MISSISSIPPI RIVER PHOSPHORUS STUDY
Section 9
LAKE PEPIN WATER QUALITY GOAL SETTING

MINNESOTA POLLUTION CONTROL AGENCY

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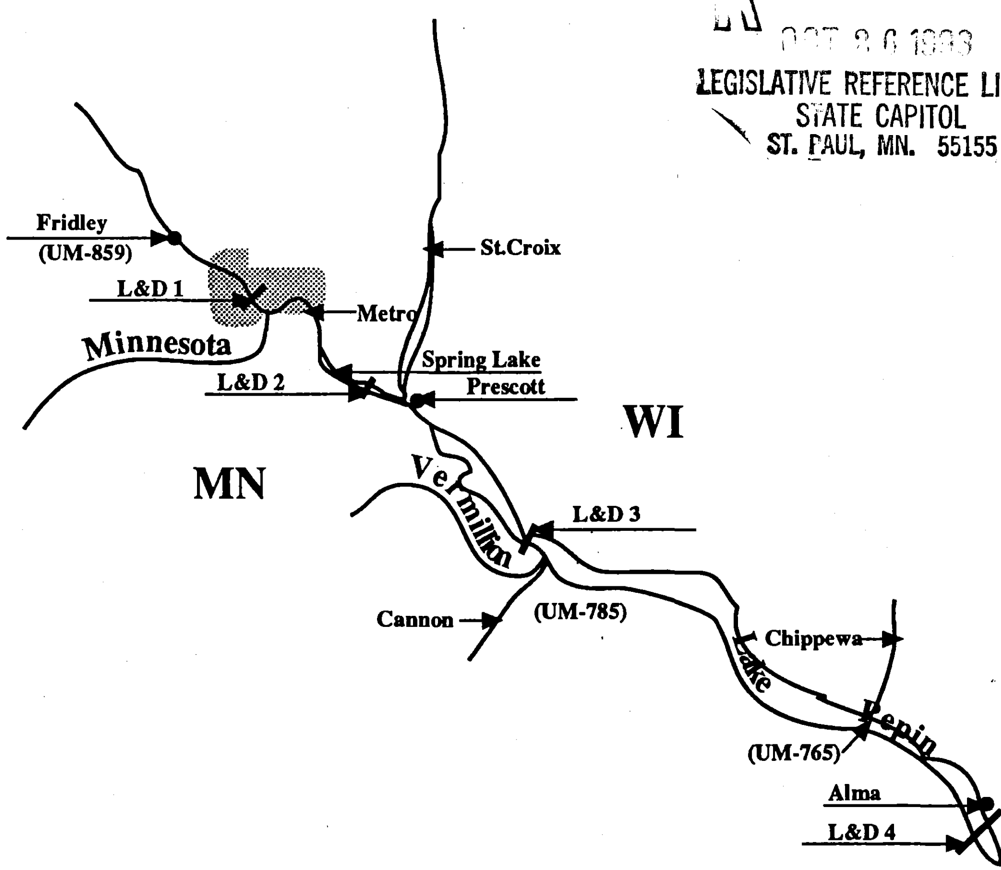

Water Quality Division
Minnesota Pollution Control Agency
February, 1993

Section 9

Lake Pepin Water Quality

Goal Setting

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Water Quality Division

Minnesota Pollution Control Agency

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Table of Contents

List of Figures

LAKE PEPIN WATER QUALITY GOAL SETTING

This report section will describe the process used for establishing a chlorophyll a goal for Lake Pepin. The discussion draws heavily from the description of Lake Pepin's water quality in Section 3. The reader is referred to Section 3 for relevant data.

Introduction

Defining what constitutes "nuisance algal blooms" in Lake Pepin is an important aspect of this study. Once defined, an appropriate water quality goal (based on chlorophyll a for example) can be established for the lake. The water quality goal can serve as a target for predictive modeling and developing management strategies for improvement or maintenance of water quality.

Total phosphorus and chlorophyll a are commonly used for identifying use impairment related to eutrophication. Both have been used in state rule making (e.g. standards and criteria development) and for goal setting (NALMS, 1992). Chlorophyll a is the better parameter for making direct linkage to nuisance algal conditions, while phosphorus is often a more appropriate parameter from a modeling and source control standpoint. Exceedance of chlorophyll a criterion levels often triggers water quality studies to identify causes of exceedance and to develop control strategies, e.g., Oregon and North Carolina (NALMS, 1992). Eutrophication criteria may be statewide or may be water body specific, e.g., total phosphorus criteria for Lake Champlain and Dillon Reservoir (NALMS, 1992). In Minnesota, phosphorus criteria have been developed based on assessment of phosphorus impacts on lake condition, impacts on lake users, and attainability

(Heiskary and Wilson, 1989). This effort resulted in phosphorus criteria appropriate to protect the "most sensitive uses" in each of four Minnesota ecoregions. Although the criteria have not gone through a formal rulemaking process, they are routinely used in Minnesota's glacial lakes for prioritizing projects for nonpoint source control, goal setting, developing water quality management plans, protection of designated trout lakes, and guiding enforcement decisions.

