LAKE AND RESERVOIR MANAGEMENT, 1988 4(1): 1–9
© 1988 NORTH AMERICAN LAKE MANAGEMENT SOCIETY

Developing Phosphorus Criteria for Minnesota Lakes

Steven A. Heiskary
Minnesota Pollution Control Agency, 520 Lafayette Road, St. Paul, Minnesota 55155

William W. Walker, Jr.
Environmental Engineer, Concord, Massachusetts

ABSTRACT

The development of practical and successful lake management strategies hinges upon setting realistic goals. Typically, management efforts have focused on the evaluation of watershed nutrient loadings and prediction of lake or reservoir eutrophication responses, expressed in terms of average epilimnetic phosphorus, chlorophyll a, and transparency. This paper describes a methodology for expressing lake conditions and model predictions in terms that are more meaningful to local resource managers and lake users because they relate more directly to perceived aesthetic qualities. Lake conditions are expressed in terms of the frequency or risk of "nuisance" algal levels, based upon extreme values of chlorophyll a ("blooms"), reduced transparency, and user-perceived impairment. Relationships between lake phosphorus concentration and nuisance frequencies of chlorophyll a (e.g., > 10, 20, 30, 60 ppb) and Secchi depth (e.g., < 2, 1, .5 meter) are developed by cross-tabulating lake monitoring data. A questionnaire is employed to collect data for relating lake measurements (phosphorus, chlorophyll a, transparency) to subjective classifications or nuisance ratings based upon physical appearance ("crystal clear" to "severe scums") and recreational suitability ("no problems" to "no swimming"). Using this approach, critical phosphorus levels corresponding to the onset of detectable nuisance frequencies can be estimated. With the nuisance ratings calibrated to user perceptions, these relationships provide a rational basis for setting phosphorus criteria or management goals related to aesthetic qualities.

Introduction

Researchers and water resource managers have taken a variety of approaches to developing standards or criteria for protection of lake water quality. A review of state water quality standards specific to nutrient enrichment (Metro. Wash. Counc. Gov. 1982) revealed a wide range in phosphorus concentrations used by various states (7–200 ppb). This range reflects variations in water use classifications, lake types, natural background phosphorus concentrations, economic factors, and the expectations and tolerances of lake users.

Because of regional diversity in lake and watershed characteristics, it is unlikely that a single total phosphorus value could be adopted as a statewide criterion for lake protection in Minnesota (Heiskary et al. 1987). A methodology is needed for developing lake water quality criteria on a regional or lake-specific basis. This methodology should take into account the following factors:

1. Phosphorus impacts on lake condition (as measured by chlorophyll *a*, transparency, and hypolimnetic oxygen depletion);
2. Water quality impacts on lake uses (aesthetics, recreation, fisheries, water supply, etc.); and
3. Achievability (as related to watershed characteristics, regional phosphorus export values, lake morphometry, etc.).

The science of limnology provides qualitative and quantitative tools for evaluating human effects on lake condition. Impacts on lake uses are more difficult to determine because they depend both upon lake conditions and upon perceptions and expectations of the users.

This paper describes a methodology for relating lake water quality measurements (phosphorus, chlorophyll, transparency) to user-perceived impairment in physical appearance or recreational suitability. These techniques express lake condition in terms of the frequencies, or "risks", of nuisance algal levels, based upon extreme values of chlorophyll, reduced transparency, and user-perceived impairment. Relating these risks to lake phosphorus concentrations provides a rationale for selecting phosphorus criteria for maintenance of desired aesthetic qualities and recreational uses. The methodology involves the evaluation of two sets of responses:

■ **Lake Responses.** Relationships between lake phosphorus concentration and nuisance level frequencies of chlorophyll *a* (e.g., >10, 20, 30, 60 ppb) and reduced transparencies (<.5, 1, 2), based upon statistical analysis of lake monitoring data.

■ **User Responses.** Relationships between lake water quality measurements and user-perceived impairment in physical appearance or recreation potential, based upon statistical analysis of user impression data (subjective opinions of lake condition) collected simultaneously with lake water quality samples.

The methodology could be applied to data from a single lake or from a collection of lakes, grouped by region (county, state, etc.), lake types, use types, or other criteria. The techniques are demonstrated in this paper using recent statewide survey data. These data constitute a relatively small fraction of information collected over the past year that is not yet compiled. For this reason, the emphasis is on the methodology, which seems applicable to other regions with sufficient lake diversity, rather than on specific results.

