Natural Variability in Lakes and Reservoirs Should be Recognized in Setting Nutrient Criteria

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Abstract

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Long-term data on total phosphorus (TP) and chlorophyll (Chl) from statewide summer monitoring of Missouri reservoirs (n=141) and daily collections from 6 summer seasons from Lake Woodrail (n=705) illustrate the magnitude of temporal variability in regional impoundments and the problem of assessing compliance with numeric nutrient criteria. Among individual observations, >24% of Chl values and >14% of TP values were >150% of long-term means in both data sets. Seasonal means varied by ~2-fold among years in Woodrail and by >3-fold in many reservoirs statewide. Simulated numeric criteria of 27 µg/L TP and 10 µg/L Chl were exceeded by 18-24% of individual measurements and 16-24% of seasonal means from reference reservoirs whose long-term means met these criteria. Seasonal mean values based on a single summer misclassified 15-17% of Missouri reservoirs with respect to the status of their long-term averages (8 or more seasons). Given this level of temporal variation, numeric criteria determined from average conditions in reference lakes should be applied only to long-term averages in target lakes. Rules for assessing compliance with nutrient standards should be framed with anticipation of the widely varying conditions in individual lakes.

Key Words: nutrient criteria, reservoirs, temporal variation

In response to the USEPA's National Strategy for the Development of Regional Nutrient Criteria, regional nutrient criteria for lakes and reservoirs are being developed based on the outline by Gibson *et al.* (2000). The effort focuses on setting numeric criteria for the causal variables, nitrogen and phosphorus, and the response variables algal chlorophyll and water transparency. The process of establishing criteria centers on the distribution of these variables in high-quality, baseline reference lakes to maintain existing water quality and protect designated uses such as water supply, recreation and fisheries in all regional lakes. A procedural protocol to implement the adopted criteria is included as part of the undertaking (Gibson *et al.* 2000). Reference conditions based on seasonal means are appropriate for establishing nutrient criteria and were used in the approach proposed by Dodds *et al.* (2006) for Kansas lakes. Gibson *et al.* stated the method of data gathering for compliance should match that used to establish criteria and cautions "the average should not exceed the criterion."

The decision making process recognizes inherent variability in causal and response variables in lakes and reservoirs. Language in the document acknowledges that extreme conditions or "excursions" that exceed the criterion are typical features of lakes and reservoirs and will be an integral factor of monitoring for compliance. What constitutes an excursion, and the frequency and duration of such events, is considered a part of criteria development that should be established based on an understanding of local water resources. As an illustration of the rule making process, the criteria document suggests that excursions occurring in less than 10% of sampling observations may be considered acceptable, or that criteria for causal and response variables must be met in three-fourths of the sampling events in 2 consecutive years (Gibson *et al.* 2000). Beyond these general suggestions, the document does not identify how excursions should be identified or considered in the process of assessing compliance with proposed criteria.

Seasonal mean concentrations of plant nutrients and algal chlorophyll (Chl) are routinely used in trophic state classification (Nürnberg 1996) and provide an appropriate basis for establishing regional numeric criteria. Limnological literature documents that large seasonal fluctuations are inherent in many lakes and reservoirs, with occasional extreme conditions being a feature of these temporal patterns (Knowlton *et al.* 1984, Walmsley 1984, Walker 1985, Marshall *et al.* 1988, France and Peters 1992, Bachmann *et al.* 2003). These

studies have repeatedly shown temporal variation increases as a function of the seasonal mean and that Chl displays greater temporal variability than does total phosphorus (TP) or total nitrogen (Knowlton *et al.* 1984, France and Peters 1992). As a result of inherent variation, nuisance algal conditions occasionally occur even in mesotrophic lakes (Bachmann *et al.* 2003, Smith 2003). For this reason, temporal variation is increasingly considered a component of data collection and interpretation (France and Peters 1992).

In this paper we evaluate features of inherent variability in Missouri reservoirs to provide basic information on the summer range of causal and response variables in our data set. This analysis is aimed at identifying the typical frequency of extreme events in Missouri's reservoirs. Extreme events represent potential excursions beyond a numeric criterion. We illustrate how these extremes might affect our ability to evaluate compliance with numeric criteria. The analysis is intended to serve as a template for assessing temporal variation in setting and monitoring nutrient criteria in Missouri and other states. Our approach is to summarize the characteristics of temporal variation in the causal variable TP and the response variable Chl in a large survey data set (141 reservoirs, >5500 observations) and in data from a single reservoir sampled daily in 6 summers (n=705).