In the case of Lake Pepin, it seems appropriate to use a similar approach (as in development of phosphorus criteria) but focus first on chlorophyll a. Important steps would include: 1) identify what concentration of chlorophyll a constitutes nuisance conditions; and 2) establish a chlorophyll a goal which, if achieved, will reduce the frequency of nuisance conditions; and 3) determine appropriate range of river flows (lake residence time) for application of the chlorophyll a goal.

Discussion

Various sources of information will be used to define what constitutes "nuisance algal conditions" in Lake Pepin and to establish an appropriate chlorophyll a goal for the lake. Lake Pepin water quality and phytoplankton data are analyzed in conjunction with the following:

a) Regional patterns in lake user perception;
b) Interviews of citizens from the Lake Pepin area conducted by the Minnesota-Wisconsin Boundary Area Commission in 1992;
c) User perceptions as recorded by CLMP volunteers on Lake Pepin in 1990.

a) Regional Patterns in User Perception

Chlorophyll a and Secchi transparency are important measures for characterizing lake trophic state (Carlson, 1977). Linking these measures with user perception can provide a basis for lake management goal setting (Smeltzer and Heiskary, 1990).

Lake Pepin is located in the Driftless Area ecoregion. This ecoregion is relatively void of lakes (other than Lake Pepin). Summer average chlorophyll a and Secchi transparency measures from reference lakes (representative and minimally impacted lakes) in two nearby ecoregions - North Central Hardwoods Forests and Western Corn Belt Plains - provide a basis for placing Lake Pepin data in perspective. The interquartile ranges for these two parameters for each ecoregion and the range of summer means for Lake Pepin are as follows:

	Chlorophyll a	Secchi
North Central Hardwood Forests	5 - 22 ug/L	1.5 - 3.2 m
Western Corn Belt Plains	30 - 80 ug/L	0.5 - 1.0 m
Lake Pepin	22 - 57 ug/L	0.5 - 1.15 m

Based on these data, summer average chlorophyll a concentrations in Lake Pepin are somewhat intermediate between values for reference lakes in these two ecoregions. Secchi transparency measures, however, seem more comparable to those of the Western Corn Belt Plains lakes.

The relationship between chlorophyll a concentration and a description of "bloom perceptions" (based on individual chlorophyll a concentrations) that is generally applicable in Minnesota is as follows (as derived from Walmsley, 1984; Heiskary and Walker, 1988):

greater than 10 ug/L - "scum evident"
greater than 20 ug/L - "nuisance blooms"
greater than 30 ug/L - "severe nuisance"
greater than 60 ug/L - "worse yet"

Secchi transparency and chlorophyll a measurements relative to perceived use impairment do vary within Minnesota (Heiskary and Wilson, 1989). Lillie and Mason (1983), in their work in Wisconsin, note that variations in perception may reflect observer or user acclimation to a particular range of conditions. Figure 1 demonstrates regional differences in user perceptions of "no swim or no use" and "high or severe algae" relative to Secchi transparency for Minnesota. For example, in the Northern Lakes and Forests ecoregion, 75 percent of the observations ranked as "no swimming" or "no use" corresponded to Secchi transparencies of 2 m or less. In contrast, in the Western Corn Belt Plains, 75 percent of the same level of user impairment corresponded to Secchi transparencies of 0.9 m or less. The Secchi transparency ranges and pattern between regions for responses of "high or severe algae" was similar to rankings of "no swimming" or "no use" (Figure 1).

The transparency ranges (by ecoregion) in Figure 1 can be used to estimate chlorophyll a concentrations that would correspond to perceptions of "no swimming or no use" and "high or severe algae" using Carlson's TSI scale (Carlson, 1977). This conversion is shown in Figure 2 and Lake Pepin summer mean measurements are included for purposes of comparison.

By overlaying the Secchi ranges from Figure 1 on the Carlson TSI scale (Figure 2) the corresponding ranges of chlorophyll a relative to perceptions of "high or severe algae" are estimated as follows:

Northern Lakes and Forests	7-20 ug/L
North Central Hardwood Forests	13-35 ug/L
Western Corn Belt Plains	40-130 ug/L

Figure 1. 1987 Citizens Lake Monitoring Program user perceptions of recreational suitability and physical appearance classes. Plots are presentations of interquartile range of Secchi measurements which correspond to perception classes 4 and 5 for Northern Lakes and Forests (NLF), North Central Hardwood Forests (CHF), and Western Corn Belt plains (WCP).

