling. General chemistry samples that required preservation were so treated at the time of collection and immediately stored at 0°C. For total phosphorus, the detection limit was 10 μg/L; the mean precision was 4.9 μg/L based on 10 percent duplicate analysis. Accuracy, expressed as a percent recovery, was 104 percent at a concentration of 20 μg/L and 101 percent at a concentration of 40 μg/L. For chlorophyll *a*, the detection limit was 1.0 μg/L, the mean precision was 2.9 μg/L based on 7 duplicate analyses. Chlorophyll accuracy expressed as a relative error was 4 percent. All chlorophyll values were collected for phaeophytin.

Average annual precipitation and evaporation data were obtained from Farnsworth et al. (1982). Regional runoff rates were derived from Minnesota Department of Natural Resources (1987) and Gunard (1985). A statistical summary of lake characteristics by ecoregion is given in Table 1.

It is hoped that the water and phosphorus budgets and the model framework may be adapted and applied in other states and regions of the country. Therefore, the mechanics of development will be briefly reviewed.

Program Structure

MINLEAP control pathways are illustrated in Figure 2. The program estimates lake water outflow and phosphorus loading using the following equations:

Equation 1

$$\text{Water Outflow} = [\text{Runoff} \times \text{Watershed Area}] + [\text{Lake Area} \times (\text{Precipitation} - \text{Evaporation})]$$

Equation 2

$$\text{Phosphorus Loading} = [\text{Lake Area} \times \text{Atmospheric Deposition}] + [\text{Watershed Area} \times \text{Runoff} \times \text{Regional Stream Total Phosphorus}]$$

Table 1.—MINLEAP Database summary by region.

VARIABLE	UNITS	ECOREGION MEANS NCHF	NLF	NGP	WCBP
Number of Lakes	—	36	30	8	11
Land Uses					
Cultivated	%	34.8	1.8	73.0	60.6
Pasture	%	18.0	3.9	9.2	5.9
Urban	%	0.7	0.0	2.0	1.5
Residential	%	6.4	4.8	0.4	9.9
Forested	%	16.4	66.2	0.0	7.0
Marsh	%	2.5	2.1	0.6	1.2
Water	%	20.9	20.9	14.4	13.6
Watershed area	ha	4670	2140	2464	756
Lake area	ha	364	318	218	107
Mean depth	m	6.6	6.3	1.6	2.5
Total phosphorus	µg/L	33	21	156	98
Chlorophyll *a*	µg/L	14	6	61	67
Secchi depth	m	2.5	3.5	0.6	0.9
Outflow	hm3/yr	6.2	5.3	0.9	1.0
Total phosphorus load	kg/yr	1004	305	1943	590
Inflow phosphorus conc.	ppb	183	58	5666	564
Areal phosphorus load	kg/km^2-yr	276	96	891	551
Hyd. residence time	years	9.3	5.0	36.2	4.8
Overflow rate	m/yr	1.3	1.7	0.4	0.8
Stream total phosphorus	ppb	148	52	1500	570*
Precipitation	m/yr	0.75	0.74	0.64	0.80
Evaporation	m/yr	0.71	0.61	0.76	0.74
Runoff	m/yr	0.13	0.23	0.05	0.13
Atmospheric load	kg/km^2-yr	30	15	20	20

*Calibrated Values
Ecoregions: NCHF—Northern Central Hardwood Forests
NLF—Northern Lakes and Forests
NGP—Northern Glaciated Plains
WCBP—Western Corn Belt Plains

Ecoregion is used to predict regional runoff (m/yr), precipitation (m/yr), evaporation (m/yr), stream phosphorus concentration (ppb) and atmospheric phosphorus deposition (kg/km^2-yr). Other input variables, including watershed area, lake area, mean depth, and observed lake quality (optional), are lake specific. Lake phosphorus concentrations are predicted using the phosphorus retention function developed by Canfield and Bachmann (1981) for natural lakes. Chlorophyll *a* and transparency are predicted using regression equations 3 and 4 developed from statewide lake data sets (Heiskary and Wilson, 1988).

$$\text{Log}_{10}\,\text{Chla} = 1.46\text{Log}_{10}(\text{TP})-1.09 \qquad \text{Equation 3}$$
$$R^2 = 0.9, N = 143$$

$$\text{Log}_{10}\,\text{SD} = -0.57\text{Log}_{10}(\text{Chla}) + 0.87 \qquad \text{Equation 4}$$
$$R^2 = 0.82, N = 103$$

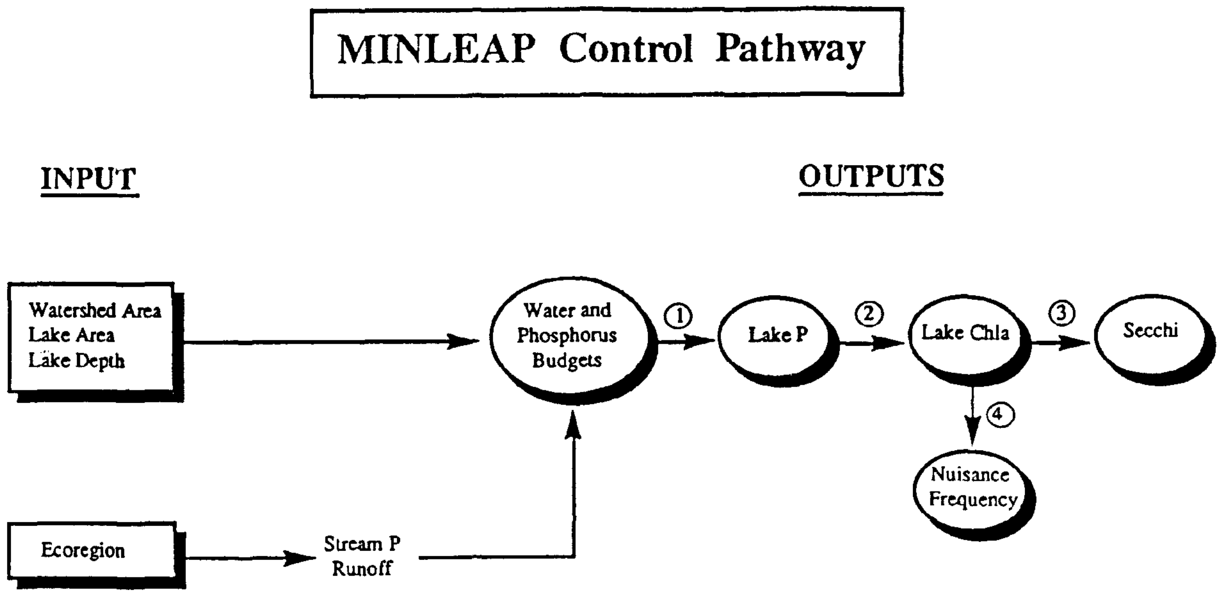
A complete listing of the program in BASIC is contained in the Appendix.