Database

Data for this assessment came from three principal sources. First, an ongoing summer inventory of Missouri reservoirs carried out between 1978 and 2004, and conducted annually since 1989, provided the basis for statewide characterization. In this effort reservoirs located within the major physiographic provinces of the state (Jones and Knowlton 1993) were sampled on, typically, 3-4 occasions during summer. Sampling commenced in mid-May of each year and was completed by the third week in August, such that individual reservoirs were sampled about every three weeks. Since 1989 annual summer collections have included 60-117 water bodies. Natural lakes (oxbows and scour ponds) were excluded from this analysis (Jones and Knowlton 2005), which is limited to reservoirs sampled in at least 4 years (n=141). Most reservoirs have been sampled in 10 (median) or more summer seasons with a range from 4 to 23 seasons. Second, Lake Woodrail, a 4-ha impoundment within the limits of Columbia, Missouri, was sampled daily between May 1992 and December 1996 (n = 1676). Only May-August data (n=597) were considered here. Third, Lake Woodrail was sampled daily during 12 May through 27 August 2004 (n=108). In each study, water was collected from the surface layer near the dam, and processed by standard methodology (Knowlton and Jones 1995).

Data on TP and Chl were considered in this study. These monitoring data were normalized by dividing individual
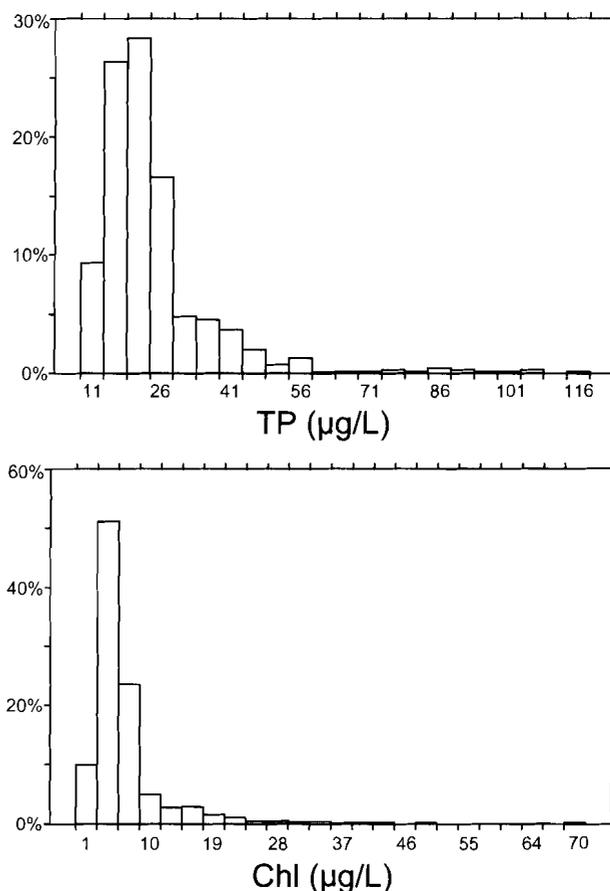

Figure 1.-Frequency distributions of TP and Chl in Woodrail Lake, May-August 1992-1996, 2004 (n=705).

observations of TP and Chl from a particular reservoir by their respective long-term means to depict distribution patterns. This approach parallels the one used by Marshall and Peters (1989) to describe seasonal patterns in temperate lakes. The data were treated at the level of individual observations, seasonal means (averages of samples in a given summer) and long-term means (averages over 4 or more summer collections). TP and Chl in these data have log-normal distributions, and all averaging was done with $\log_{10}$-transformed data. Averages presented in the text are back-transformed values (geometric means) unless otherwise stated.