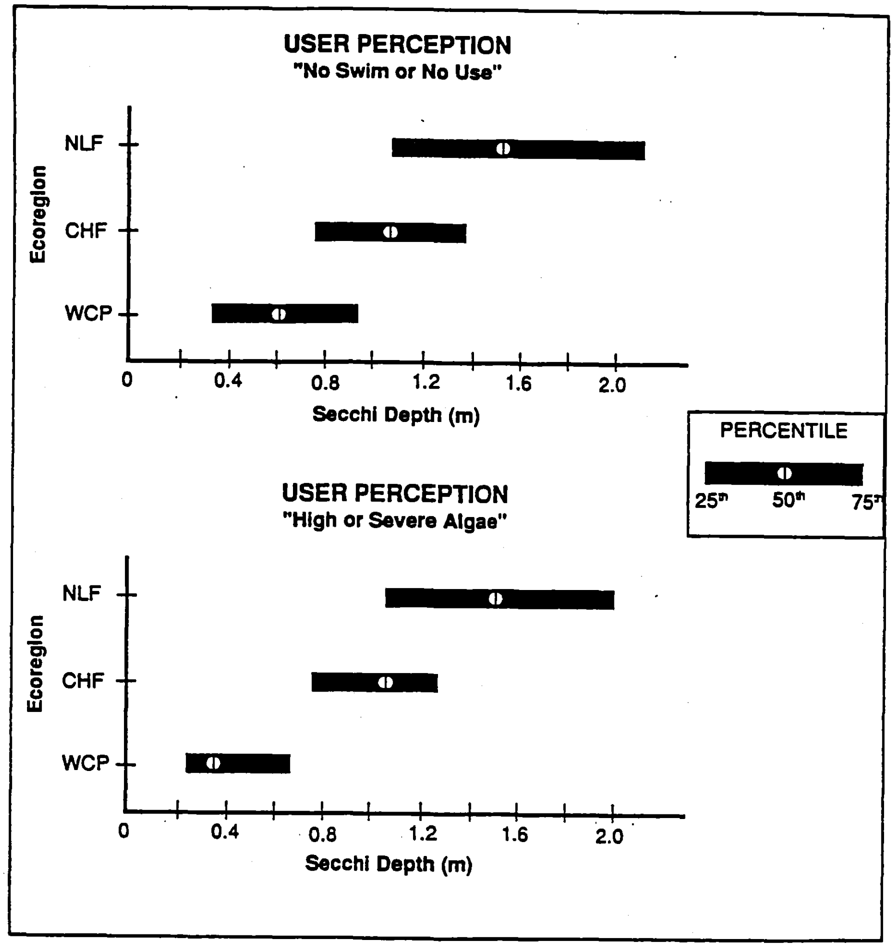
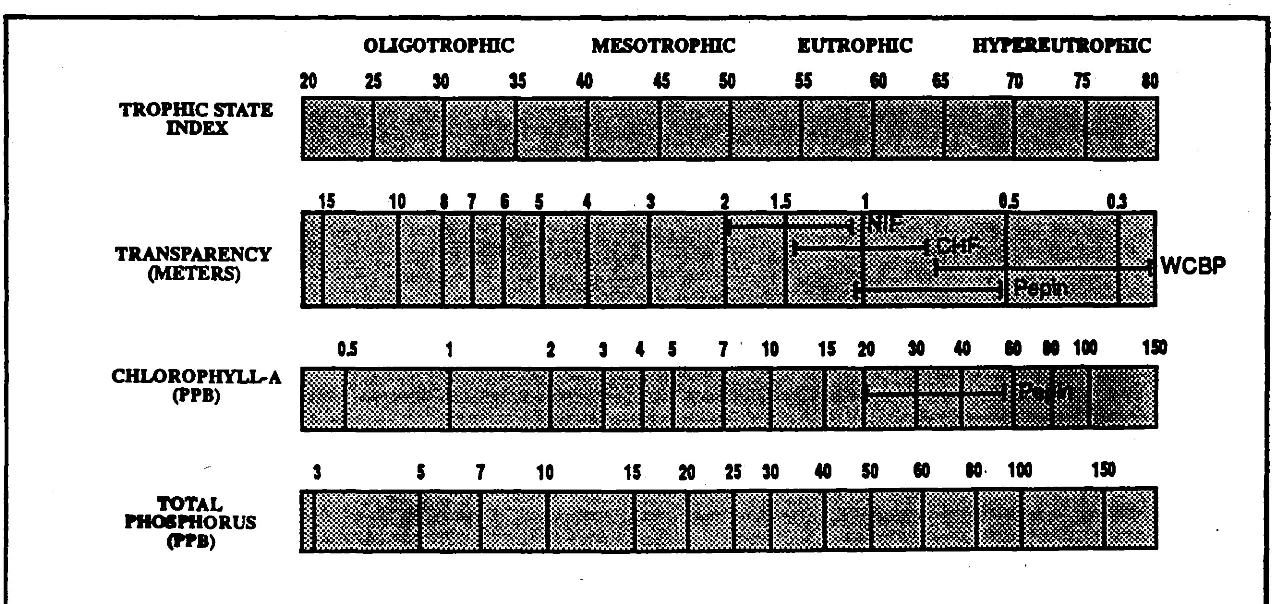


Figure 2. Carlson's TSI values relative to user perception. Secchi transparency interquartile ranges from Figure 1 by ecoregion for the perception "high or severe algae." Range of summer mean Secchi and chlorophyll a for Lake Pepin noted.