MINLEAP was calibrated to the ecoregion data set by manually adjusting stream phosphorus concentrations by ecoregion to give unbiased predictions of lake phosphorus concentration. These calibrated values were compared with measured mean stream total phosphorus values by ecoregion in Table 2. The calibrated values for the Northern Lakes and Forests and North Central Hardwood Forest ecoregions are quite similar to the measured mean values.

Calibrated stream concentrations vary with the sedimentation model used for predicting lake phosphorus concentrations. The second order equations of Canfield and Bachmann (1981) and Walker (1985) result in higher stream phosphorus estimates than the first order Vollenweider (1976) model (Table 2). The MINLEAP program employs the natural lake version of the Canfield and Bachmann (1981) retention model. The residual model errors, calculated for each model application over the range of phosphorus stream values shown in Table 2, are quite similar. Therefore, no statistical basis exists for deciding which retention model is best for Minnesota lakes without direct measurement of loading. Until further studies are completed to define these ranges of phosphorus loading, it will not be feasible to better define the model application.

For the Western Corn Belt Plains and Northern Glaciated Plains, calibrated stream phosphorus concentrations exceed mean measured values by factors of 1.8 and 6.9, respectively. It is unlikely that mean stream phosphorus concentrations adequately reflect high-flow conditions that are responsible for the bulk of the phosphorus loading (Walker, 1985).

Figure 2.—



Models	
①	Phosphorus Retention
②	Chl-P Regression
③	Secchi-Chl Regression
④	Frequency Distribution

Table 2.—Calibrated stream phosphorus concentrations versus model and region.

	PHOSPHORUS RETENTION MODEL				
REGION	A	B	C	OBS	NSTREAM
NLF	55	32	48	46	335
NCHF	150	85	70	145	225
WCBP	600	420	220	304	406
NGP	1500	1050	220	218	265
RSE	0.179	0.171	0.182		

Phosphorus Retention Models
A Canfield and Bachmann (1981)
B Walker (1985) Second Order Sedimentation
C Vollenweider (1976)
NLF—Northern Lakes and Forests
NCHF—Northern Central Hardwood Forests
WCBP—Western Corn Belt Plains
NGP—Northern Glaciated Plains
OBS Mean Measured Stream Phosphorus Conc. (throughout ecoregion)
Number of lakes sampled per Ecoregion: NLF = 30; NCHF = 36; WCBP = 11; and NGP = 8
RSE Residual Standard Error – Log10 (Lake P)
NStream Number of stream measurements for the period 1970–1985.

Stream phosphorus concentrations can increase dramatically under high runoff conditions, particularly in agricultural watersheds. Infrequent runoff events account for much of the total annual loading and are not adequately reflected by mean values derived from routine periodic stream sampling. The calibrated stream phosphorus concentration for Northern Glaciated Plains is relatively uncertain because of the small number of lakes sampled (8 versus 11 to 36 in other regions) and long lake retention times.

Phosphorus retention by lakes in the Western Corn Belt Plains and Northern Glaciated Plains may also be less than that predicted by the Canfield/Bachmann model. These lakes are relatively shallow and have high surface areas, characteristics conducive to wind-induced turbulence and phosphorus recycling by following mechanisms: (1) polymictic behavior (intermittent periods of stratification, anoxic, and sediment phosphorus release); (2) high vertical transport rates for dissolved and particulate phosphorus; (3) mixing of dissolved phosphorus from anoxic zones via methane gas ebullition (Bostrom et al. 1982); and (4) turbulence induced bottom-mixed turbidity. Therefore, the phosphorus/chlorophyll response may strongly deviate from statewide relationships within these regions of the state.

It is important to distinguish between "error" and "variability." Error refers to a difference between an observed and a predicted mean value. Variability refers to spatial and temporal fluctuations in concentration about the mean. Both error and variability estimates have been incorporated into MINLEAP.

Observed versus predicted phosphorus, chlorophyll *a*, and transparency are shown on LOG_{10} scales in Figures 3, 4, and 5, respectively. Explained variance (R^2 statistics) and residual standard errors are displayed by ecoregion in Figures 6 and 7, respectively. Generally, the model performed similarly across ecoregions, as gauged by residual standard errors (Fig. 7). The proportions of explained variance (R^2) within ecoregions range from less than zero for Northern Glaciated Plains to .50 for total phosphorus in Western Corn Belt Plains. Negative R^2 values indicate that residual variance exceeds observed variance, or that we can do better by assuming that lake phosphorus concentration is constant within a given ecoregion, instead of trying to predict lake phosphorus concentrations using the model network. On a statewide basis, the model explains 74 percent of the total phosphorus variance, 66 percent of the chlorophyll *a* variance, and 67 percent of the transparency variance. Corresponding residual standard errors are .18, .31, and .20, respectively, and in ranges typical of empirical eutrophication models, based upon literature review (Walker, 1982*a*). Alternative model structures using land use as a predictor of runoff and stream phosphorus concentration (in place of ecoregion) were also investigated, but gave residual errors that are slightly higher than those shown in Figure 7.