Lake Response

Evaluation of lake response is based upon total phosphorus, chlorophyll *a*, and transparency data from 99 lakes included in a recent survey program designed to establish baseline conditions in Minnesota lakes (Fig. 1). Lake selection was based upon the ecoregion concept developed by the Environmental Protection Agency, Corvallis Environmental Research Laboratory (Omernik, 1987). Factors such as maximum depth, surface area, and fishery classification were considered in selecting representative lakes for sampling within each ecoregion (Heiskary et al. 1987). The intent of the survey program was to focus on relatively "unim-

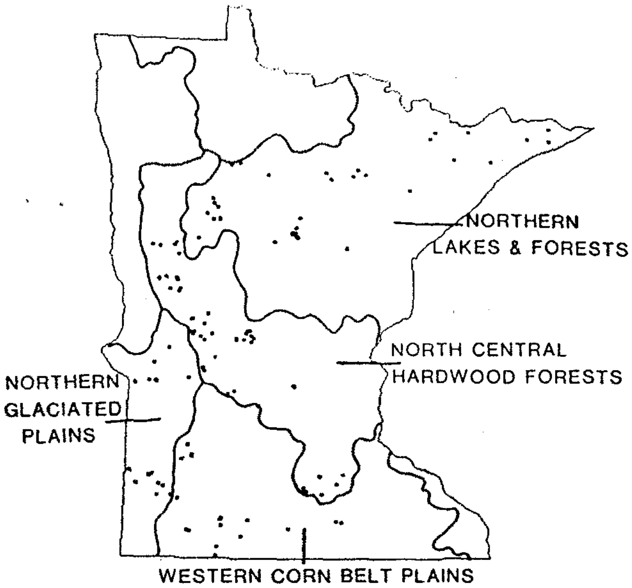

Figure 1.–Regional distribution of sampled lakes.

pacted" lakes so those with major urban areas, known point sources, and/or major feedlots were excluded. Samples were collected between April and October in 1985 and 1986, usually at two sites on each lake. Total phosphorus and chlorophyll *a* are derived from 2-m, vertically integrated samples and analyzed using approved methods (U.S. Environ. Prot. Agency, 1973, 1979).

The monitoring program provided 641 paired phosphorus/chlorophyll measurements and 630 paired phosphorus/transparency measurements for use in evaluating relationships between phosphorus concentration and nuisance-level frequencies of chlorophyll *a* and transparency, e.g., "How does the risk of encountering an algal bloom (e.g., chlorophyll *a* >30 ppb or transparency <1 m) vary with phosphorus concentration?" These relationships are distinguished from mean chlorophyll *a* versus mean total phosphorus regression models typically used to represent lake eutrophication responses (Jones and Bachman, 1976).

The risk analysis approach is derived from a classification system developed by Walmsley (1984) for South African reservoirs. This system expresses lake condition based upon the frequency of extreme chlorophyll *a* concentrations ("blooms"), as opposed to average concentrations. User-perceived problems related to algae tend to be episodic, rather than continuous in nature. Bloom frequency more adequately reflects temporal variability in lake conditions and is thought to be a better indicator of potential use impairment. The phrase "nuisance criteria" refers to specific chlorophyll *a* or transparency levels that result in perceived impairment. A wide range of criteria has been tested for each lake response variable (>5, 10, 20, 30, 40, and 60 ppb for chlorophyll *a* and <.5, 1, 2, 3, and 5 m for transparency). The selection of appropriate nuisance criteria is discussed under "User Response".

One approach to evaluating the desired frequencies would be to link regression models relating lake-mean phosphorus to lake-mean chlorophyll (Jones and Bachman, 1976) with frequency distribution models to represent model error and chlorophyll *a* variability in time (Walker, 1984b). A simpler, nonparametric procedure based upon cross-tabulation is employed here. This involves the following steps:

1. Assemble the data set of paired phosphorus and chlorophyll *a* measurements (641 observations);
2. Divide the data set into 10 intervals based upon increasing phosphorus concentrations so that each interval has 60 observations; discard the remaining 41 observations with phosphorus concentrations exceeding 190 ppb;
3. Within each phosphorus interval, compute the frequency of each chlorophyll *a* class (i.e., percent of samples exceeding 5, 10, 20, 30, 40, and 60 ppb);
4. Plot the frequency of each chlorophyll *a* class against the median phosphorus concentration in each phosphorus interval.

The procedure is repeated using phosphorus/transparency pairs. Results are shown for chlorophyll *a* versus phosphorus and transparency versus phosphorus in Figure 2. As a result of missing value distributions, slightly different phosphorus intervals were used for the chlorophyll *a* and transparency cross-tabulations. Additional analyses indicate that results are insensitive to regions within Minnesota and to the number of paired measurements (range 40–100) within each phosphorus interval.

For both chlorophyll *a* and transparency, extreme value frequencies exhibit a nonlinear response to increasing phosphorus concentrations. For example, the observed frequency of chlorophyll *a* concentrations exceeding 30 ppb (Walmsley's (1984) "severe nuisance" condition) is 0 percent at phosphorus concentrations below approximately 30 ppb; this frequency increases steadily to approximately 70 percent at a phosphorus concentration of 100–120 ppb, and levels off at higher phosphorus concentrations. This response is similar to that observed for transparencies less than 1 m. The "threshold" phosphorus concentration corresponds to the onset of detectable nuisance frequencies (in this example, 30 ppb).