These ranges of chlorophyll a suggest that the description of "bloom perceptions" as taken from Heiskary and Walker (1988) are fairly applicable to the Northern Lakes and Forests and North Central Hardwoods Forest ecoregion (i.e., chlorophyll a greater than 20 ug/L - "nuisance blooms"). However, lake users in the Western Corn Belt Plains are somewhat more tolerant of low transparency and higher chlorophyll a concentrations (Heiskary and Wilson, 1989). Subsequently, phosphorus criteria (for the protection of "swimmable use") for the Northern Lakes and Forests and North Central Hardwood Forests (30 and 40 ug P/L respectively) are much lower than the phosphorus criteria for the Western Corn Belt Plains (< 90 ug/L). The intent for the Northern Lakes and Forests and North Central Hardwood Forest ecoregion is to maintain swimmable conditions for the vast majority of the summer. In contrast, in the Western Corn Belt Plains, the intent is minimizing the frequency of severe nuisance algal blooms (Heiskary and Wilson, 1990). Considering the range in Lake Pepin's water quality (in terms of Secchi transparency and chlorophyll a concentrations) and its proximity to the Western Corn Belt Plains, an approach similar to that for the Western Corn Belt Plains seems reasonable (i.e., reducing the frequency of severe nuisance algal blooms).

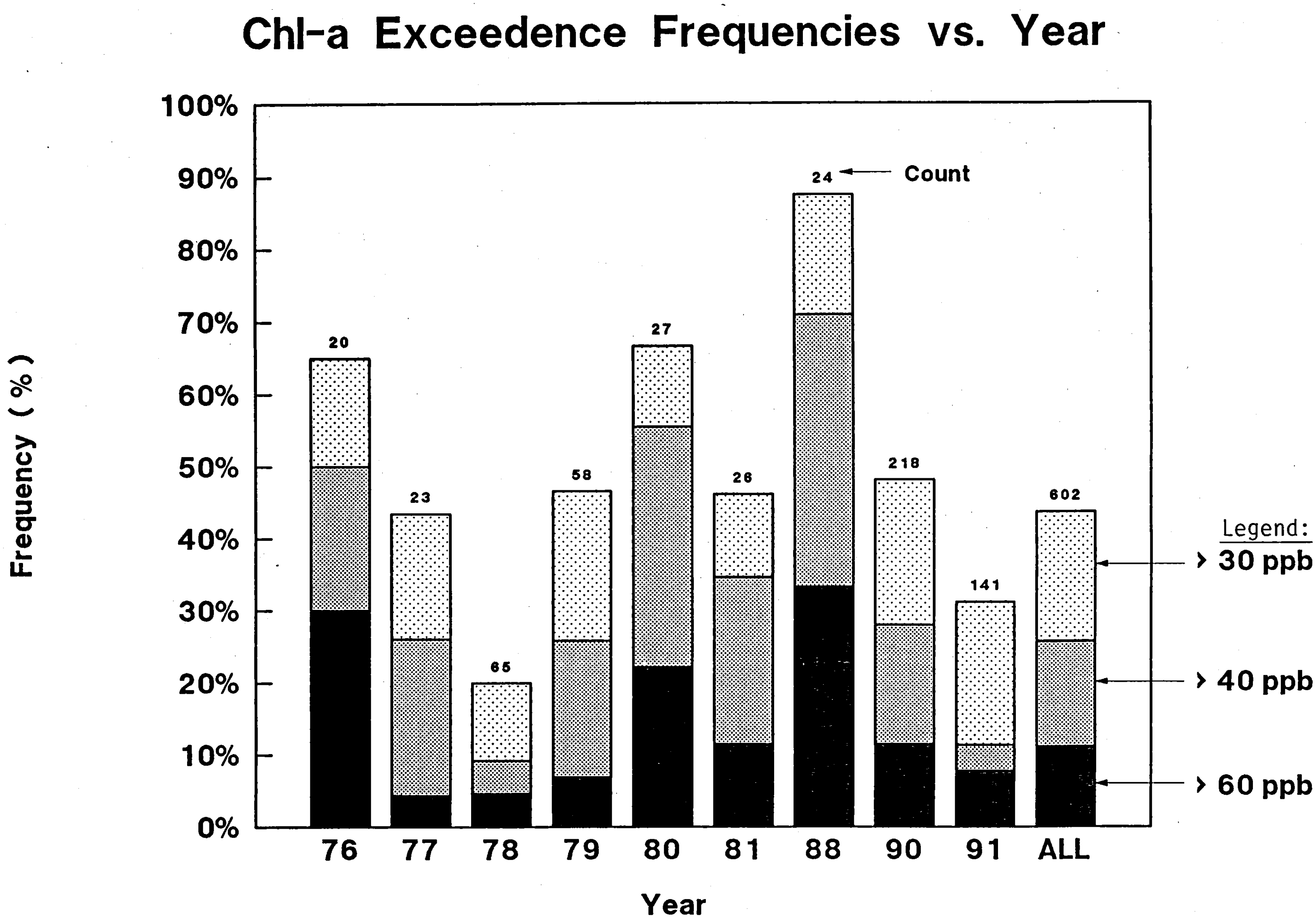
b) Citizen Interviews and Lake Pepin Chlorophyll a

Water quality conditions in Lake Pepin in 1988 were unacceptable to users of the lake. This is based both on numerous complaints received by MPCA, MDNR, and Wisconsin DNR during the summer of 1988 and interviews of local citizens conducted by the Minnesota-Wisconsin Boundary Area Commission in the spring of 1992 with citizens from the area. The majority of the respondents who participated in the spring 1992 interview indicated that once-in-ten-year water quality problems like those that occurred in 1976 and 1988 are unacceptable (Harrison, 1992; Section 8). Thus, 1988 and 1976 data serve as an indication of what are considered unacceptable or nuisance conditions with respect to algae in Lake Pepin. However, the data will not reveal an exact threshold above which this response is triggered.