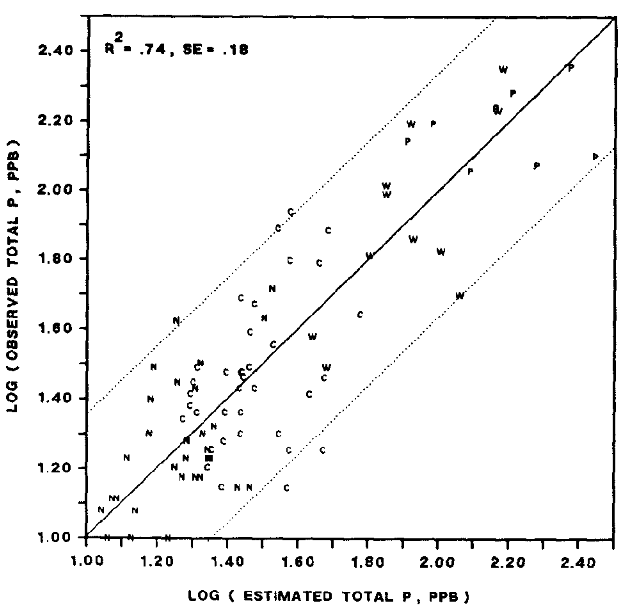


Figure 3.—Observed versus predicted total phosphorus mean + 2 standard errors by ecoregion. Legend: Base-10 logarithmic scales. Symbols: N = Northern Lakes and Forests, C = Northern Central Hardwood Forests, P = Northern Glaciated Plains, W = Western Corn Belt Plains.

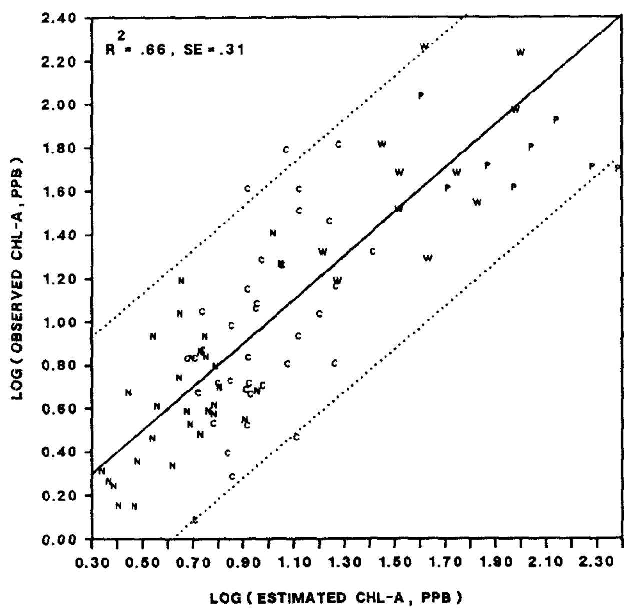


Figure 4.—Observed verus predicted chlorophyll $\underline{a}$ mean + 2 standard errors by ecoregion. Legend: base-10 logarithmic scales. Symbols: N = Northern Lakes and Forests, C = Northern Central Hardwood Forests, P = Northern Glaciated Plains, W = Western Corn Belt Plains.

With one exception, MINLEAP provides unbiased predictions (mean residual not significantly different from zero) for each ecoregion and lake response variable. The average chlorophyll *a* residual for Northern

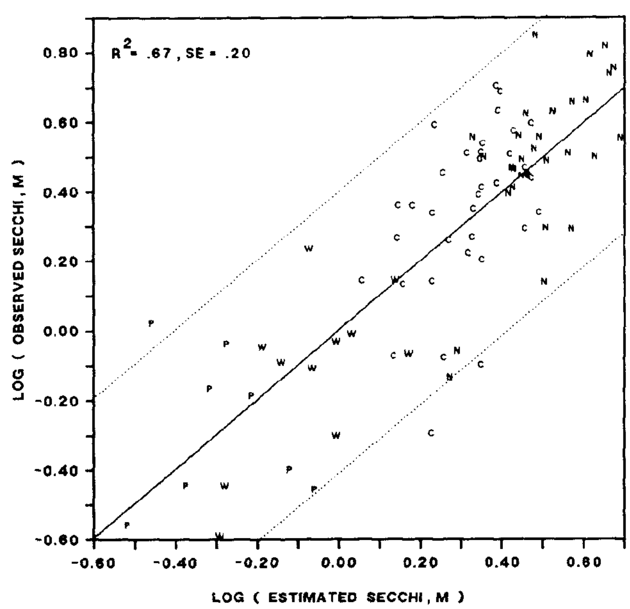


Figure 5.—Observed versus predicted Secchi transparency mean + 2 standard errors by ecoregion. Legend: base-10 logarithmic scales. Symbols: N = Northern Lakes and Forests, C = Northern Central Hardwood Forests, P = Northern Glaciated Plains, W = Western Corn Belt Plains.

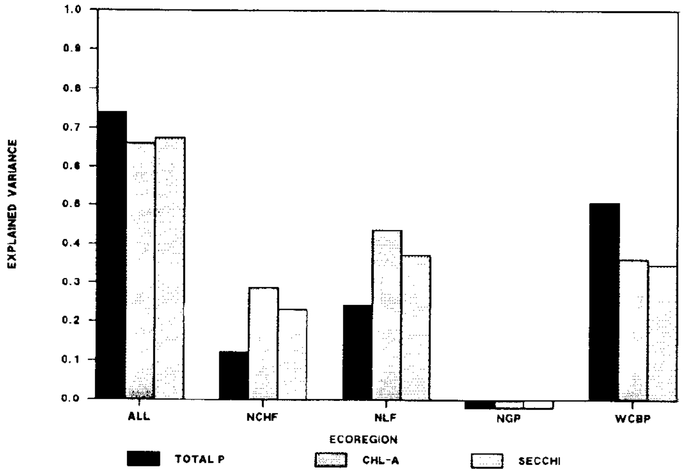


Figure 6.—MINLEAP calibration: R-squared values by ecoregion and eutrophication variable. Legend: base-10 logarithmic scales. Symbols: N = Northern Lakes and Forests, C = Northern Central Hardwood Forests, P = Northern Glaciated Plains, W = Western Corn Belt Plains.

