Eleven Years of Lake Eutrophication Monitoring in Vermont: A Critical Evaluation

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ABSTRACT

Vermont has conducted one of the most extensive and long-term state lake eutrophication monitoring programs in the country. Sampling for spring total phosphorus, summer chlorophyll a, and summer Secchi disk transparency has been conducted during the past 11 years under programs that included up to 195 lakes within the state. These data are critically evaluated to determine the extent to which the original goals of the monitoring programs have been attained. An analysis of the data indicates that estimates of mean values for water quality parameters have been refined to a relatively high degree of statistical precision for most lakes included in the long-term monitoring programs. The level of precision attained is generally sufficient to support intended uses of the data, including the establishment of baseline water quality conditions and the development of regional empirical lake eutrophication models. The level of precision is not sufficient, however, to document incremental water quality changes of relatively small magnitude that would be expected in most situations of increasing cultural eutrophication in Vermont. It would generally be unrealistic to expect the current data base to detect emerging lake eutrophication problems using simple statistical tests. A variance component analysis is used to show ways in which the sampling programs could be modified to increase the precision of the long-term water quality means for a given level of sampling effort. Similarities with other state lake data sets indicate that these findings could be applicable beyond Vermont lakes.

Introduction

The State of Vermont has conducted one of the longest running and most extensive state lake eutrophication monitoring programs in the country. Sampling for spring total phosphorus, summer chlorophyll a, and summer Secchi disk transparency has been conducted for 11 years under programs that included up to 195 lakes. These monitoring programs were initiated in 1977 with a number of goals in mind. The purpose of this paper is to evaluate the extent to which these goals have been attained.

The original goals of Vermont's lake monitoring programs can be expressed as follows: (1) to provide a perspective on the range of eutrophication conditions found in the state's lakes; (2) to describe water quality conditions in individual lakes; (3) to provide data useful in developing regional empirical eutrophication models; (4) to detect trends of deteriorating water quality caused by nutrient pollution.

Monitoring Programs and Methods

Spring total phosphorus measurements have been made on 195 Vermont lakes since 1977. As shown in Table 1, a total of 84 lakes have been sampled during four or more years, although only 20 lakes have been sampled every year from 1977 to 1987. The sampling and analytical methodology has been consistent since the beginning of the program. Samples are obtained by the Vermont Department of Environ-

Table 1.—The scope of Vermont's lake eutrophication monitoring programs 1977–1987.

NUMBER OF YEARS SAMPLED	NUMBER OF LAKES		
	SPRING PHOSPHORUS	SUMMER CHLOROPHYLL a	SUMMER TRANSPARENCY
1 or more	195	55	56
2 or more	125	52	53
3 or more	106	48	47
4 or more	84	45	43
5 or more	66	39	40
6 or more	57	28	31
7 or more	46	16	27
8 or more	37	10	23
9 or more	36	5	15
10 or more	36	0	0
11	20	0	0

mental Conservation staff during spring turnover between the time of ice-out and the onset of thermal stratification.

Vertically integrated samples of the water column are obtained at either two or three stations on each lake using a hose sampler lowered to a depth of 22 meters, or to 1 meter above the bottom, whichever is less at the lake station being sampled. Three replicate hose samples are obtained at each station, analyzed separately, and then averaged to calculate the phosphorus concentration for each station. Individual station values are then averaged to calculate the lake's spring total phosphorus concentration. Total phosphorus is analyzed in the samples using an automated, persulfate-digestion, ascorbic acid method (U.S. Environ. Prot. Agency, 1983, Method 365.1).

Summer chlorophyll *a* and Secchi disk transparency measurements have been made on 55 and 56 Vermont lakes, respectively, since 1979 (see Table 1). A number of stations on Lake Champlain have also been monitored for summer total phosphorus in addition to chlorophyll *a* and transparency, but the Lake Champlain data are not included in this analysis except where specifically indicated. Table 1 shows that four or more years of data have been collected on 45 of these lakes for chlorophyll *a* and on 43 of the lakes for transparency.

The sampling and analytical methods for these parameters have remained consistent since the program began. Sampling is conducted weekly during June through August by citizen volunteers under the Vermont Lay Monitoring Program (Warren, 1984). Chlorophyll *a* measurements are made on vertically integrated "euphotic zone" samples obtained using a hose sampler lowered to a depth of twice the Secchi disk depth determined at the time of sampling, or to 1 meter above the lake bottom, whichever depth is less. Chlorophyll *a* values for each sample date are based on the average of duplicate hose samples obtained at one deep-lake station. Secchi disk values are based on the average of single measurements obtained at two lake stations on each sample date. Chlorophyll *a* samples are filtered in the field and immediately frozen for later transport to the laboratory where they are ground and extracted in 90 percent acetone, followed by fluorometric analysis with a correction for the presence of pheophytin *a* (Stand. Methods, 1981).