The 1988 summer mean chlorophyll a was 57 ug/L and the maximum was 202 ug/L based on MPCA data. The summer of 1976 (a comparable low flow year) exhibited a summer mean of 52 ug/L with a maximum of about 83 ug/L, based on MWCC data (Table 6, Section 3). The difference in measured maxima between years may be function of sample site location (i.e. MWCC data was collected at two mid-lake sites only) and the relatively small sample size in both years (20 and 24 chlorophyll measures for 1976 and 1988, representing six and three samples dates, respectively). Blue-green algae were dominant in samples taken in early July of 1988 (MPCA and Wisconsin DNR). Both 1988 and 1976 were characterized by a high percentage of "high" chlorophyll a values (i.e., > 30, > 40, and > 60 ug/L). For example, based on 1988 chlorophyll a data, 87 percent of the measures were greater than 30 ug/L, 70 percent greater than 40 ug/L, and 30 percent greater than 60 ug/L (Figure 3). These levels of chlorophyll are often associated with severe nuisance conditions. In comparison, 1990 and 1991 were characterized by substantially lower "frequencies" of these three levels of chlorophyll a (Figure 3).

Other questions posed to the citizens sought comparisons in water quality between the years 1991, 1990, and 1988. In references to the water quality in 1991, 52 percent of the 26 respondents indicated that 1991 water quality was improved over previous years, while 19 percent suggested that water quality was poor. With respect to 1990, 38 percent felt water quality was

Figure 3. LAKE PEPIN CHLOROPHYLL a FREQUENCIES.
Graphic Developed by W.W. Walker, Jr.



Lake Pepin, MPCA & MWCC Data, June-September improved over prior years, while 24 percent felt it was poor. When asked to characterize "bad water quality," 57 percent of 40 responses noted odors and 52 percent of responses noted heavy green/blue-green scums. Other responses to the question included "brown slime," "algae made marina unbearable," and "dog days earlier and longer." In terms of seasonal changes in water quality, 48 percent of 19 responses indicated "good spring quality, worsens as summer progresses" and 19 percent "algae reduces clarity/quality starting in June." In terms of recreational use, 38 percent of 18 responses noted more recreational use in 1990 and 1991 as compared to 1988-1989. In contrast, 1988-1989 was characterized by less swimming and fishing in about 29 percent of the responses.

In general, the survey group showed little tolerance for periodic pollution episodes of significant magnitude. Sixty-eight percent said occasional, isolated episodes of water quality degradation (like 1988) were not acceptable. Seventy-one percent said water quality protection should be assured for all circumstances at all times.

c. Lake Pepin User Perceptions

User perception of Lake Pepin water quality in 1990 as noted by CLMP volunteers has been previously discussed (Heiskary and Vavricka, 1993; Section 3). The observers ranked the "physical condition" of the lake as (3) "definite algal green" or worse and recreational suitability as (3) "swimming impaired" or worse on all dates. Some ratings of "no swimming" or "high algal levels and mild odor" were applied to some dates in July and August.

For site 201 (near UM-781) and site 203 (near UM-771) perceptions of "impaired swimming" and "algal green" corresponded to chlorophyll a concentrations in the 25-40 ug/L range (Figure 4). The observer at site 201 sampled weekly between July 4 and September 26, 1990. This observer recorded ratings of "no swimming" on August 26, 1990, and September 2, 1990. Secchi transparency was 0.6 m on those dates. Chlorophyll a concentrations at a nearby site (181.3, UM-781) were about 120 ug/L and 60 ug/L respectively (Figure 4). Blue-green algae comprised about 30 percent of the algal population during that period of time.