Glaciated Plains is −.24, indicating the observed chlorophyll *a* concentrations average 58 percent of the predicted values. This result may reflect high phosphorus concentrations (mean = 156 μg/L) and high non-algal turbidities in this ecoregion. It was preferable to leave this bias in the model for the Northern Glaciated Plains region, rather than adjust the phosphorus/chlorophyll *a* regression, which provides unbiased predictions for the rest of the state.

Several investigators have discussed the implications of regional variations in inorganic suspended solids concentrations with respect to lake nutrient response (Bostrom et al. 1982; Hoyer and Jones, 1983; Brown, 1984; Reckhow and Clements, 1984; Pearse, 1984; Reckhow, 1988). Mineral turbidities cause deviations in phosphorus retention, phosphorus/chlorophyll *a*, and chlorophyll *a*/Secchi relationships.

Total suspended solids (TSS) and inorganic suspended solids (ISS) concentrations (total suspended solids minus volatile suspended solids) found in lakes vary with Minnesota ecoregion. Typical ranges (25th to 75th percentiles) of total suspended solids found in minimally impacted lakes of the Northern Lakes and Forests and the North Central Hardwood Forests are less than 2 mg/L and 4 mg/L, respectively. Lakes in the data set from the agricultural regions, the Northern Glaciated Plains and Western Corn Belt Plains, have typical ranges of total suspended solids concentrations of 7-18 mg/L and 10-30 mg/L, respectively. Inorganic suspended solids concentrations constitute about 40-50 percent of the total suspended solids values in the Western Corn Belt Plains and about 50 percent of the Northern Glaciated Plains values.

A first-order error analysis has been conducted to propagate error variance through the model network (Walker, 1982b; Reckhow and Chapra, 1983). Sources of error for each predicted variable are given in Table 3. Measurement errors in the observed mean lake response variables account for 16 percent, 14 percent, and 9 percent of the total residual error for phosphorus, chlorophyll *a*, and transparency, respectively. This suggests that sampling frequencies employed in developing the ecoregion data set are adequate for modeling purposes, although year-to-year variance components should be further investigated.

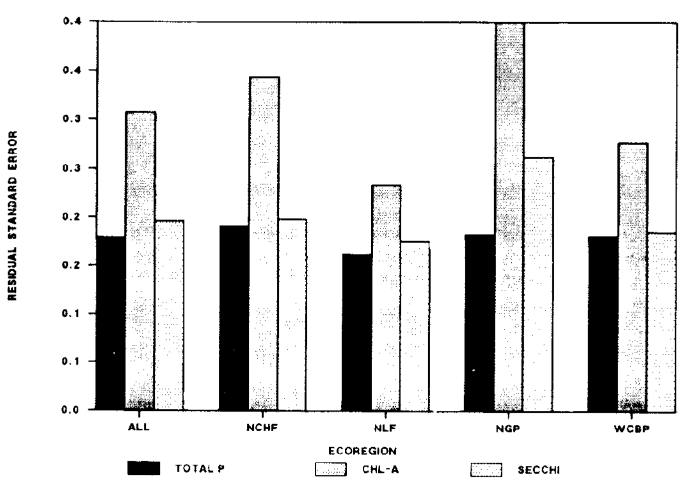


Figure 7. MINLEAP calibration: residual standard error by ecoregion and eutrophication variable. Legend: base-10 logarithmic scales. Symbols: N = Northern Lakes and Forests, C = Northern Central Hardwood Forests, P = Northern Glaciated Plains, W = Western Corn Belt Plains.

The phosphorus retention model is the major source of residual variance for each variable. It accounts for 74 percent of the residual variance for phosphorus, 53 percent for chlorophyll *a*, and 45 percent for transparency. The importance of this error term reflects the relatively long retention times of these lakes, which averaged over four years in each ecoregion, and the resulting sensitivity of lake phosphorus concentrations to internal processes (sedimentation, recycling, etc.). This is in contrast to reservoir data sets (Walker, 1985) which tend to have much shorter mean retention times, often less than .25 years, and less dependence on internal processes. The phosphorus balances in reservoirs were dominated by inflows and outflows, as opposed to retention.

Table 3.—MINLEAP residual error components.

	TOTAL PHOSPHORUS		CHLOROPHYLL *A*		SECCHI DEPTH	
ERROR SOURCE	VARIANCE	PERCENT	VARIANCE	PERCENT	VARIANCE	PERCENT
Inflow phosphorus	0.017	9.7	0.035	7.0	0.012	5.9
Phos. retention	0.126	73.6	0.269	53.3	0.094	45.1
Residence time	0.002	1.1	0.004	0.8	0.001	0.7
Chla/Phos. model	0.000	0.0	0.126	24.9	0.044	21.0
Secchi/chl *a* model	0.000	0.0	0.000	0.0	0.038	18.3
Measurement	0.027	15.7	0.071	14.0	0.019	9.1
TOTAL	0.172	100.0	0.505	100.0	0.208	100.0

Variance Components Expressed in Terms of Natural Logarithms

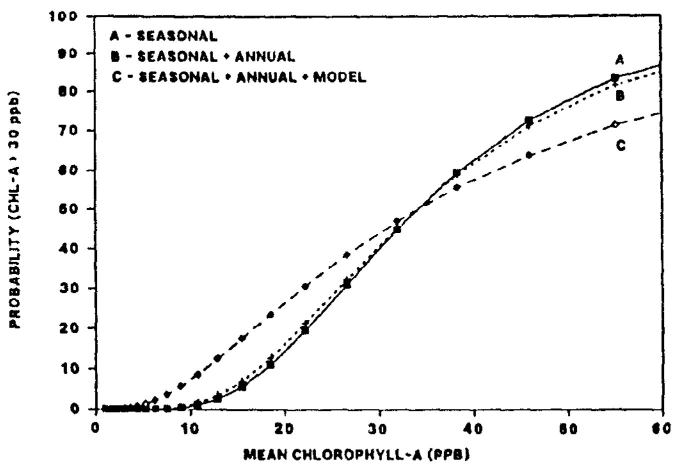


Figure 8. Algal nuisance frequencies versus mean chlorophyll a.