Description of Lakes

Table 2 provides descriptive statistics for the lakes included in the data set. Information on mean and maximum depth is not available for all lakes. The lakes sampled for chlorophyll *a* and Secchi disk transparency are a subset of the 195 lakes sampled for spring phosphorus. The statistics for the water quality variables reported in Table 2 are based on the statewide distribution of sampled lakes using the long-term means for each lake. The majority of the lakes included in the monitoring programs are natural lakes, as opposed to artificial impoundments, and their watersheds are mostly rural or forested. The sampled lakes are not randomly selected from the population of all 719 lakes recognized in the state's Lakes and Ponds Inventory. The selection is biased toward the larger and more heavily used lakes within the state.

Attainment of Goal 1

The first goal of the lake monitoring program is to provide a statewide perspective on the range of eutrophication conditions found in Vermont lakes. The data is intended to support lake classification, restoration priority ranking, and resource assessment activities. The statewide frequency distributions for the three water quality variables are illustrated in Figure 1. Spring phosphorus and summer chlorophyll *a* are distributed approximately lognormally among lakes with Vermont, while summer Secchi disk transparency is distributed approximately normally.

Table 2.—Descriptive statistics for lakes included in Vermont's lake eutrophication monitoring programs.

	NUMBER OF LAKES	MINIMUM	25th PERCENTILE	MEDIAN	75th PERCENTILE	MAXIMUM
Spring Phosphorus (µg/L)	195	3	7	10	14	220
Summer Chlorophyll *a* (µg/L)	55	1.4	2.9	4.2	6.6	79.4
Summer Transparency (m)	56	.9	3.4	5.0	6.3	9.9
Latitude (degrees N)	195	42.73	43.65	44.27	44.58	45.02
Lake Area (km^2)	195	.06	.13	.28	.73	9.55
Drainage Area (km^2)	195	.2	2.3	6.0	18.3	1792
Mean Depth (m)	121	.6	2.4	4.9	7.6	21.6
Maximum Depth (m)	175	1.2	4.0	9.1	16.8	93.9

Parameters for these frequency distributions are indicated in Figure 1. These data provide a quantitative description of eutrophication conditions across all of Vermont's major recreational lakes. This information has been used most recently as part of the Vermont Lake Water Quality Assessment developed under the provisions of the Federal Water Quality Act of 1987 (Vermont Dep. Environ. Conserv. 1988).

Attainment of Goal 2

The second goal – establishing a baseline of water quality conditions in individual lakes – depends on developing precise estimates of long-term mean values for water quality variables. The coefficient of variation for the multiyear mean (CVm) is a useful statistic for describing the level of precision attained for individual lakes. The CVm statistic is simply the standard error of the mean divided by the mean, and its value depends on the natural variability among years and on the number of years of data according to Equation 1.

$$CV_m = S_y / (\sqrt{N_y}\bar{x}) \quad (1)$$

Where S_y = standard deviation among yearly mean values for a water quality variable

N_y = number of years sampled

$\bar{x}$ = the long-term mean for a lake

Figure 2 shows the cumulative frequency distributions for CV_m for Vermont lakes having four or more years of data for the indicated water quality variable. Most of these lakes have attained a precision level of 0.15 or better for all three water quality variables from the monitoring effort to date. However, very few lakes have attained a CV_m value of less than 0.05.

It is interesting to note from Figure 2 that the precision of mean Secchi disk transparency is refined more readily than for chlorophyll *a* or spring phosphorus. This result is not a consequence of sample size, because the sampling effort for Secchi

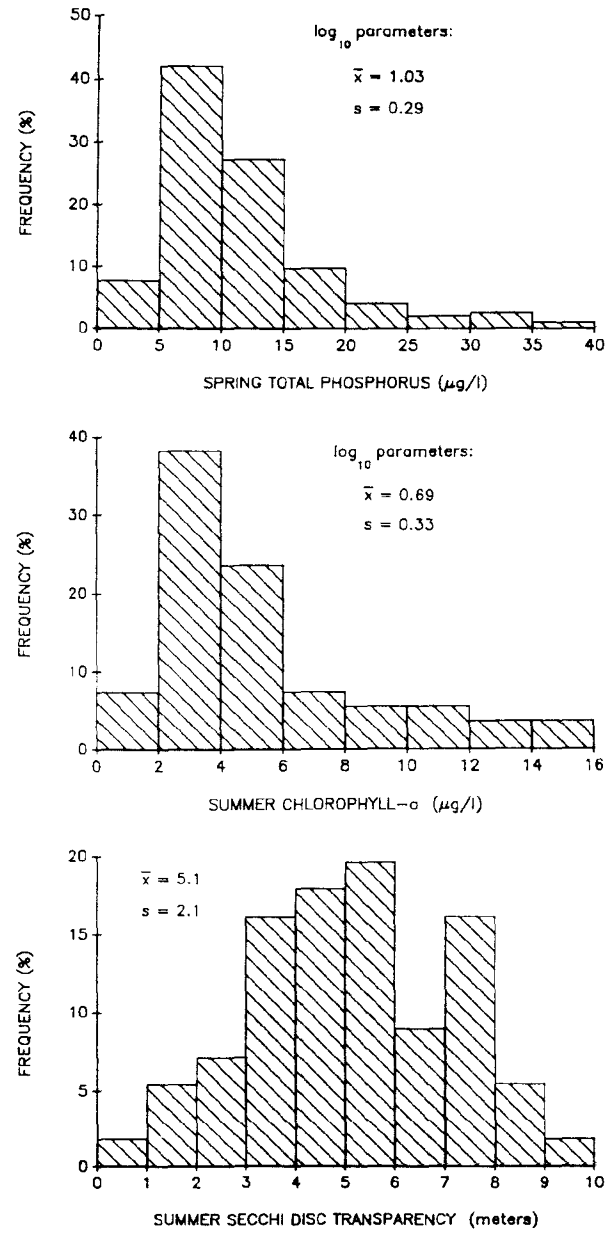

Figure 1.—Statewide frequency distributions for spring total phosphorus, summer chlorophyll a, and summer Secchi transparency, based on long-term means for Vermont data.