The presence of a phosphorus threshold is important because it represents a logical focus for criteria development, provided that an appropriate nuisance algal level (e.g., 20, 30, vs. 40 ppb chlorophyll *a*) can be defined. A phosphorus standard of 30 ppb was recommended for Cherry Creek Reservoir, Colorado, based upon phosphorus threshold and chlorophyll *a* nuisance frequency concepts (Walker, 1984a). Independent analyses of data sets derived from U. S. Army Corps of Engineers reservoirs and Lake Champlain (Walker, 1987) suggest phosphorus threshold values are similar to those shown in Figure 2 for extreme chlorophyll *a* values but vary for reduced transparencies, probably because of the effects of nonalgal turbidity (Walker, 1987).

User Response

The second, and more difficult task is to calibrate user or observer responses, i.e., by determining chlorophyll *a* or transparency levels that correspond to perceived nuisance conditions or impairment of water uses. Literature review, data sources, methods, and preliminary results are described here.

Classification systems relating chlorophyll *a* or transparency measurements to subjective impressions of aesthetic quality or use impairment are summarized from the literature in Table 1. Variations in algal species, background color, nonalgal turbidity, region, lake uses, and observers probably contribute to variations in these classification systems.

Table 1 suggests that definitions of "acceptable" or "objectionable" lake water quality vary regionally. These variations may reflect observer or user acclimation to a particular range of conditions, as noted by Lillie and Mason (1983). A lake user in a region dominated by oligotrophic lakes would probably expect transparency and lower algal levels than a lake user in a region dominated by hypereutrophic lakes.

Because of the wide ranges and regional associations of lake types in Minnesota (trophic and morphometric), it is likely that user expectations also vary among regions. Typical (25–75th percentile) values for summer-mean transparency in each of Minnesota's ecoregions are: 2–4 m in the Northern lakes and forests, 1–2.5 m in the North Central Hardwood Forests, and <60.5 m in the Western