MINLEAP output also includes t-statistics for testing whether observed and predicted lake means differ significantly. Error in the predicted variable is calculated using a first-order error analysis. Error in the observed variable is assumed to be typical of the model development data set. If the absolute value of the calculated t-statistic is less than 2.0, then the observed mean is not significantly different from the predicted mean at the 95 percent percent confidence level. These comparisons are of particular in use in identifying "problem lakes" or "outliers."

Chlorophyll a Interval Frequencies

In addition to predicting average phosphorus, chlorophyll *a*, and transparency values, MINLEAP calculates the frequencies of extreme chlorophyll *a* values (Chl-a > 10, 20, 30, 60 ppb). These frequencies are estimated from the predicted mean value and coefficient of variation by employing a log-normal distribution function (Walker, 1984).

Recent evaluations of lake survey variance components for Minnesota and other states (Knowlton et al. 1984; Smeltzer et al. 1989; Marshall et al. 1988) have been used to refine the algorithm used for predicting chlorophyll *a* interval frequencies. The temporal coefficient of variation (CV) has been set equal to the median, within-year coefficient of variation derived from variance component analysis of Minnesota lake survey data (CV = .48). The predicted interval frequencies have also been modified to account for year-to-year variability in the mean and for model error in predicting the long-term mean. These modifications are illustrated in Figure 8, which shows three relationships between mean chlorophyll *a* and the frequency or probability of instantaneous values above 30 ppb. These curves differ in their development and interpretation as follows:

(A) "**SEASONAL**" – The mean chlorophyll *a* on the X-Axis refers to a particular year and is known precisely. The predicted nuisance frequency curve refers only to that particular year and accounts for seasonal variation only (median CV = .48).

(B) "**SEASONAL + ANNUAL**" – The mean chlorophyll *a* on the X-Axis refers to the long-term mean for the particular lake and is known precisely. The predicted nuisance frequency curve refers to all years combined and accounts for seasonal and year-to-year variations. There is little difference between "A" and "B" because the within-year variations in chlorophyll *a* (CV = .48) are much stronger than among-year variations (CV = .20). Curve "B" is derived by pooling the within-year and among-year variance components (Pooled CV = (.48^2 + .20^2).5 = .52).

(C) "**SEASONAL + ANNUAL + MODEL**" – The mean chlorophyll *a* on the X-Axis refers to the long-term mean for a particular lake, as predicted by MINLEAP. The predicted nuisance frequency curve refers to all years combined and accounts for seasonal variations, year-to-year variations, and model error in predicting the long-term mean (CV = .66, based upon MINLEAP error analysis results). The difference between Curves C and A/B reflects the impact of model uncertainty on the prediction of nuisance frequencies.

Presentation of frequency or risk of "nuisance" algal levels in this manner reflects the effects of temporal variability and model error upon the predicted ranges of chlorophyll *a* values. Chlorophyll *a* nuisance criteria may be calibrated to user perceptions by conducting observer surveys (Heiskary and Walker, 1988). Expression of lake conditions in this manner provides a rational basis for setting phosphorus criteria or management goals related to user perceptions of nuisance conditions.

MINLEAP Case Study

Lake Volney is located in the southern range of the North Central Hardwood Forests ecoregion. The lake covers an area of 112 ha and has a predominantly agricultural watershed of 750 ha. Citizens have been concerned that the lake has undergone recent degradation and complain of extensive and severe nuisance conditions that exist most of the summer. Based upon lake monitoring data from summer 1985, Secchi transparency averaged 1.5 m, total phosphorus averaged 160 μg/L, and chlorophyll *a* averaged 40 μg/L. The principal issue was whether the observed lake conditions were "typical," based upon the lake's setting and morphometry.

The appropriate data for Lake Volney were entered at the prompts ("?") in the MINLEAP Input Section (Fig. 9). Output Section 1 provided generalized water- and phosphorus-budget summaries. Output Section 2 compared observed and predicted conditions. Output Section 3 predicted chlorophyll *a* interval frequencies.

Predicted mean total phosphorus and chlorophyll *a* for Lake Volney were 27 and 8 μg/L, respectively. These were significantly lower than observed values, 160 and 40 μg/L, respectively, based upon the t-statistics. The measured average transparency of 1.6 m was influenced by the dominance of *Aphanizomenon flos-aquae* (based upon direct field observations) and was not significantly different from the predicted transparency of 2.3 m.

The variability of growing season conditions as expressed by chlorophyll *a* interval frequencies was displayed in Output Section 3. In this instance, one season of data suggested observed chlorophyll *a* concentrations would exceed 10, 20, 30, and 60 μg/L about 99.6 percent, 89 percent, 64 percent, and 14 percent of the time, respectively. The MINLEAP

```
Minnesota Lake Eutrophication Analysis Procedure
ENTER INPUT VARIABLES
LAKE NAME ? VOLNEY
ECOREGION NUMBER 1=NLF,2=CHF,3=WCP,4=NGP ? 2
WATERSHED AREA (HA)            ? 638
LAKE SURFACE AREA (HA)         ? 112
LAKE MEAN DEPTH (M)            ? 6.9
OBSERVED MEAN LAKE TP (UG/L)   ? 160
OBSERVED MEAN CHL-A (UG/L)     ? 40
OBSERVED MEAN SECCHI (M)       ? 1.6
```

INPUT SECTION

```
LAKE = VOLNEY                          ECOREGION = CHF
AVERAGE INFLOW TP = 178.8506  UG/L     TOTAL P LOAD        = 156.3512  KG/YR
LAKE OUTFLOW      = .8742  HM3/YR      AREAL WATER LOAD    = .7805357 M/YR
RESIDENCE TIME    = 8.840083  YRS      P RETENTION COEF    = .8502369
```