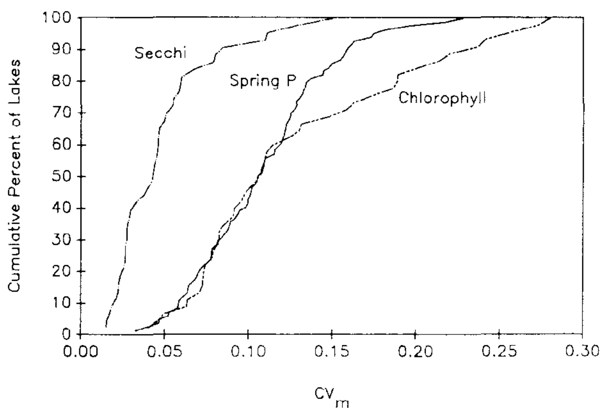

Figure 2.–Cumulative frequency distribution for the coefficient of variation of the long-term water quality means (CV_m) for Vermont lakes having four or more years of monitoring data.

disk transparency has been equivalent or less than the other variables (see Table 1). The inherent variability of mean summer Secchi disk transparency appears to be less than for summer chlorophyll *a* or spring total phosphorus. This finding should encourage citizen volunteer monitoring programs and other state efforts that are limited to Secchi disk monitoring because of its simplicity and ease of measurement.

Attainment of Goal 3

Reckhow and Clements (1984) advocated the development of regional, as opposed to national or global, empirical water quality models as a means for improving the local predictive value of these models. The construction of such models, like the development of a good baseline of water quality data for individual lakes, depends on lake water quality means having good precision.

Knowlton et al. (1984) demonstrated that the degree of within-season temporal variability in water quality data significantly affects the regression relationships between seasonal means for chlorophyll *a* and total phosphorus. High variability lake sets produced regression equations with lower slope coefficients and lower R^2 values. It is likely that between-year variability would affect a regional regression model based on long-term means in the same manner. Refining the CV_m values for long-term water quality means used in developing these models should therefore be a goal of state monitoring efforts.

Figure 3 shows a long-term mean chlorophyll-phosphorus regression developed for Vermont lakes with long-term mean spring phosphorus values less than 100 µg/L. The data for the regression model shown in Figure 3 were transformed using the base 10 logarithm to equalize the variance about the regression line, and were arbitrarily restricted to lakes having chlorophyll *a* and phosphorus CV_m values less than or equal to 0.15. The regression equation shown in Figure 3 has a higher R^2 value (0.65 vs. 0.54) and a higher slope (1.08 vs. 0.99) than an alternative model developed using all the data (regardless of the CV_m values) although the difference in slopes is not statistically significant.

If a CV_m value of 0.15 can be regarded as an appropriate criterion for the inclusion of lake data in an empirical model based on long-term water quality means, then it can be concluded that the Vermont lake monitoring effort has provided a sound basis for developing regional models such as that illustrated in Figure 3. Using a first-order error analysis, it can be shown that less than 29 percent of the error variance in the regression (Figure 3) can be attributed to imprecision in the mean phosphorus and chlorophyll *a* values.

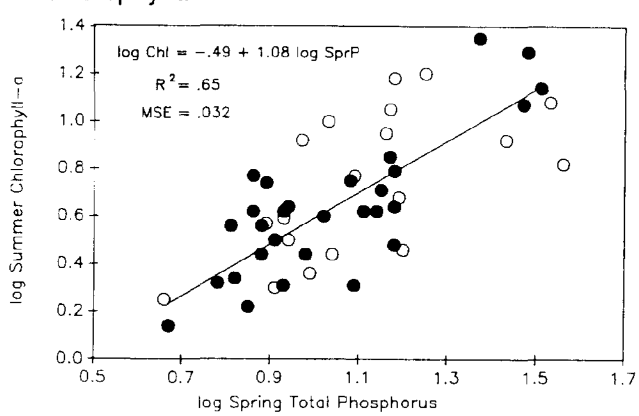

Figure 3.–Regression of summer chlorophyll *a* versus spring total phosphorus (units are ug/L). The regression equation is developed for Vermont lakes having chlorophyll *a* and spring phosphorus CV_m values less than or equal to 0.15 (•). The (○) represent lakes having chlorophyll *a* or spring phosphorus CV_m values greater than 0.15, which are not used in the regression model.