Results

Variation among Individual Samples and Seasonal Mean Values

Among the 705 daily samples collected from mesotrophic Lake Woodrail during 6 summer seasons, TP averaged 22 µg/L and Chl averaged 5.0 µg/L. Both parameters exhibited the right-tailed, log-normal distributions typical of trophic
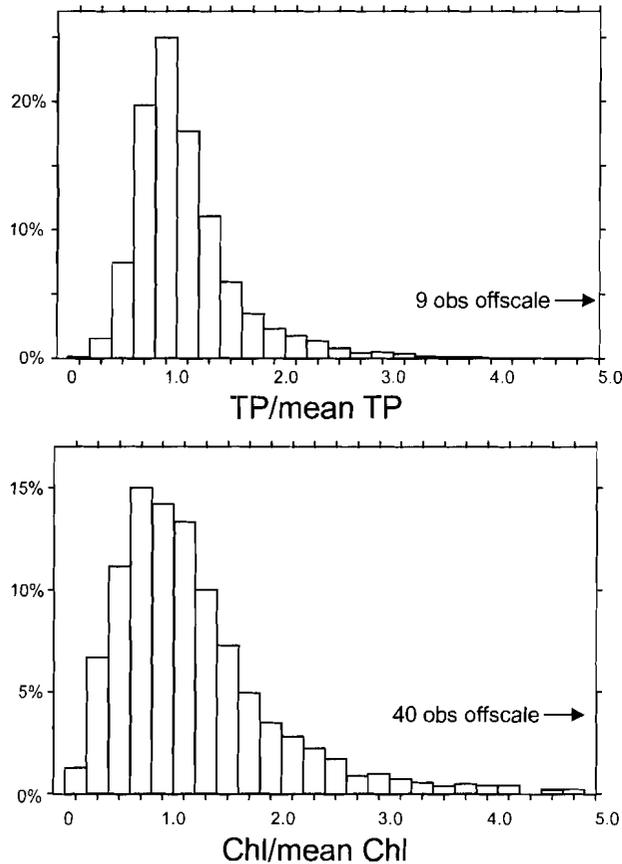
Figure 2.-Frequency distributions of TP (n=5570) and Chl (n=5592) in 141 Missouri reservoirs, individual observations standardized to the reservoir mean. Offscale observations ranged up to 9.1 for TP, 19.3 for Chl.
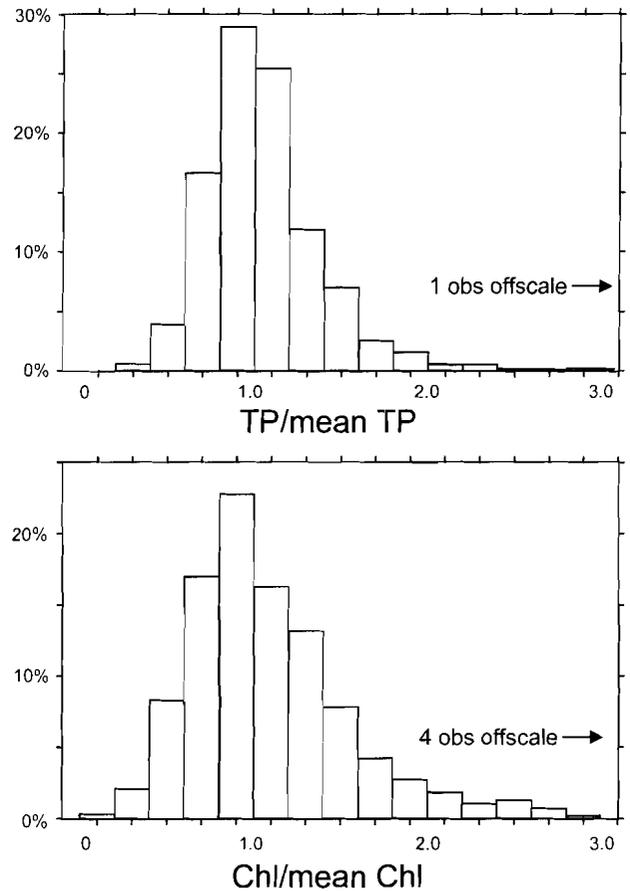
Figure 3.-Frequency distribution of seasonal mean TP (n=1543) and seasonal mean Chl (n=1543) in 141 Missouri reservoirs. Seasonal mean values are standardized to the lake mean. Offscale observations ranged up to 3.3 for TP, 6.8 for Chl.

state variables (Fig. 1). The response variable Chl showed the greatest variation with 20% of the samples containing ≥ 1.5-times the mean and 12% double the mean. TP was somewhat less variable with 15% of values ≥ 150% of the mean and 6% double the mean (Fig. 1).