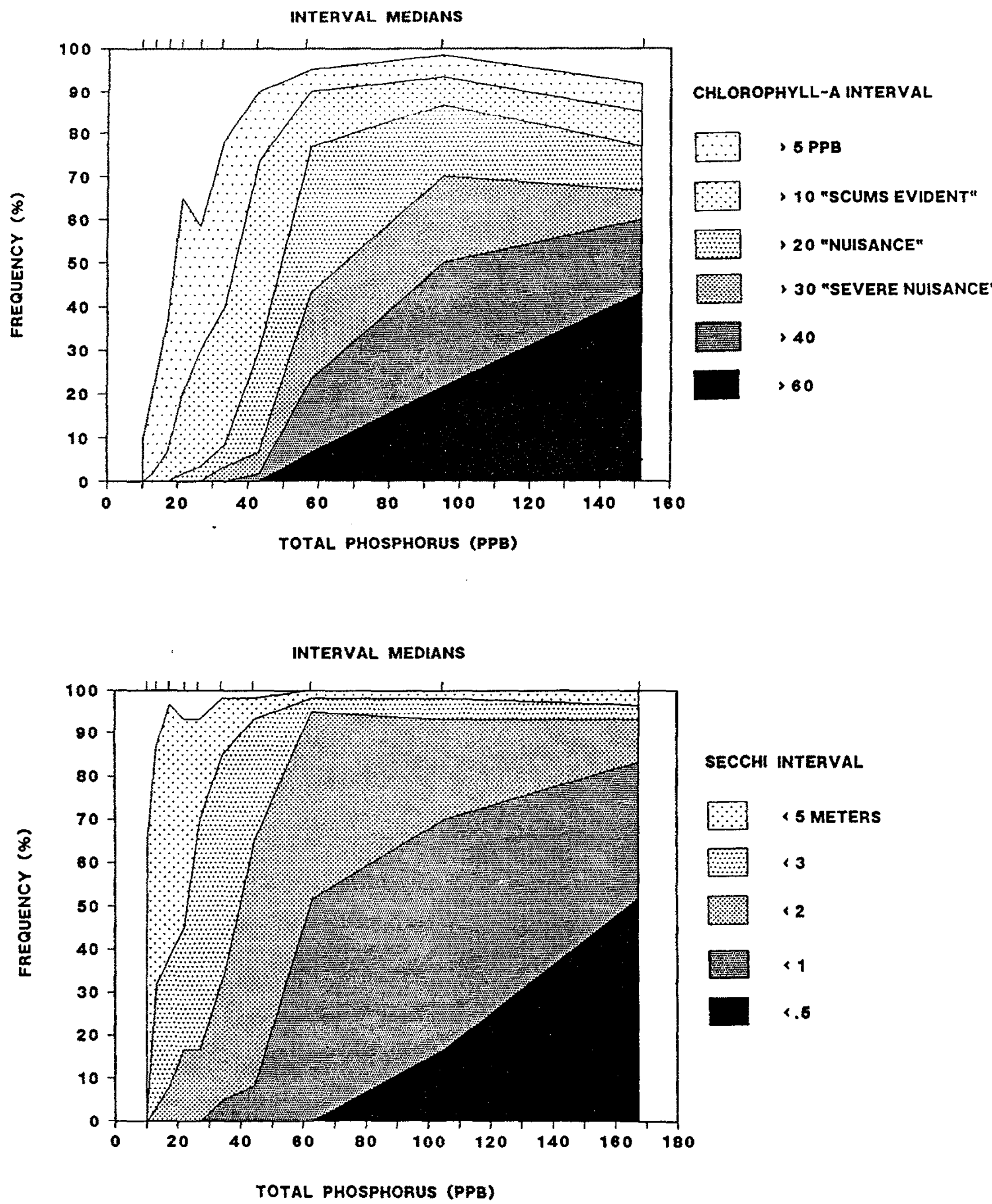

Figure 2.–Chlorophyll a and transparency interval frequencies vs. total phosphorus.

Corn Belt Plains and Northern Glaciated Plains (Heiskary et al. 1987). Because of regional and other factors contributing to variability in algal nuisance criteria, calibration to local lakes and user communities seems appropriate.

A lake observer survey (Table 2) is the primary source of information for calibrating user response. This survey was developed for application in Vermont (Garrison and Smeltzer, 1987). Use of a common format will facilitate future comparisons between Vermont and Minnesota. Two response categories are considered, one based upon physical appearance and the other upon recreation potential. Within each category, observers are asked to select one of five ratings that most accurately reflects their impressions of conditions at the time of sampling.

Table 1.—Aesthetic or use impairment classification systems based upon chlorophyll-a or transparency.

AUTHOR/ LOCATION	CHL-A (PPB)	SECCHI DEPTH (M)	RATING
Walmsley (1984) South African Reservoir	0–10		No Problems
	10–20		Scums Evident
	20–30		Nuisance
	> 30		Severe Nuisance
Burden et al. (1985) Louisiana	14 (a)	1.2	Excellent to Good
	30 (a)	0.8	Good to Acceptable
	32 (a)	0.7	Acceptable to Marginal
Barica (1975) Canadian Prairie Ponds	0–25	> 1	Clear, No Blooms
	25–100	.4–1	Moderate Blooms
	100–200	< .4	Dense Colonies & Scums
McGhee (1983) North Carolina	> 15		Unsuitable for Trout
	> 40 (b)		Severe Nuisance
Lillie and Mason (1983) Wisconsin	< 1	> 6	Excellent
	1–5	3–6	Very Good
	5–10	2–3	Good
	10–15	1.5–2	Fair
	15–30	1–1.5	Poor
	> 30	< 1	Very Poor
Effler et al. (1984) New York		> 1.2	State Standard for Beaches
MDPH (1969) Massachusetts		> 1.2	State Standard for Beaches

[a] Class means.
[b] North Carolina standard.

The survey has been completed concurrent with water quality sampling conducted in 1987 under the following monitoring programs:

1. Minnesota Pollution Control Agency (MPCA) Lake Monitoring Program staff (40 lakes);
2. Metropolitan Council Staff (Osgood, 1987) (10 lakes);
3. MPCA Lake Assessment Program, lay monitors (7 lakes);
4. MPCA Citizen Lake Monitoring Program, lay monitors (250 lakes).

Programs 1, 2, and 3 will provide concurrent water quality data on phosphorus, chlorophyll *a*, and transparency, whereas 4 will provide transparency data only. Cross-tabulating the water quality measurements against the observer survey categories will provide a basis for calibrating nuisance criteria statewide and regionally. To supplement these surveys, information on public perceptions of water quality problems is also being derived from review of requests for aquatic nuisance control permits submitted to the Minnesota Department of Natural Resources (MDNR) and complaints on lake water quality conditions submitted directly to the Minnesota Pollution Control Agency (MDCA).

Table 2.—Lake observer survey.

A. Please circle the one number that best describes the physical condition of the lake water today:

1. Crystal clear water.
2. Not quite crystal clear, a little algae present/visible.
3. Definite algal green, yellow, or brown color apparent.
4. High algal levels with limited clarity and/or mild odor apparent.
5. Severely high algal levels with one or more of the following: massive floating scums on lake or washed up on shore, strong foul odor, or fish kill.

B. Please circle the one number that best describes your opinion on how suitable the lake water is for recreation and aesthetic enjoyment today:

1. Beautiful, could not be any nicer.
2. Very minor aesthetic problems; excellent for swimming, boating, enjoyment.
3. Swimming and aesthetic enjoyment slightly impaired because of algal levels.
4. Desire to swim and level of enjoyment of the lake substantially reduced because of algal levels (would not swim, but boating is okay).
5. Swimming and aesthetic enjoyment of the lake nearly impossible because of algal levels.