Attainment of Goal 4

The simplest form of trend analysis using lake monitoring data would be a before and after comparison of water quality means suspected of having changed as a result of some event in a lake's history. The ability of the monitoring data to detect such a change can be expressed as the least significant difference (LSD), representing the minimum difference between the before and after multiyear water quality means that would be declared statistically significant (Snedecor and Cochran, 1967).

$$LSD = t\sqrt{2Sy^2/Ny} \quad (2)$$

Where t = value for the Student's t-statistic (one-tailed if testing for a trend in a specific direction) at the appropriate significance level (e.g., 0.05) and $2(N_y-1)$ degrees of freedom

S_y^2 = the pooled estimate of the among-year variance

N_y = the number of years of data for the before and after means

The LSD concept can also be expressed as a minimum fractional change (f) between the before mean (x_1) and the after mean (x_2).

$$x_2 = x_1 + f x_1 \quad (3)$$

If the LSD value is equal to the difference between x_1 and x_2, then

$$LSD = f\,x_1 = t\sqrt{2Sy^2/Ny} \quad (4)$$

By making some simplifying assumptions for the purpose of this discussion for independent and normally distributed data, equal sample sizes and equal variances in the before and after data sets, equations 1 and 4 can be combined to give the following expression.

$$f = \sqrt{2}\, t\, CV_m \quad (5)$$

Equation 5 indicates, for example, that a phosphorus increase of 40 percent or greater ($f=0.40$) between two sets of five years would be statistically detectable at the 5 percent significance level ($t = 1.86$) for a lake having a 0.15 CV_m value for phosphorus. A precision level of $CV_m = 0.15$ or less has been attained for most Vermont lakes from the monitoring effort to date (see Figure 2), indicating that for most lakes a water quality baseline has been established against which future changes larger than 40 percent could be detected. Detecting a phosphorus increase as small as 20 percent, however, would require a CV_m value of less than 0.08. Figure 2 shows that this degree of precision has been attained for relatively few Vermont lakes for spring phosphorus or summer chlorophyll *a*, although this degree of precision has been attained for most of the long-term transparency means.

The number of years of sampling necessary to refine the CV_m value to a particular level can be calculated for each monitored lake by rearranging Equation 1 and assuming that the number of samples per year and the variance components remain constant.

$$N_y = (S_y / (CV_m x))^2 \quad (6)$$

Figure 4 shows the cumulative frequency distribution for the number of years of sampling (N_y) necessary to attain a CV_m value of 0.08. Knowlton et al. (1984) presented the theoretical relationship between sample size and the power of a t-test (i.e., the probability of detecting a true difference between water quality means). The relationships shown in Figure 4 represent an alternative way of expressing statistical power as a function of sample size, derived empirically from the Vermont data set.

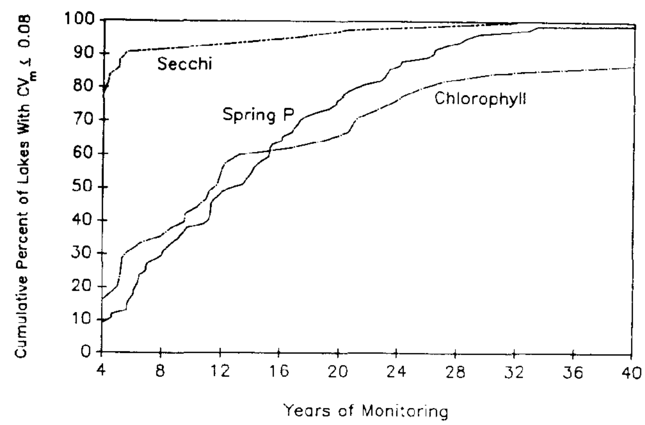

Figure 4.—**Cumulative frequency distributions for the number of sampling years needed to refine the precision of the long-term water quality means to CV_m = 0.08 or less. The curves are generated using Equation 6 for lakes having four or more years of monitoring data.**

As shown in Figure 4, the year-to-year variability of Vermont lake water quality data is such that even with 10 years of spring phosphorus or summer chlorophyll *a* data, less than half of the lakes would be expected to have attained a water quality data baseline against which a future 20 percent increase in eutrophication would be detected. However, 10 years of monitoring should produce a Secchi disk transparency data baseline in nearly all lakes sufficiently precise to detect a future 20 percent degradation in water clarity.

The experience of lake managers in Vermont indicates that most instances of increasing cultural eutrophication in Vermont lakes are the result of incremental nonpoint source nutrient loadings, rarely producing a 20 percent increase in phosphorus concentrations in a particular lake over a time period of one or two decades. The monitoring effort conducted to date in Vermont has not been sufficient for most lakes to detect phosphorus or chlorophyll *a* trends of this relatively small magnitude using a before and after comparison of multiyear means, although Secchi disk transparency might be a more sensitive indicator.

A more powerful statistical test, such as regression analysis with time as the independent variable, would be better suited for detecting small, gradual changes. Spooner et al. (1987) presented a method for calculating the minimum detectable change in water quality variables when using linear regression techniques. In many practical situations, however, taking remedial action after detecting a deteriorating water quality trend requires some evidence that specific newly-added nutrient sources in a lake's watershed (e.g., an altered farming practice or a new commercial development) are the cause of the trend. A simple before and after comparison would still be required in many situations to justify a lake restoration proposal or to document water quality improvements following a lake restoration project.