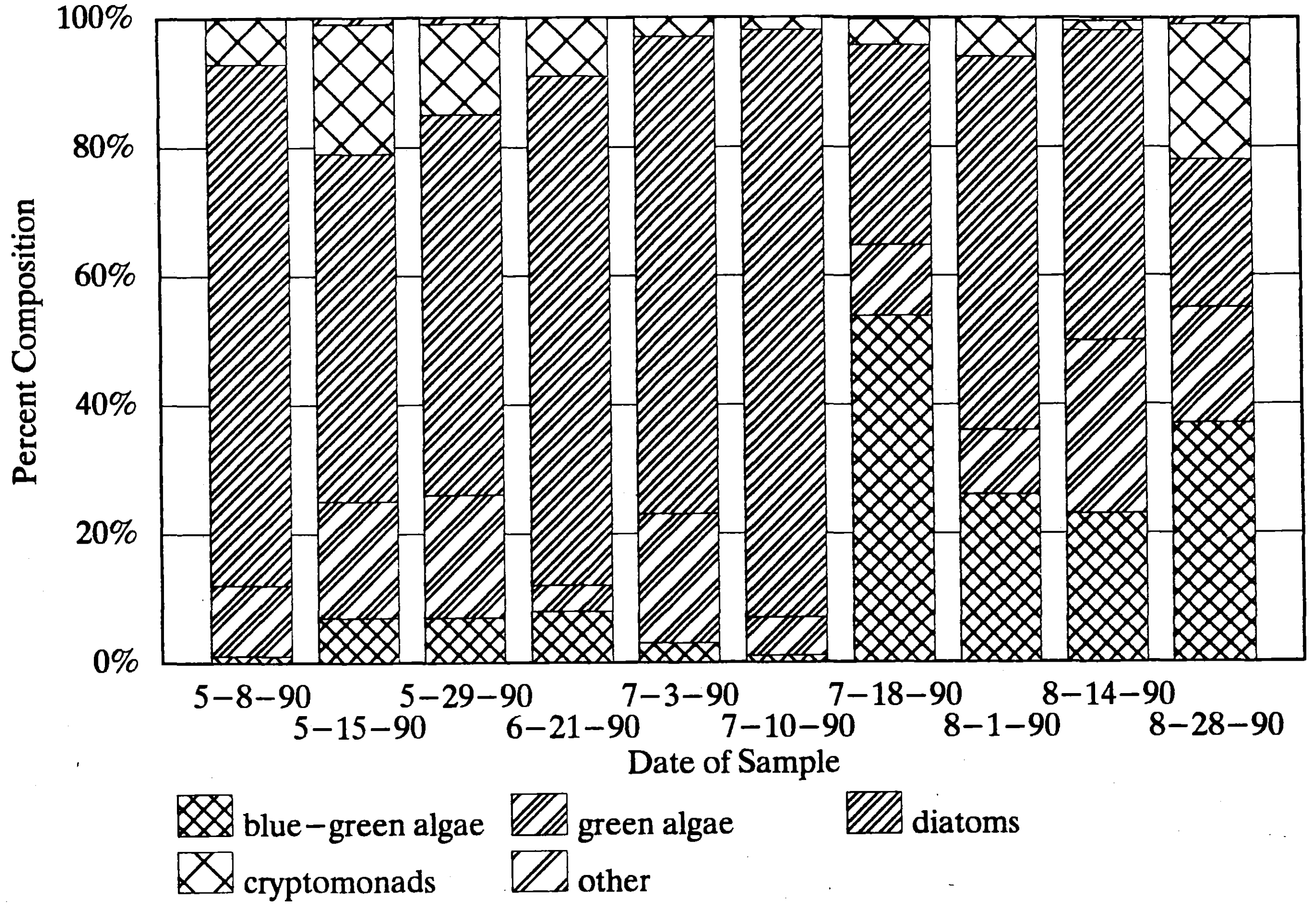
The observer at site 202, near UM-774, ranked conditions as "no swimming" for the period from July 13, 1990, to August 21, 1990, based on weekly sampling. Secchi transparency during that period ranged from 0.3 - 0.6 m. During that period, chlorophyll a ranged from about 25-75 ug/L. Blue-green algae comprised about 30 percent of the algal community at a nearby site (175.3, UM-775) from July 18 to August 1, 1990.

The other two participants sampled less frequently (site 203 - four observations, site 204 - three observations) and characterized conditions as "swimming impaired" or worse on dates in late July and early August. Secchi transparency ranged from 0.6 - 0.75 m at site 203 (UM-771) and from 1.05 - 1.35 m at Site 204 (UM-764) on those dates. Chlorophyll a concentrations were on the order of 25-40 ug/L. Blue-green algae comprised between 30-60 percent of the algal community from mid-July to late August at a nearby site (171.3, UM-771).

Figure 4. PHYTOPLANKTON COMPOSITION and CHLOROPHYLL a CONCENTRATIONS

LAKE PEPIN PHYTOPLANKTON COMPOSITION

Site 181.3 (UM – 781)



LAKE PEPIN CHLOROPHYLL a

Site 781.3 (i.e. 201)