Normalized sample values (observations/reservoir mean; Fig. 2) from the Missouri reservoir monitoring program (3 or 4 samples per summer) were distributed similarly to data from Lake Woodrail. Some 24% of Chl samples contained ≥ 1.5-times the mean and ~13% contained more than double the mean (Fig. 2). Again, TP was less variable, with 14% of samples containing concentrations ≥ 150% of the mean and 6% more than double the mean (Fig. 2). Samples rarely (<1%) contained more than 5 times the mean for either Chl or TP. Among seasonal means from these 141 Missouri reservoirs (Fig. 3), dispersion around long-term means was less than dispersion among unaveraged observations, but >15% of Chl seasonal means exceeded the reservoir mean by >1.5 times, and 5% of seasonal means doubled the overall mean.

For TP the corresponding percentages were 9% and 4%. Exceedances of 125% were relatively common, occurring in about 1 of 3 years for Chl and 1 of 5 years for TP. Data from Forest Lake illustrate this pattern (Fig. 4) with summer mean values of Chl and TP varying widely and exceeding the long-term mean by >25% in 4 of 20 summers.

This analysis illustrates that temporal variation produces wide ranging conditions within Missouri reservoirs in a given summer and may also result in large differences in seasonal averages over time. Among impoundments with at least 8 years of data (n=98 reservoirs), more than a third exhibited a >3-fold range in seasonal mean TP and a large majority (74%) showed a >3-fold range for Chl. These large among-year differences partly reflect the uncertainty of measuring the mean in any given year (Knowlton et al. 1984), but year to year differences are genuine. In Lake Woodrail where daily collections precisely quantify the summer mean, TP varied by >2-fold during the six seasons of study and mean Chl varied by 1.8-fold.

A Mock Example of Setting Nutrient Criteria and Evaluating Compliance

Using the trisection method (median of the lowest third of the ranked long-term reservoir mean values in our data set) to derive mock reference values for the Plains region of the state (Prairie Ecological Division; Nigh and Schroeder 2002) resulted in values of 27 µg/L TP and 10 µg/L Chl. Given the inherent temporal variation in Missouri reservoirs, even among Plains reservoirs with long-term means that fit within these reference criteria (n=14), averages of 18% (Chl) and 24% (TP) of individual measurements and 16% (Chl) and 24% (TP) of the seasonal means exceed these upper limits. In a few reservoirs over a third of the individual values, seasonal averages or both exceeded the criteria even though long-term averages complied.

Gibson et al. (2000) suggested a decision making protocol in which criteria for causal and response variables must be met in three-fourths of sampling events in 2 consecutive years. To evaluate how often Missouri reservoirs might fail to comply with this protocol we tabulated the number of times that 25% of samples in paired consecutive years exceeded the mock criteria in reservoirs with long-term mean <27 µg/L TP (n=49 reservoirs and 438 pairs) and those with <10 µg/L Chl (n=46 reservoirs and 412 pairs, both assessments include reservoirs statewide). The result was a failure rate of 21% for TP and 14% for Chl. As expected, the rate of exceedance increased as long-term averages approach these criteria. For impoundments with mean TP of 20-27 µg/L (n=19 reservoirs, 171 pairs) or mean Chl of 6-10 µg/L (n=13 reservoirs, 115 pairs) the failure rate was 52% for TP and 43% for Chl and was higher still for those reservoirs closest to the criteria. These illustrations show that reservoirs in compliance with numeric criteria over the long-term will not consistently meet a short-term protocol assessment. Uncertainty in determining average conditions translates into uncertainty about whether a lake complies with a criterion, suggesting the need for statistical assessment of criteria compliance on the basis of long-term averages.