This analysis indicates that it would generally be unrealistic to expect the current lake monitoring programs in Vermont to detect before and after changes in phosphorus or chlorophyll *a* concentrations of the relatively small magnitude typical of most situations of increasing cultural eutrophication in the state. To the extent that Secchi disk transparency is sensitive to nutrient and algal increases, it may provide a better monitoring tool for early detection of increasing eutrophication. However, establishing the cause of a transparency decline would often require supporting data on phosphorus and chlorophyll *a* changes as well.

Improving Monitoring Efficiency

Variance components analyses were conducted on the Vermont data in order to investigate possibilities for increasing the efficiency of the monitoring programs. These analyses were used to determine the impact of sample program design on the precision of estimated long-term mean spring phosphorus, summer chlorophyll *a*, or summer transparency values for a particular lake. Sampling design parameters were expressed in terms of two sampling frequencies:

N_d = average number of sampling dates per lake station per year; and

N_y = number of years per station.

Precision was expressed in terms of CV_m, the coefficient of variation of the long-term arithmetic mean.

Following analytical approaches described by Walker (1980) and by Knowlton et al. (1984), a variance component analysis was conducted on logarithmic scales to estimate the within-year and among-year variance components for each water quality variable and lake station. Knowlton et al. (1984) described a more elaborate procedure that also considers sampling error at a given station and date as a third variance component. Since this error is generally small in relation to the other variance components, it was ignored to simplify the analysis.

Equations in Table 3 were used to estimate precision in the long-term arithmetic mean for a given set of variance components and sampling frequencies. The analysis was conducted on logarithmic scales to reduce dependence of variance on the mean and improve normality (Heyman et al., 1984). Serial dependence of the observations was assumed to be small, which is a reasonable assumption for typical lake monitoring frequencies (Knowlton et al., 1984).

Table 3.—Variance component analysis of Vermont lake data.

The following procedure is designed for application to data from one lake station monitored for N_y years at average of N_d sampling dates per year, within appropriate depth and seasonal strata (e.g., mixed layer, summer or growing season):

1. Average the measurements by sampling date
2. Transform the data to natural logarithms
3. Conduct a one-way analysis of variance (Snedecor and Cochran, 1967), with groups defined based upon sampling year. The analysis yields the following mean square statistics:
   M_y^2 = mean squared deviation among years
   M_d^2 = mean squared deviation within years
4. Estimate among-year and within-year variance components:
   $S_y^2 = (M_y^2 - M_d^2)/N_d$
   $S_d^2 = M_d^2$
5. To evaluate a given sampling program design (N_y, N_d), calculate the error variance of the grand mean of the log-transformed data:
   $S_m^2 = (S_y^2/N_y) + (S_d^2/(N_y N_d))$
6. From the theory of the lognormal distribution (Aitchison and Brown, 1963) calculate the coefficient of variation of the long-term arithmetic mean:
   $CV_m = \sqrt{(\exp(S_m^2) - 1)}$

Figure 5 was developed from typical results, based on median variance components and design parameters for Vermont's lake monitoring programs. For each variable the frequency distributions of within-year and among-year variance components were estimated across lake stations. Since Vermont's spring phosphorus monitoring program involves only one sampling date per year for each lake, the within-year standard deviation (S_d = 0.25) for phosphorus was estimated from a special study for which four lakes were sampled 8 to 10 times during one spring.

The resultant value is similar to the median within-year standard deviation (0.26) estimated from another data set involving June through August sampling of 18 Vermont inland lakes for 1 to 6 years. While they are typical, variance components shown in Figure 5 do not necessarily apply to every lake because of lake-to-lake variation in sampling design parameters and variance components, as described below.

Median variance components are used in Figure 5 to examine the sensitivity of precision of the long-term mean to sampling design parameters N_d and N_y. For each variable, precision of the long-term mean improves rapidly over the first few years of monitoring, after which progress is slow. The shapes of these curves reflect the fact that CV_m is nearly inversely related to the square root of the number of years monitored.

For all variables, precision is clearly improved as the number of samples per year increases from 1 to 3. Sensitivity to N_d subsequently decreases because at high values of N_d the variance of the long-term mean is controlled by the among-year variance component (S_y^2), according to the equation for Sm in Table 3. For example, more would be learned about the "average" lake condition by sampling monthly for three years, e.g., CV_m for chlorophyll *a* = 0.20, than by sampling weekly for one year, CV_m = 0.27.