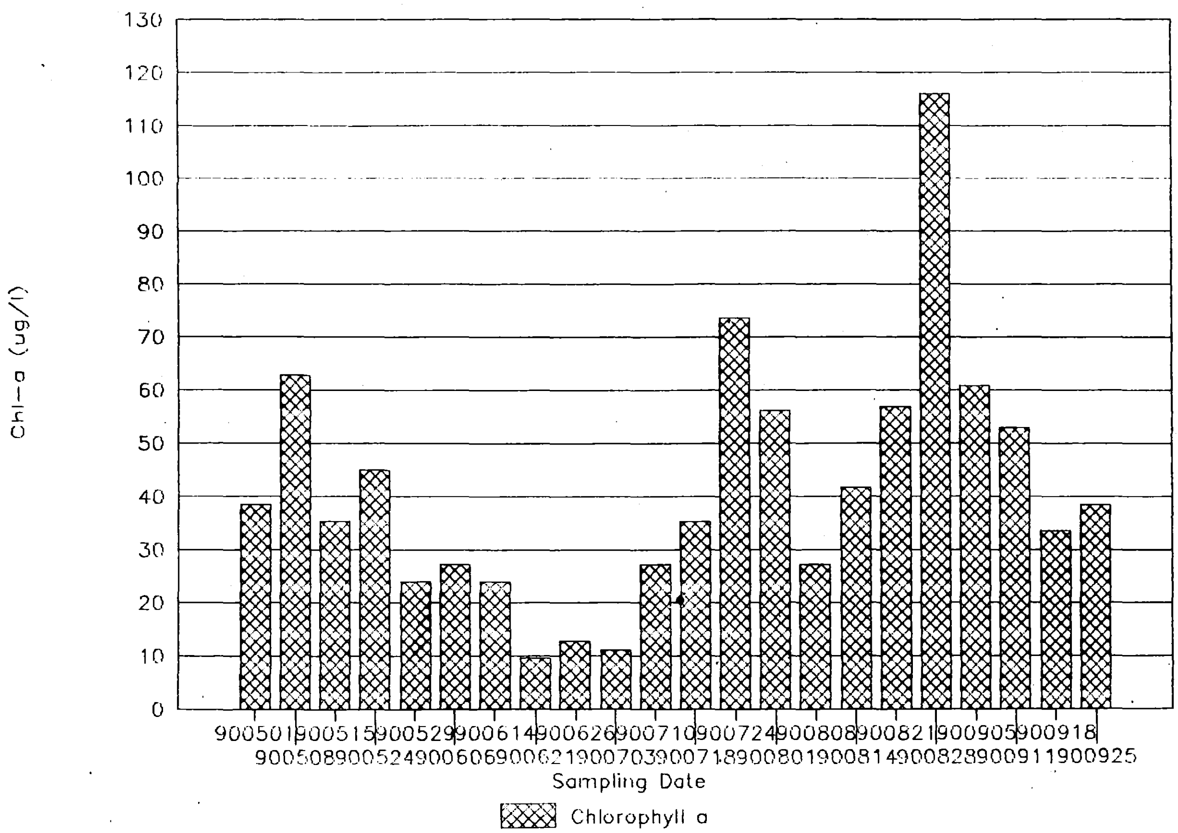
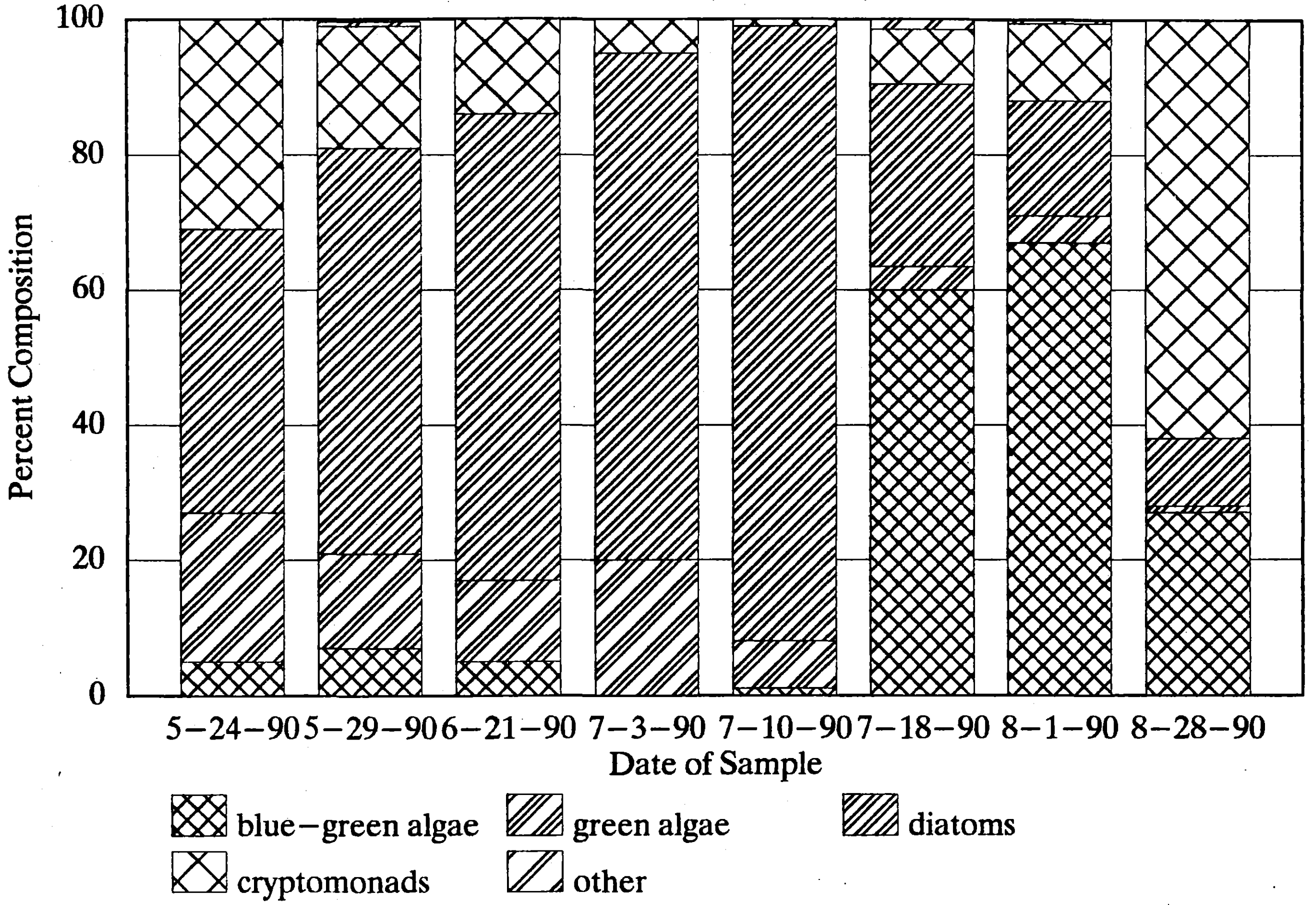