OUTPUT SECTION 1

```
VARIABLE  UNITS        OBSERVED PREDICTED STD ERROR  RESIDUAL    T-TEST
TOTAL P   (UG/L)        160.00     26.79     10.79      0.78      4.11
CHL-A     (UG/L)         40.00      8.03      5.52      0.70      2.18
SECCHI    (METERS)        1.60      2.27      1.02     -0.15     -0.74
NOTE: RESIDUAL = LOG10(OBSERVED/PREDICTED)
      T-TEST FOR SIGNIFICANT DIFFERENCE BETWEEN OBS. AND PREDICTED
```

OUTPUT SECTION 2

```
CHLOROPHYLL-A INTERVAL FREQUENCIES (%)
CHL-A           PREDICTED PREDICTED PREDICTED
  PPB  OBSERVED   CASE A    CASE B    CASE C
  10      99.60    24.29     25.97     34.86
  20      88.59     1.62      2.41     11.64
  30      64.08     0.14      0.29      4.81
  60      13.88     0.00      0.00      0.68
CASE A = WITHIN-YEAR VARIATION CONSIDERED
CASE B = WITHIN-YEAR + YEAR-TO-YEAR VARIATION CONSIDERED
CASE C = CASE B + MODEL ERROR CONSIDERED
```

OUTPUT SECTION 3

Figure 9. Application of MINLEAP to Lake Volney, Minnesota.

predicted frequencies for one season of data (Case A, Fig. 9) were 24 percent, 2 percent, $\sim$0 percent and $\sim$0 percent, respectively.

Consideration of additional years of data along with model error (Case C, Fig. 9) would result in predicted nuisance frequencies of 35 percent, 12 percent, 5 percent, $\sim$1 percent, respectively.

This assessment strongly indicated that Lake Volney was subject to excessive nutrient loading (unusually high for this ecoregion). Further stream sampling indicated that two feedlots were likely affecting lake water quality. This illustrates applying MINLEAP to identify problem lakes for further investigation and possible corrective action.

In another example, Middle Cormorant Lake, MINLEAP was used to assess lake water quality from a different perspective. Middle Cormorant Lake is located in the northwestern range of the North Central Hardwood Forest ecoregion. The lake covers an area of about 153 ha with a watershed of 3,239 ha. Land usage is varied and consists of about 28 percent agricultural (with about 28 percent of the agricultural land in row crops), 11 percent pasture, 20 percent forested, 3 percent urban and 38 percent water/wetland. The lake has been a popular resort/vacation area since the Northern Pacific Railroad opened the area in about 1900. Water levels have not been strongly affected by droughts, reportedly because of ground water entering the lake. The lake association and residents are concerned about protecting the lake's excellent water quality. Based on monitoring conducted in 1987 and 1988, Secchi transparency averaged 3.3 m, total phosphorus averaged 19 μg/L, and chlorophyll averaged 3.7 μg/L.

With the appropriate data for Middle Cormorant Lake, MINLEAP-predicted average values were: Secchi, 1.4 m; total phosphorus, 49 μg/L, and chlorophyll *a*, 19 μg/L. In this case, the predicted values were all significantly different (worse) than the observed. This would imply that this lake is a resource meriting protective measures as no nuisance conditions (e.g., chlorophyll 20 μg/L) have been observed. This is in contrast to the predicted chlorophyll *a* frequency, which suggested that nuisance conditions may be expected to occur during 9 percent of the summer.

Conclusions

State and local resource managers are frequently faced with the task of determining reasonable water quality patterns and providing understandable summaries to a variety of decisionmakers involved in resource management. This process has been facilitated in Minnesota by using aquatic ecoregion framework and standard assessment methodologies. To facilitate "first cut" analyses of lake water quality, MINLEAP was developed in BASIC IBM-PC compatible format for use by county and regional lake resource managers. The framework employed in developing the procedure should be adaptable to other ecoregions in the country. Not all states may have the diversity of lake water quality implied in the development of MINLEAP; therefore, a similar network of models for such regions should be based upon a sufficiently defined data set that generates statistically sound predictions. The network of models described in this paper are cross-sectional in nature and, therefore, do not necessarily define individual lake variabilities resulting from lake specific biologies and geochemistries. The model is meant to be used as a tool to flag lakes that may deserve further study and resources. MINLEAP is not intended to be used in defining detailed water and nutrient balances and in-lake characteristics.

Translating the results of modeling into everyday expectations for the average lake user has been a difficult task complicated by the subjective nature of user preferences, the large diversity of lakes in Minnesota, temporal variations in water quality, and predictive uncertainty. The use of probabilistic presentations of chlorophyll *a* concentrations in the assessment methodology has facilitated this translation. Comparisons of observed water quality measures to regionally predicted values facilitates interpretation by the local lake residents, lake associations, and resource managers.

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References

Bostrom, B., M. Jansson, and C. Forsberg. 1982. Phosphorus release from lake sediments. Arch. Hydrobiol. Bah. 18:5-59.

Brown, R. 1984. Relationships between suspended solids, turbidity, light attenuation, and algal productivity. Lake Reserv. Manage. 2:198-205.

Canfield, D.E. and R.W. Bachmann. 1981. Prediction of total phosphorus concentrations, chlorophyll a, and Secchi depths in natural and artificial lakes. Can. J. Fish. Aquat. Sci. 38:4414-23.

Farnsworth, R.K., E.S. Thompson, and E.L. Peck. 1982. Evaporation atlas for the continguous 48 United States. NOAA Tech. Rep. Natl. Weather Serv. 33.

Gunard, K. T. 1985. Natural water summary-surface water resources. Water Supply Pap. 2300. U.S. Geol. Surv. St. Paul, MN.

Heiskary, S.A. and C.B. Wilson. 1988. Minnesota lake water quality assessment report. Div. Water Qual. Minn. Pollut. Control Agency, St. Paul.

Heiskary, S.A., C.B. Wilson, and D.P. Larsen. 1987. Analysis of regional patterns in lake water quality: Using ecoregions for lake management in Minnesota. Lake Reserv. Manage. 3:337-44.

Heiskary, S. and W.W. Walker, Jr. 1988. Developing phosphorus criteria for Minnesota lakes. Lake Reserv. Manage. 4:1-9.