Source: Garrison and Smeltzer (1987).

The data analyzed in the following paragraphs are derived from MPCA staff monitoring in early summer 1987 (Program 1 above). This includes 137 samples taken from 40 lakes and constitutes a small fraction of the total data base, which has yet to be compiled. Because the survey was completed by professional staff, it does not constitute a true "user" survey. Analysis of the complete data base will permit evaluation of differences in nuisance criteria as perceived by professional versus lay observers.

Figure 3 displays interquartile ranges of measurements within each category (physical appearance, recreation potential) and rating (1–5). One-way analyses of variance (ANOVA) (Snedecor and Cochran, 1967) indicate that average phosphorus, chlorophyll *a*, and transparency levels vary significantly ($p < .01$) across response ratings in each category. Based upon the ANOVA F statistics, transparency is most strongly associated with both the physical appearance and the recreation ratings. The data base is too small to permit definition of the extreme ratings in each category (see A(5) and B(5)

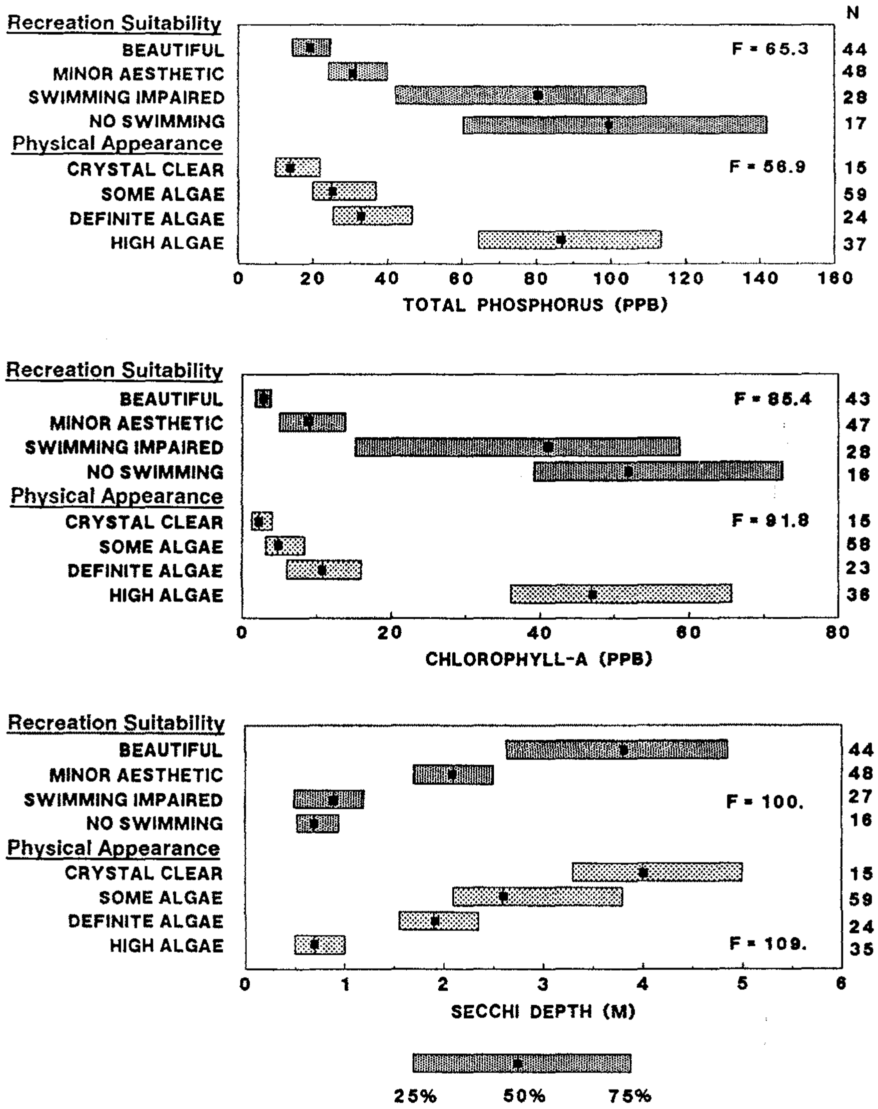

Figure 3.–Interquartile ranges of measurements in each response category. Legend: N = number of observations; F = variance ratio (among-group mean square/within-group mean square) derived from one-way analysis of variance on logarithmic scales.

in Table 2), which contained 2 and 0 samples, respectively, out of a total of 137. For this reason, these ratings are not shown.