The analysis suggests that increasing the frequency of spring phosphorus sampling in Vermont lakes from 1 to 3 samples per year would result in substantial improvement in the precision of long-term lake mean values. Conversely, the chlorophyll *a* and Secchi within-year samples

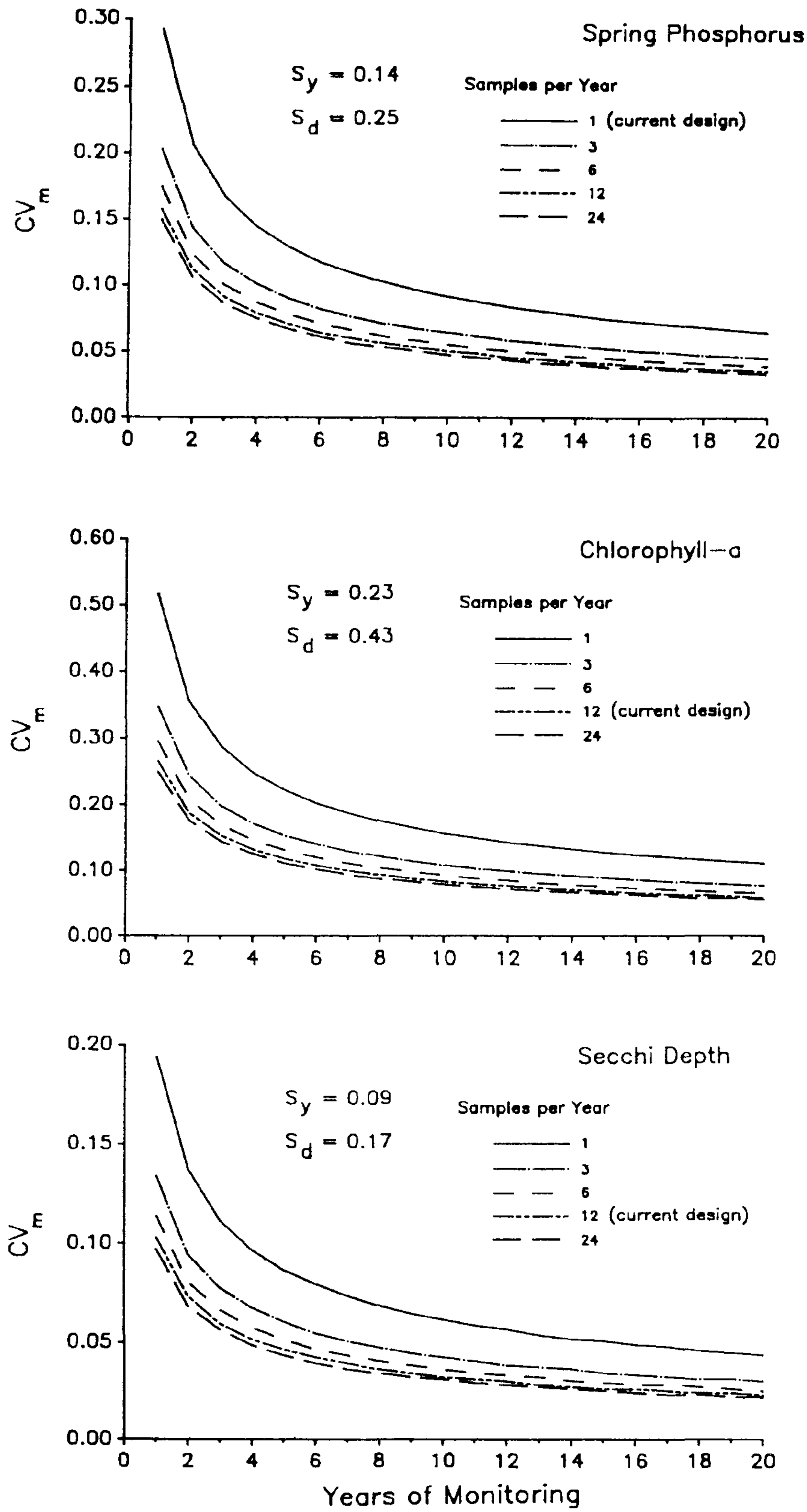

Figure 5.—Precision in long-term means versus monitoring frequencies. Curves are based upon median variance components (S_y and S_d) for Vermont lakes.

could be reduced from 12 to 6 on a weekly to biweekly frequency without much loss in precision.

While such adjustments might result in significant reduction in labor and laboratory costs, this analysis applies only to the stated objective of maximizing the precision of the long-term mean. Results and recommendations might be considerably different, for example, if the objective of the monitoring program were to estimate the seasonal maximum chlorophyll *a* or bloom frequencies, or to provide data for detailed modeling and evaluation of eutrophication control options. The definition of objectives is the most important, and usually the most difficult, aspect of sampling program design.

Comparisons with Other States

Figure 6 shows cumulative frequency distributions of the within-year standard deviation for various lake and reservoir groups, based on data derived from the literature. These values correspond to the term Sd defined in Table 3, and are simply the standard deviations of lake measurements within each year transformed to natural logarithms. Both random sampling error and true temporal variability contribute to the range of coefficients within each lake group. Chlorophyll *a* and transparency tend to be more variable in the Corps of Engineers Reservoir data set, reflecting lake and reservoir differences, effects of flushing rate, etc., as well as seasonal factors. The reservoir data set includes