Monitoring for Compliance

Given this degree of temporal variation, determining whether a lake or reservoir complies with a criterion requires multiple observations spanning a representative time period. Determinations based on too few observations will have a high rate of misclassification. For example, using data from reservoirs with 8 or more years of sampling (n=98), we determined how well means based on the first 1-6 seasons of collection agreed with the long-term mean in classifying the reservoirs as above or below the 27 µg/L TP and 10 µg/L Chl criteria (Fig. 5). Means based on a single summer (n=3 or 4 samples) had an 18-19% rate of false negatives (long-term mean exceeded the criterion, but the short-term mean complied) and an 8-
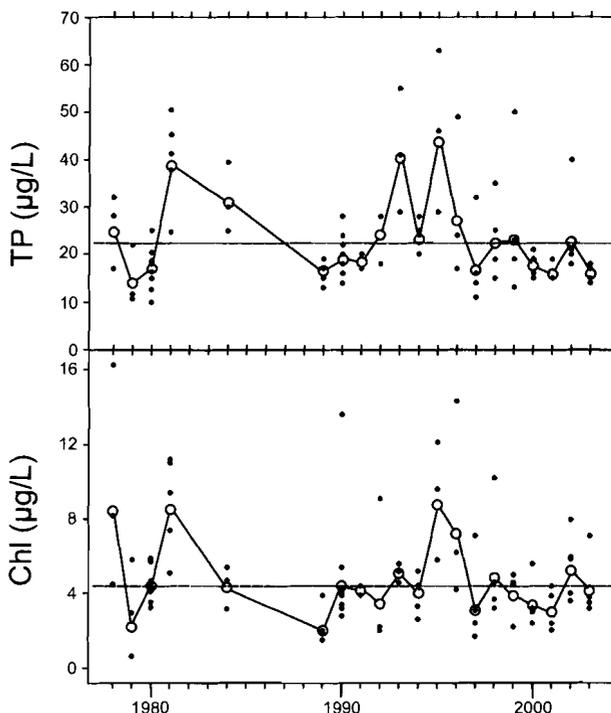

Figure 4.-TP and Chl in Forest Lake 1978–2003. Solid circles are individual observations, open circles are seasonal means. Horizontal lines are the long-term lake means.
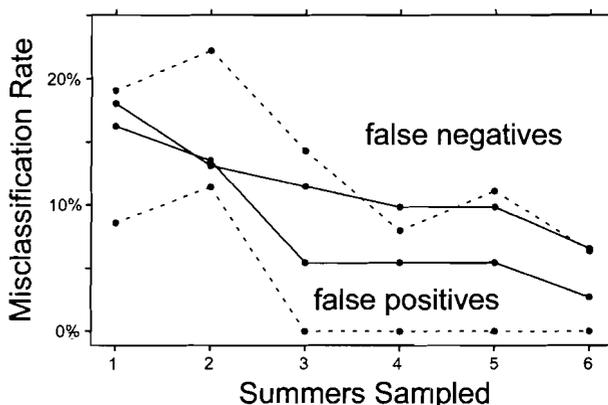

Figure 5.-Proportions of reservoir means of TP (solid lines) and Chl (dashed lines) that were greater than the numeric criteria when the long-term mean was less (false positive) or that were less than the numeric criteria when the long-term mean was greater (false negative) in relation to the number of summers sampled. Data are from 98 reservoirs with ≥ 8 summers of data.

16% rate of false positives (short-term mean exceeded the criterion, but long-term mean complied). Combining the two (data not shown), one summer of monitoring effort misclassified 17% of the reservoirs for TP and 15% for Chl. Three or more years of data provided an overall misclassification rate below 10% for both TP and Chl, but even with 5 years of data, 10-11% of reservoirs with long-term means exceeding the criteria were misclassified as compliant (Fig 5).

Discussion

This analysis of temporal variation in Missouri reservoirs illustrates that causal and response variables have wide distributions (Figs.1 and 2) and exhibit inter-annual differences in seasonal means over time. Differences of ~2 fold among seasonal means during only 6 years of summer data from Lake Woodrail provide incontrovertible evidence of the potential magnitude of this variation. Another example comes from Mark Twain Lake, a large (7550 ha) multipurpose reservoir in northeast Missouri (Knowlton and Jones 1995). In the summer of 1989 near the end of a prolonged drought, TP in Mark Twain averaged 18 µg/L, which fits within the lowest 25% of seasonal means in our data base. The following summer, after a rainy spring, TP averaged 163 µg/L, which fits in the upper 3% of our data. Which one of these summers represents an extreme relative to the norm? Obviously with such large temporal variation long-term data is required to assess lake trophic status. But are the examples of Mark Twain Lake and Missouri reservoirs in general, applicable to lakes elsewhere? Large scale assessments of temporal variation are relatively rare but available data suggest that variation in Missouri reservoirs, within and among years (Knowlton et al. 1984), is within the range observed in other reservoirs (Walker 1985), north-temperate lakes (Marshall et al. 1988, France and Peters 1992, Smeltzer et al. 1989, Larsen et al. 1995, Larsen et al. 2001) and Florida lakes (Terrell et al. 2000).