Figure 3 shows that the contrast between the "definite algae" (A(3), Table 2) and "high algae" (A(4), Table 2) is quite distinct with respect to phosphorus, chlorophyll *a*, and transparency measurements. Walmsley's (1984) "nuisance" (20 ppb) and "severe nuisance" (30 ppb) chlorophyll *a* levels fall between the interquartile ranges of "definite algae" and "high algae" ratings. "Impaired swimming" and "no swimming" ratings generally have phosphorus levels exceeding 40 – 60 ppb, chlorophyll *a* levels exceeding 20 – 40 ppb, and transparencies of less than 1 m.

Cross-tabulation results are displayed for physical appearance and recreation categories in Figures 4 and 5, respectively. These figures have been developed using the procedure discussed above (see **"Lake Response"**). Each measurement interval includes 15 observations. The figures permit estimation of the probability of any nuisance rating as a function of phosphorus, chlorophyll *a*, or transparency level. Future analyses of larger data sets will permit definition of the frequency responses as a function of region and observer type (professional versus lay).

Available data from the MPCA Citizen Lake Monitoring Program (50 samples) indicate that swimming impairment may begin at Secchi transparencies of less than 3 m for participants in northern Minnesota and less than 1 m for those in southern Minnesota. "No swimming" typically begins at Secchi transparencies of less than 2 m for participants in northern Minnesota and less than 0.5 m for participants in southern Minnesota. Participants from the central portion of the state are generally intermediate between these two extremes. All participants associate transparencies of less than 0.5 m with "no swimming" and transparencies from 0.5 to 1 m as either "swimming impaired" or "no swimming."

Setting Criteria

The types of information described can provide a rational basis for setting phosphorus, chlorophyll *a*, or transparency criteria for protection of lakes against perceived problems. This involves specifying of the following:

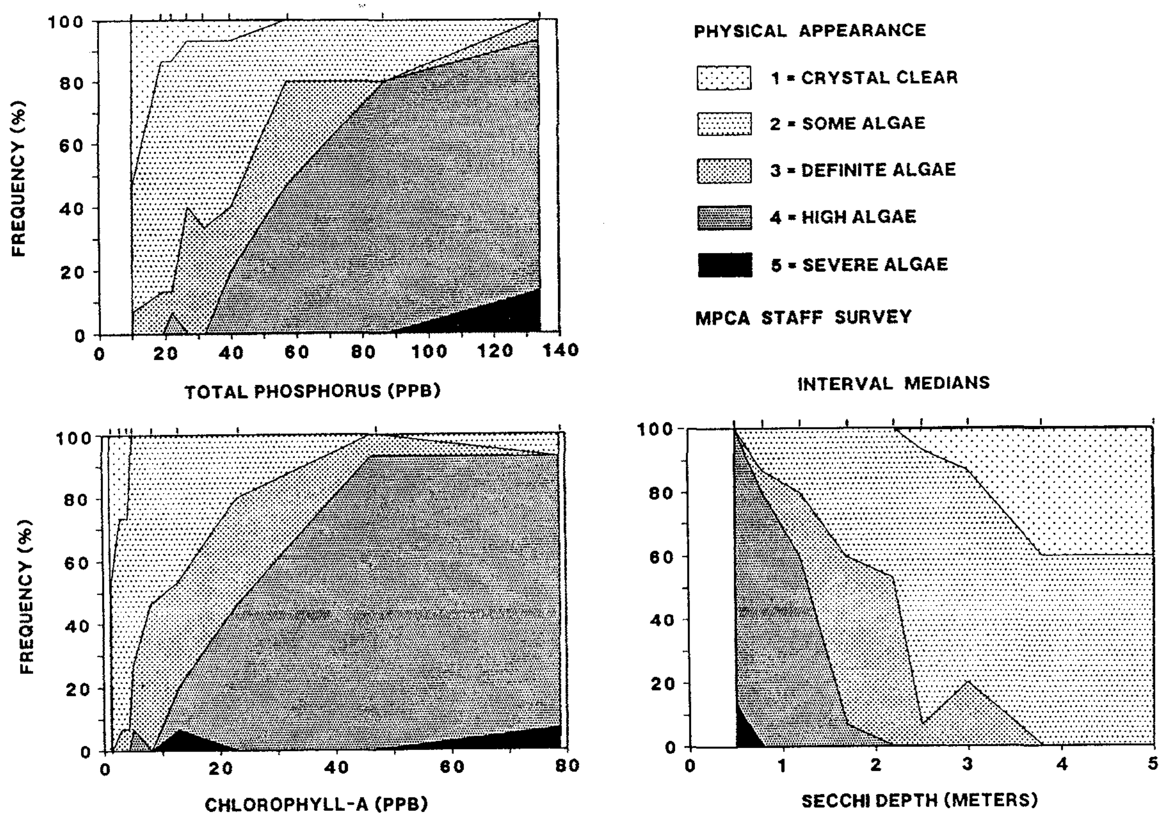

Figure 4.–Physical appearance ratings vs. lake water quality measurements.