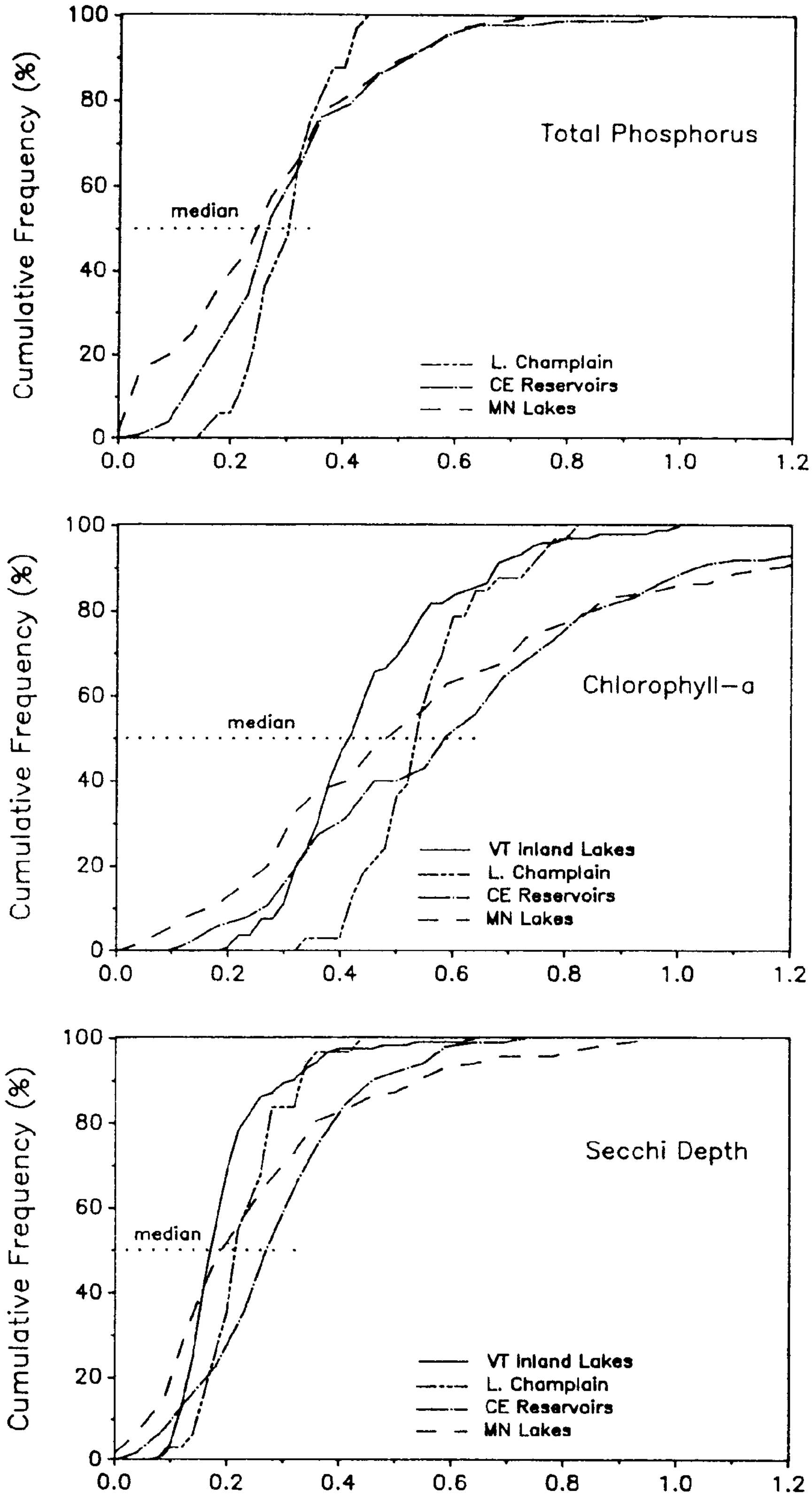

Figure 6. —Cumulative frequency distributions for within-year standard deviations for different lake data sets. Vermont inland lakes: Lay Monitoring Program data, Vermont Dep. Environ. Conserv.; Lake Champlain Lay Monitoring Program data: Vermont Dep. Environ. Conserv.; U.S. Army Corps Eng. Reservoirs: nationwide, Walker (1980, 1982); Minnesota lakes: Frandrei et al. 1988.