Hoyer, M.V. and J.R. Jones. 1983. Factors affecting the relation between phosphorus and chlorophyll a in Midwestern reservoirs. Can. J. Fish. Aquat. Sci. 40:192-99.

Knowlton, M.F., M.V. Hoyer, and J.R. Jones. 1984. Sources of variability in phosphorus and chlorophyll, and their effects on use of lake survey data. Water Resour. Bull. 20:397-407.

Marshall, C.T., A. Morin, and R. H. Peters. 1988. Estimates of mean chlorophyll a concentration: Precision, accuracy, and sampling design. Water Resour. Bull. 24(5):1027-34.

Minnesota Department of Natural Resources. 1987. Summary: The economic value of water. Prep. Legis. Comm. Minn. Resour. St. Paul.

Moyle, J.B. 1956. Relationships between chemistry of Minnesota surface waters and wildlife management. J. Wildl. Manage. 30(3):303-20.

Omernik, J. 1987. Ecoregions of the conterminous United States. Annal. Ass. Am. Geogr. 77(1):118-25.

Omernik, J. and A. Gallant. 1988. Ecoregions of the upper Midwest states. EPA/600/3-88-037. U.S. Environ. Prot. Agency, Washington, DC.

Pearse, J. 1984. Phytoplankton-nutrient relationships in South Carolina reservoirs: Implications for management strategies. Lake Reserv. Manage. 2:193-97.

Reckhow, K.H. 1988. Empirical models for trophic state in southeastern United States lakes and reservoirs. Water Resour. Bull. 24(4):723-34.

Reckhow, K.H. and S.C. Chapra. 1983. Engineering Approaches for Lake Management. Vol. 1: Data Analysis and Empirical Modeling. Butterworth Publ. Boston, MA.

Reckhow, K.H. and J.T. Clements. 1984. A cross-sectional model for phosphorus in southeastern United States lakes. Lake Reserv. Manage. 2:186-92.

Smeltzer, E., V. Garrison, and W.W. Walker Jr. 1989. Eleven years of lake eutrophication monitoring efforts in Vermont: A critical evaluation. Proc. Conf. Enhancing States' Lake Manage. Progr. Chicago, May 1988. Northwest. Ill. Planning Comm., N. Am. Lake Manage. Soc. U.S. Environ. Prot. Agency.

Stauffer, R.E. 1985. Relationship between phosphorus loading and trophic state in calcareous lakes of southeastern Wisconsin. Limnol. Oceanogr. 30:123-45.

Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist. Ital. Idrobiol. 33:53-83.

Walker, W.W. 1982a. Empirical Methods For Predicting Eutrophication in Impoundments - Report 2 - Model Testing. Prep. Chief Eng., U.S. Army, Tech. Rep. E-81-9, Waterways Exp. Sta., Vicksburg, MS.

———. 1982b. A sensitivity and error analysis framework for lake eutrophication modeling. Water Resour. Bull. 18(1):53-60.

———. 1982c. Calibration and testing of a eutrophication analysis procedure for Vermont lakes. Prep. Vermont Agency Environ. Conserv., Water Qual. Div. Montpelier.

———. 1984. Statistical bases for mean chlorophyll a criteria. Lake Reserv. Manage. 2:57-62.

———. 1985. Empirical Methods for Predicting Eutrophication in Impoundments - Report 3 - Model Testing. Prep. Chief Eng., U.S. Army, Tech. Rep. E-81-9, Waterways Exp. Sta. Vicksburg, MS.

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APPENDIX—MINLEAP Program Listing.

```
10 REM MINLEAP LISTING - VERSION 11/14/88
100 CLEAR 1000:KEY OFF:CLS
130 REM INPUT SECTION
140 PRINT"Minnesota Lake Eutrophication Analysis Procedure"
142 PRINT"ENTER INPUT VARIABLES"
150 INPUT "LAKE NAME ";RN$
155 INPUT"ECOREGION NUMBER 1=NLF,2=CHF,3=WCP,4=NGP ";EN
160 IF EN<1 OR EN>4 THEN 155
170 INPUT"WATERSHED AREA (HA)                 ";AW
180 INPUT"LAKE SURFACE AREA (HA)              ";AL
190 INPUT"LAKE MEAN DEPTH (M)                 ";ZM
200 INPUT"OBSERVED MEAN LAKE TP (UG/L)        ";TP
210 INPUT"OBSERVED MEAN CHIL-A (UG/L)         ";CA
220 INPUT"OBSERVED MEAN SECCHI (M)            ";SD
230 REM REGIONAL VALUES
240 REM RUNOFF IS CALCULATED FOR AVERAGE CONDITIONS
250 REM CHANGE RO VALUES IN LINES 270-300 IF OTHERWISE
260 REM
265 'regional stream p, precip, evap, runoff, atmos load
270 IF EN=1 THEN CE=52  :PT=.74:PE=.61:RO=.23:WA=15     'NLF VALUES
280 IF EN=2 THEN CE=148 :PT=.75:PE=.71:RO=.13:WA=30     'CHF VALUES
290 IF EN=3 THEN CE=570 :PT=.8  :PE=.74:RO=.13:WA=30    'WCBP VALUES
300 IF EN=4 THEN CE=1500:PT=.64:PE=.76:RO=.05:WA=30     'NGP VALUES
310 '
320 'error analysis parameters
330 '
340 V1=.01:V2=.202:V3=.04:V4=.126:V5=.038             'error terms
350 V6=.027:V7=.071:V8=.019                           'obs tp,chla,secchi
360 CR(1)=10:CR(2)=20:CR(3)=30:CR(4)=60               'chla criteria
370 S1=.48                                            'chla seasonal ln std dev
380 S2=.2                                             'chla year-to-year ln std dev
390 EN$(1)="NLF":EN$(2)="CHF":EN$(3)="WCP":EN$(4)="NGP"   'ecoregion names
400 '
410 'CALCULATIONS ...........................................................................
420 '
430 AL = AL*.01                   'CONVERSION TO kM2
440 AW=AW*.01                     'CONVERSION TO kM2
450 QO=AW*RO+AL*(PT-PE)           'OUTFLOW VOLUME    hm3/yr
460 V=AL*ZM                       'LAKE VOLUME CALC    hm3
470 QS=QO/AL                      'WATER LOAD IN M/YR
480 TW=V/QO                       'WATER RESIDENCE TIME YEARS
500 WP=AL*WA+AW*RO*CE             'PHOSPHORUS LOAD kg/yr
505 PI = WP/QO                    'AVERAGE INFLOW TP    ppb
510 PT = PI/(1+.162*PI^.458*TW^.542)   'CANFIELD BACHMANN EQUATION
520 RP=1-PT/PI                    'RETENTION COEFFICIENT
525 '
530 EP=V3*(1-2*.46*RP+.46^2*RP^2)+V2*RP^2+V1*RP^2*.46^2      'error var(p)
540 IF TP>0 THEN R1=LOG(TP/PT):T1=R1/SQR(EP+V6) ELSE T1=0:R1=0 't-test for P
550 CL=.0661*PT^1.46              'mean chla
560 EC=EP*1.46^2+V4               'error var(chla)
570 IF CA>0 THEN R2=LOG(CA/CL):T2=R2/SQR(EC+V7) ELSE T2=0:R2=0 'T TEST FOR CHLA
580 SC=7.76*CL^-.59               'mean secchi depth
590 ES=EC*.59^2+V5                'error var (sec)
600 IF SD>0 THEN R3=LOG(SD/SC):T3=R3/SQR(ES+V8) ELSE T3=0:R3=0 'T test for sec
610 '
620 'chlorophyll-a quantiles...........................
630 FOR I=1 TO 4
640 C=CR(I)                       'criterion
650 CM=CA                         'observed mean
660 SL=S1                         'seasonal
670 GOSUB 780:F0(I)=F
680 CM=CL                         'estimated mean
690 SL=S1                         'seasonal
700 GOSUB 780:F1(I)=F
710 SL=SQR(S1^2+S2^2)             'seasonal + annual
720 GOSUB 780:F2(I)=F
730 SL=SQR(SL^2+EC)               'seasonal + annual + model
740 GOSUB 780:F3(I)=F
```