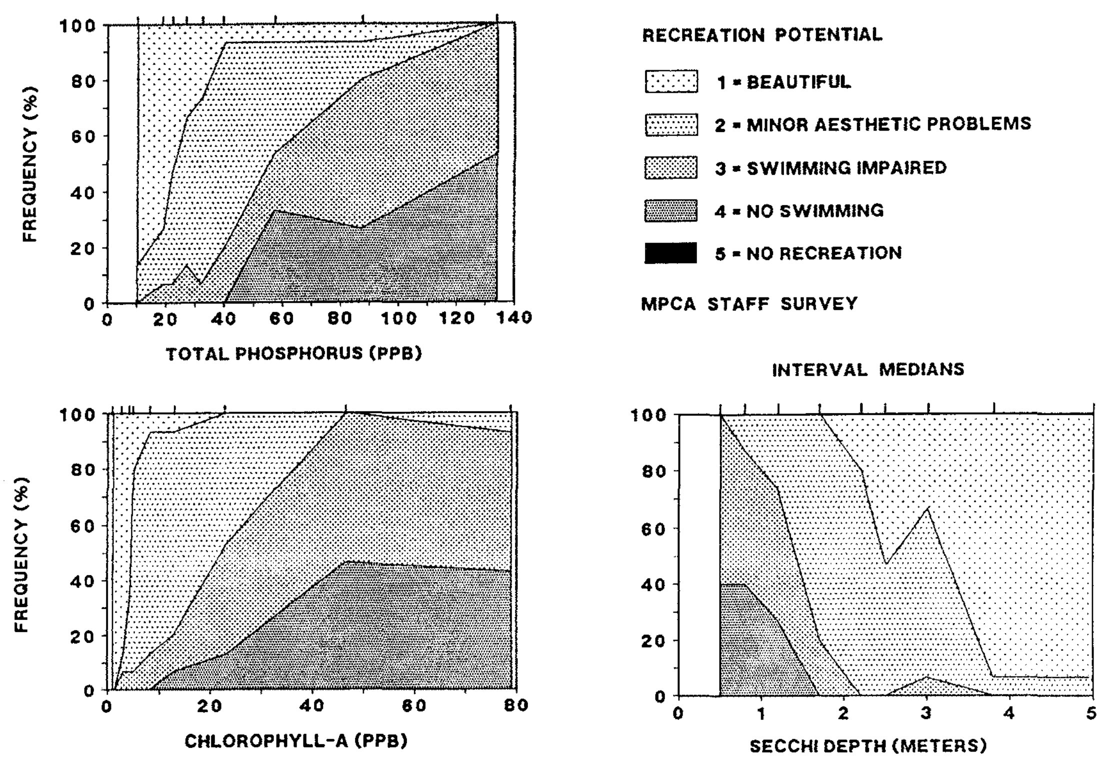

Figure 5.–Recreation potential ratings vs. lake water quality measurements.

■ **Nuisance criterion:** extreme chlorophyll *a* (e.g., Chl-a > 30 ppb), reduced transparency (e.g., Secchi < 1 m), recreation potential rating (e.g., "impaired swimming), physical appearance rating (e.g, "high algae").

■ **Acceptable risk level,** or probability that nuisance condition will be encountered (e.g., 1, 5, 10 percent, etc.).

By interpolating the frequency responses shown in Figures 2, 4, and 5, phosphorus concentrations corresponding to various nuisance frequencies can be estimated. Figure 6 plots phosphorus levels corresponding to <1, 10, and 25 percent probabilities of encountering each nuisance criterion. Note that the relatively low sample size (137) limits the accuracy of the criteria estimates, particularly at low risk levels. The procedure assumes that the chlorophyll *a*/phosphorus response in the collection of lakes is relatively homogeneous. Similar plots could be developed for relating subjective nuisance ratings to chlorophyll *a* or transparency measurements.