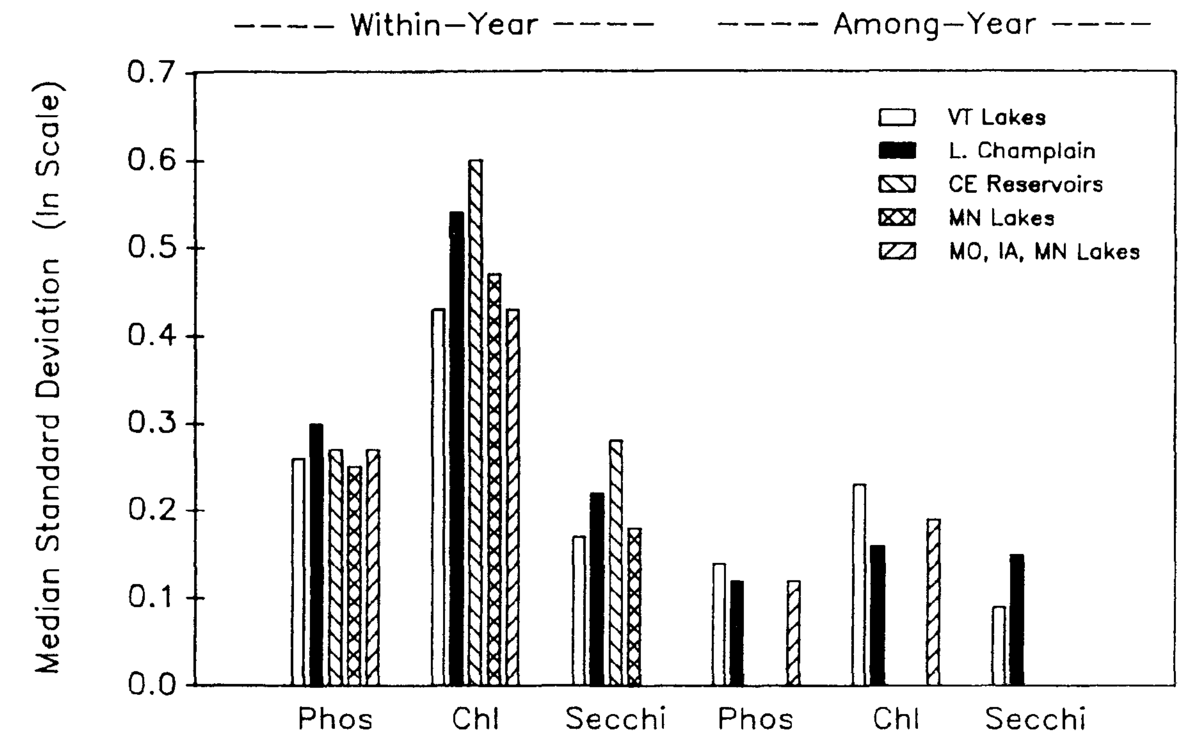

Figure 7.—Median within-year and among-year standard deviation for different lake data sets. Vermont inland lakes: Lay Monitoring Program data, Vermont Dep. Environ. Conserv.; Lake Champlain Lay Monitoring Program data: Vermont Dep. Environ. Conserv.; U.S. Army Corps Eng. Reservoirs: nationwide, Walker (1980, 1982); Minnesota lakes: Frandrel et al. 1988. Missouri, Iowa, and Minnesota lakes and reservoirs: Knowlton et al. 1984.

measurements from April through October, whereas measurements in the other data sets are usually restricted to June through August.

As illustrated in Figure 7, median standard deviations (S_d and S_y) are reasonably constant across lake groups. These median values provide an *a priori* basis for designing a monitoring program for a particular lake or reservoir. Ranges of median within-year standard deviations (S_d) are 0.26 to 0.30 for total phosphorus, 0.43 to 0.60 for chlorophyll *a*, and 0.17 to 0.28 for Secchi depth. The values are in reasonable agreement with median S_d values reported by Knowlton et al. (1984).

Since the general characteristics of the sample design curves (Fig. 5) depend upon the relative magnitudes of S_y and S_d, their applicability may extend beyond Vermont lakes. Similar curves can be developed for any particular lake or set of lakes using the equations in Table 3 and an appropriate lake-monitoring data set. The similarity of variance components between Vermont and other lake data sets also suggests that the findings discussed earlier about the attainability of the goals of Vermont's lake monitoring programs may be applicable to other states.

Conclusions

This analysis shows that much progress has been made in attaining the original goals of Vermont's lake monitoring programs since the efforts were initiated in 1977. A statewide perspective on the range of spring total phosphorus, summer chlorophyll *a*, and summer Secchi disk transparency levels has been developed. A precise data baseline of water quality conditions has been established for many individual lakes, with coefficients of variation for long-term phosphorus, chlorophyll *a*, and transparency means reduced to less than 15 percent for most lakes having four or more years of data. A data base suitable for developing regional eutrophication models has also been developed.

The goal of using the monitoring data to detect trends of deteriorating water quality caused by nutrient pollution has proved to be somewhat unrealistic, however, except in cases where large changes (e.g., greater than 40 percent) in water quality variables have occurred over a short period of time. For most lakes, the year-to-year variability is too large to permit the detection of smaller changes that are more typical of increasing cultural eutrophication in Vermont. Even with the sampling program design improvements suggested by the variance components analysis, it would generally not be possible within a reasonable monitoring period to statistically detect a realistically small (e.g., 20 percent) change before and after a discrete event in a lake's history.

The implications of these findings are that lake monitoring programs should not be relied on to provide early detection of the small, incremental eutrophication trends typical of nonpoint source pollution. Irreversible land use changes could occur before a resulting water quality deterioration was documented. Instead, more emphasis should be placed on lake protection programs to prevent such changes from occurring in the first place. Technical justification for state lake protection programs should come from existing knowledge about how certain watershed activities increase phosphorus loadings to lakes and from empirical models linking phosphorus loading to lake eutrophication response (e.g., Welch, 1989).

Finally, this analysis provides a basis for the design of lake monitoring programs in Vermont or other states, once realistic program goals are defined. Typical variance components for the lake data sets discussed in this paper, or other variability information independently available for a lake region, can be used with the procedure applied to the Vermont data (Table 3) to design an efficient sampling program. This procedure provides a means for choosing a within-year sampling frequency and program duration for state monitoring efforts where the goal is to refine the precision of long-term water quality means.

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