APPENDIX—MINLEAP Program Listing. *(continued)*

```
750 NEXT I
760 GOTO 870
770 '
780 'frequency subroutine input: c=criterion, cm=mean, sl=ln std deviation
790 '                          output: f = frequency (%)
800 Z-(LOG(C)-LOG(CM)+.5*S1^2)/SL
810  V=EXP(-Z^2/2)/2.507
820  W=(1+.33267*ABS(Z))^  1
830  X=V*(.436184*W-.121676*W^2+.937298*W^3)
840  IF Z>0 THEN F=X ELSE F=1-X
850  F=F*100
860 RETURN
870 '
880 PRINT ""
890 'OUTPUT SECTION
900 PRINT"INPUT DATA:"
920 PRINT"LAKE NAME =";RN$," ECOREGION=";EN$(EN)
930 PRINT"LAKE AREA =";AL*100;" HA"
940 PRINT"WATERSHED AREA (EXCLUDING LAKE) =";AW*100;" HA"
950 PRINT"MEAN DEPTH =";ZM;" METERS"
960 PRINT"OBSERVED MEAN TP =";TP;" UG/L"
970 PRINT"OBSERVED MEAN CHL-A =";CA;" UG/L"
980 PRINT"OBSERVED MEAN SECCHI =";SD;" METERS"
990 PRINT ""
995 PRINT"<press ENTER to view results>";LINE INPUT Q$:CLS
996 '
1000 PRINT"LAKE = ";RN$;TAB(40);"ECOREGION = ";EN$(EN)
1010 PRINT"AVERAGE INFLOW TP          =";PI;" UG/L";TAB(40);
1012 PRINT"TOTAL P LOAD               =";WP;" KG/YR"
1020 PRINT"LAKE OUTFLOW               =";QO;" HM3/YR";TAB(40);
1025 PRINT"AREAL WATER LOAD           =";QS; "M/YR"
1030 PRINT"RESIDENCE TIME             =";TW;" YRS";TAB(40);
1042 PRINT"P RETENTION COEF           =";RP
1050 PRINT
1055 '
1060 F1$="\        \"
1070 F2$="#######.##"
1080 '
1090 PRINT USING F1$;"VARIABLE";"UNITS";" OBSERVED";" PREDICTED";
1092 PRINT USING F1$;" STD ERROR";" RESIDUAL";"     T-TEST"
1100 PRINT USING F1$;"TOTAL P";"(UG/L)";
1110 PRINT USING F2$;TP;PT;SQR(EP)*PT;R1/2.303;T1
1120 PRINT USING F1$;"CHL-A";"(UG/L)";
1130 PRINT USING F2$;CA;CL;SQR(EC)*CL;R2/2.303;T2
1140 PRINT USING F1$;"SECCHI";"(METERS)";
1150 PRINT USING F2$;SD;SC;SQR(ES)*SC;R3/2.303;T3
1152 PRINT"NOTE: RESIDUAL = LOG10(OBSERVED/PREDICTED)"
1153 PRINT"        T-TEST FOR SIGNIFICANT DIFFERENCE BETWEEN OBS. AND PREDICTED"
1160 '
1165 PRINT
1170 PRINT"CHLOROPHYLL-A INTERVAL FREQUENCIES (%)"
1171 PRINT"CHL-A";
1172 PRINT USING F1$;" ";" PREDICTED";" PREDICTED";" PREDICTED"
1175 PRINT" PPB";
1180 PRINT USING F1$;" OBSERVED";" CASE A";" CASE B";" CASE C"
1190 FOR I=1 TO 4
1192 PRINT USING "####";CR(I);
1200 PRINT USING F2$;FO(I);F1(I);F2(I);F3(I)
1210 NEXT I
1220 PRINT "CASE A = WITHIN-YEAR VARIATION CONSIDERED"
1222 PRINT "CASE B = WITHIN-YEAR + YEAR-TO-YEAR VARIATION CONSIDERED"
1224 PRINT "CASE C = CASE B + MODEL ERROR CONSIDERED"
1300 END
```