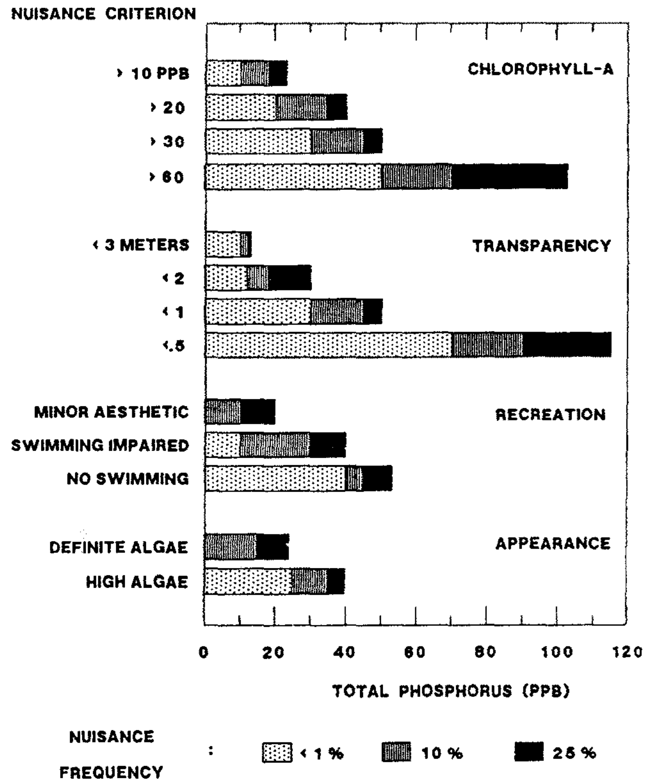

Figure 6.—**Phosphorus criteria based upon nuisance frequencies.**

Conclusion

This paper presents a methodology for phosphorus criteria development. While the focus has been on perceived impairment in aesthetics or recreation potential, other factors, such as linkages between phosphorus and hypolimnetic oxygen depletion, specific lake uses, and regional patterns in lake phosphorus concentration and phosphorus export should also be considered in the criteria development process. This methodology permits definition of aesthetic and recreational impairment and helps to quantify the "fishable-swimmable" goals of the Clean Water Act in a lake management context. Risk of perceived impairment or episode frequency can be related to lake phosphorus concentration, which in turn, can be predicted using phosphorus loading models. The methodology is particularly useful for expressing lake conditions in terms that are easily grasped by the public. Better public understanding promotes the development of realistic goals and wiser lake management decisions. Future analyses of larger data sets will permit refinements in the methodology and resulting criteria.

References

Barica, J. 1975. Summerkill risk in prairie ponds and possibilities of its prediction. J. Fish Res. Board Can. 32:1283-88.

Burden, D. G., R. F. Malone, and J. Geaghen. 1985. Development of a condition index for Louisiana lakes. Pages 68-73 in Lake Reservoir Manage. – Practical Applic. Proc. 4th Annu. Conf. Int. Symp., N. Am. Lake Manage. Soc., McAfee, N.J., 16-19 Oct., 1984.

Effler, S. W., M. C. Wodka, and S. D. Field. 1984. Scattering and absorption of light in Onondaga lake. J. Environ. Eng. Div. Am. Soc. Civ. Eng. 110: 1134-45.

Garrison, V. and E. Smeltzer. 1987. Personal commun. Vermont Dep. Water Resour. Environ. Eng. Montpelier.

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. In Lake Reservoir Manage. Proc. 5th Annu. Conf. Int. Symp. 5-8, Nov. 1986, N. Am. Lake Manage. Soc., Portland, OR.

Jones, J. R. and R. W. Bachman. 1976. Prediction of phosphorus and chlorophyll levels in lakes, J. Water Pollut. Control Fed. 48: 2176-82.

Lillie, R. A. and J. W. Mason. 1983. Limnological characteristics of Wisconsin lakes. Tech. Bull. 138. Dep. Nat. Resour., Madison, WI.

Massachusetts Department of Public Health. 1969. State Sanitary Code, Art. 7 Reg. 10.2B, Boston.

McGhee, R. F. 1983. Experiences in developing a chlorophyll a standard in the Southeast to protect lakes, reservoirs, and estuaries. Pages 163-5 in Lake Restoration Protection and

Management. Proc. 2nd Annu. Conf. N. Am. Lake Manage. Soc. 26-29 Oct. 1982. Vancouver, BC. EPA 440/5-83-001. U.S. Environ. Prot. Agency, Washington, DC.

Metropolitan Washington Council of Governments. 1982. A review of state water quality standards which pertain to nutrient enrichment. Washington, DC.

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

Osgood, R. A. 1987. Unpublished data. Metro. Counc., St. Paul, MN.

Snedecor, G. W. and W. G. Cochran. 1967. Statistical Methods. 6th ed. Iowa State Univ. Press, Ames.

U.S. Environmental Protection Agency. 1973. Biological field and laboratory methods for measuring the quality of surface waters and effluents. EPA 670/4-73-001. Natl. Environ. Res. Center., Cincinnati, OH.

———. 1979. Methods for chemical analyses of water and wastes. EPA-600/4-79-020. Washington, DC.

Walker, W. W.. 1984a. Eutrophication impacts quality and objectives for Cherry Creek reservoir, Colorado. Rep. prepared for City of Greenwood Village in support of testimony before Colorado Water Quality Control Commission.

———. 1984b. Statistical bases for mean chlorophyll a criteria. Pages 57-62 in Lake and Reservoir Management – Practical Applications. Proc. 4th Annu. Conf. N. Am. Lake Manage. Soc., McAfee, NJ.

———. 1987. Cross-tabulation as a tool for analyzing large monitoring data bases. Presented at Symp. Monitoring, Modeling, and Mediating Water Quality. Am. Water Resour. Assn., Syracuse, NY.

Walmsley, R.D. 1984. A chlorophyll a trophic status classification system for South African impoundments. J. Environ. Qual. 13: 97-104.