Results from Missouri may not precisely apply to lakes in other regions. For example, Smeltzer et al. (1989) observed extremely low temporal variation in transparency in Vermont lakes, suggesting that minimal data would provide adequate assessment. On the other hand, for lakes in neighboring New York, Larson et al. (1995) measured year-to-year variance in Chl >3 times greater than the median for midwest reservoirs and lakes (including Missouri reservoirs) recorded by Knowlton et al. (1984). Currently it is not possible to accurately generalize about the normal range of temporal variability in all regions and lake-types. But all available information suggests that high levels of variability are not unusual and should be assumed to exist unless there is a sound quantitative basis for deciding otherwise.

Quantitatively, year-to-year variation is an inherent feature of the causal and response variables in lakes, making it

necessary to sample individual systems over several years to assess their long-term average, or "normal" condition. For this purpose sampling over multiple years is required. The statistics of sampling design are outside the scope of this presentation, but this analysis was based on at least 4 summer collections with 3 or 4 samples per season. In Minnesota, lake assessments are based on at least 12 or more measurements (MPCA 2004), and evaluation of Kansas lakes and reservoirs by Dodds et al. (2006) was based on at least 4 surveys in separate years, as was the analysis of Florida lakes by Terrell et al. (2000). Others have suggested 6 consecutive years of information are necessary to overcome effects of annual variation in data analysis (Molot and Dillon 1991). Collectively, these studies point toward need for multiple years of data for lake characterization and assessment (Heyman et al. 1984).

Qualitatively, an "excursion" could be defined as an infrequent event resulting in an observation for a control or response variable that exceeds the typical lake condition and exceeds the criterion. Gibson et al. (2000) acknowledged excursions as part of normal variation and considered it acceptable if no more than 10% of observations contributing to the seasonal average exceed the criterion. This qualification seems overly restrictive if criteria are based on average conditions in reference lakes. For a lake with a long-term geometric mean exactly matching a criterion, about half of individual measurements would be expected to exceed the criterion given that geometric means approximate the median in log-normally distributed data. For our TP and Chl distributions, the top 10% of all individual observations exceeded 169% and 219%, respectively, of their long-term means (Fig. 2). Thus to comply with a 10% exceedance rule, these reservoirs would need to have a long-term TP value of only 59% (1/1.69=0.59) of the criterion and a mean Chl of just 46% (1/2.19=0.46) of the criterion. Seasonal means (Fig. 3) were much less variable than individual observations (Fig. 2) but still span a wide range in most lakes. If, for example, criteria for seasonal means were set at 150% of the reference condition to allow for temporal variation, seasonal means for a reservoir with a long-term mean equaling the reference would exceed these relaxed criteria about 1 year in 11 for TP and 1 year in 7 for Chl. Setting criteria at about twice the reference condition would be required to achieve error rates of <5%. Obviously excursions are within the natural temporal variability affecting all lakes and are a component of the normal condition in a given water body. Rulemaking efforts to limit exceedances should be scaled to the magnitude of variation in regional lakes.

Compliance with numeric criteria in lakes and reservoirs should be evaluated on the basis of the mean condition, preferably with statistical tests. Assessing compliance with reasonable assurance will require long-term collections from lakes and reservoirs that encompass the normal range of

variation for each water body. Experience with Missouri reservoirs suggests 4 or more seasons of survey data are needed to fairly assess what is normal. In some instances longer term data will be needed. Regulatory language specifying nutrient criteria and compliance should explicitly recognize the need for long-term data and statistical validity of results. We agree with Gibson *et al.* (2000) that the method of data gathering for compliance should match that used to establish criteria and suggest at least 4 seasons of information for each effort as a minimum effort to account for inherent variability.

EPA protocols suggest using lake population statistics to establish numerical criteria based on characteristics of the general population or a subset of high quality reference lakes. In this analysis we used the "tri-section" method as an example. In practice, nutrient criteria will likely be defined by individual states on the basis of designated uses of the target lake population and empirical information about specific nutrient-related impairments of those uses. Regardless of the process used to establish nutrient criteria, rules defining compliance with any numeric standard should be formulated with an understanding of temporal variability in regional lakes. Numeric criteria will be far more conservative if applied to individual observations or single seasonal means than the long-term average. Environmental regulations should be established with a clear understanding of the outcome. Projecting the outcome of numeric nutrient criteria requires a quantitative understanding of temporal variability in lakes.

Acknowledgments

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