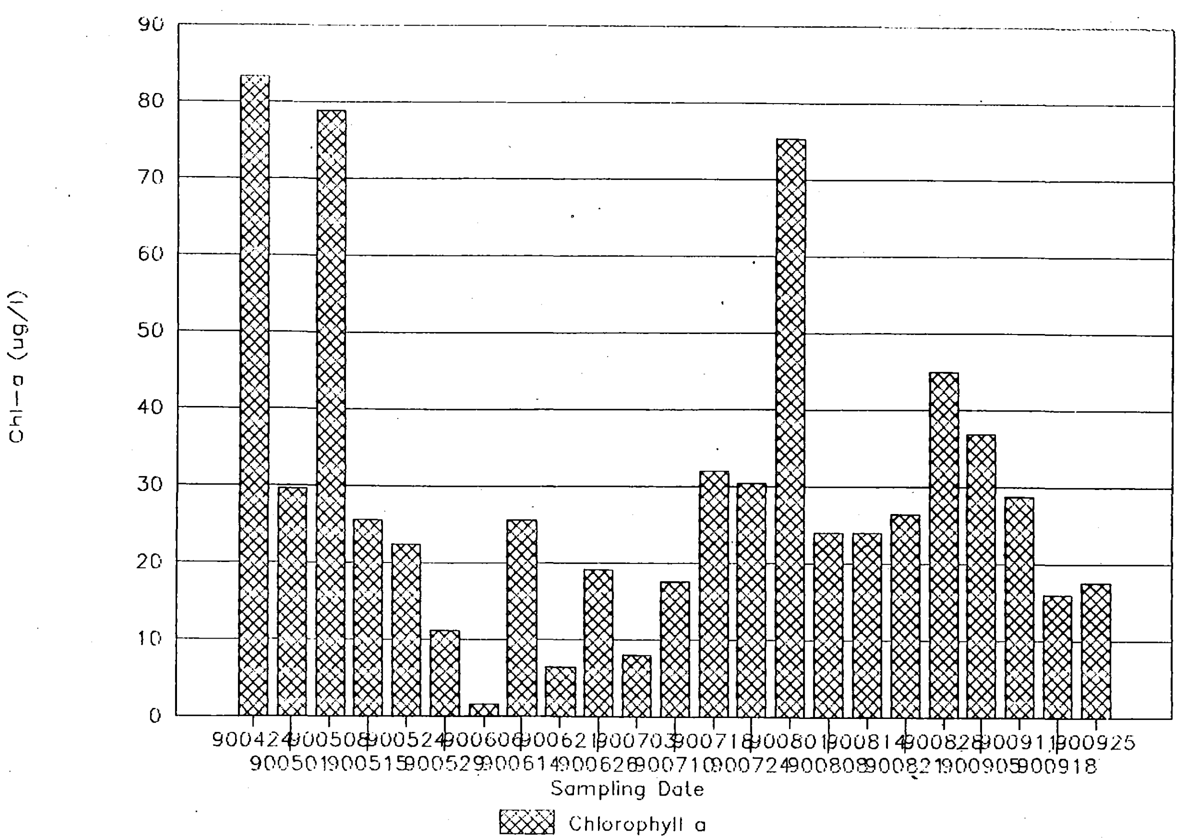
Figure 4. Continued.

LAKE PEPIN PHYTOPLANKTON COMPOSITION

Site 171.3 (UM – 771)



LAKE PEPIN CHLOROPHYLL a
Site 771.3 (i.e. 203)



Goal Setting

From a goal or criteria setting standpoint, it is often appropriate to specify an average (or minimum or maximum) concentration for a parameter for a specific period of time (e.g., summer mean chlorophyll a). From a water quality rule perspective, it is also important to associate standards (goals) with a flow recurrence interval, e.g., 7Q10 (seven consecutive days of low flow with a one-in-ten year recurrence interval). In the case of Lake Pepin, we have elected to establish a chlorophyll a goal for the summer (June through September) period. Of particular interest is maintaining sufficiently low chlorophyll a concentrations during summers of low to average flow so that the frequency of nuisance algal blooms is minimized. An additional benefit of reducing chlorophyll a concentrations is the reduction in organic material (algae) deposited to the lake sediments, which should serve to lessen sediment oxygen demand and potentially lead to a reduction in the rate of internal phosphorus recycling.

Though our primary focus is on reducing the frequency of "extreme" or "nuisance" chlorophyll a concentrations, it is desirable to express the chlorophyll a goal in terms of an average concentration. Walker (1985) provides the following advantages of the use of mean chlorophyll a as a relative measure of lake condition:

1) Estimates of mean values derived from a given monitoring program would generally have a lower variance (i.e., be more reliably estimated from limited data) than other summary statistics (e.g. maximum);

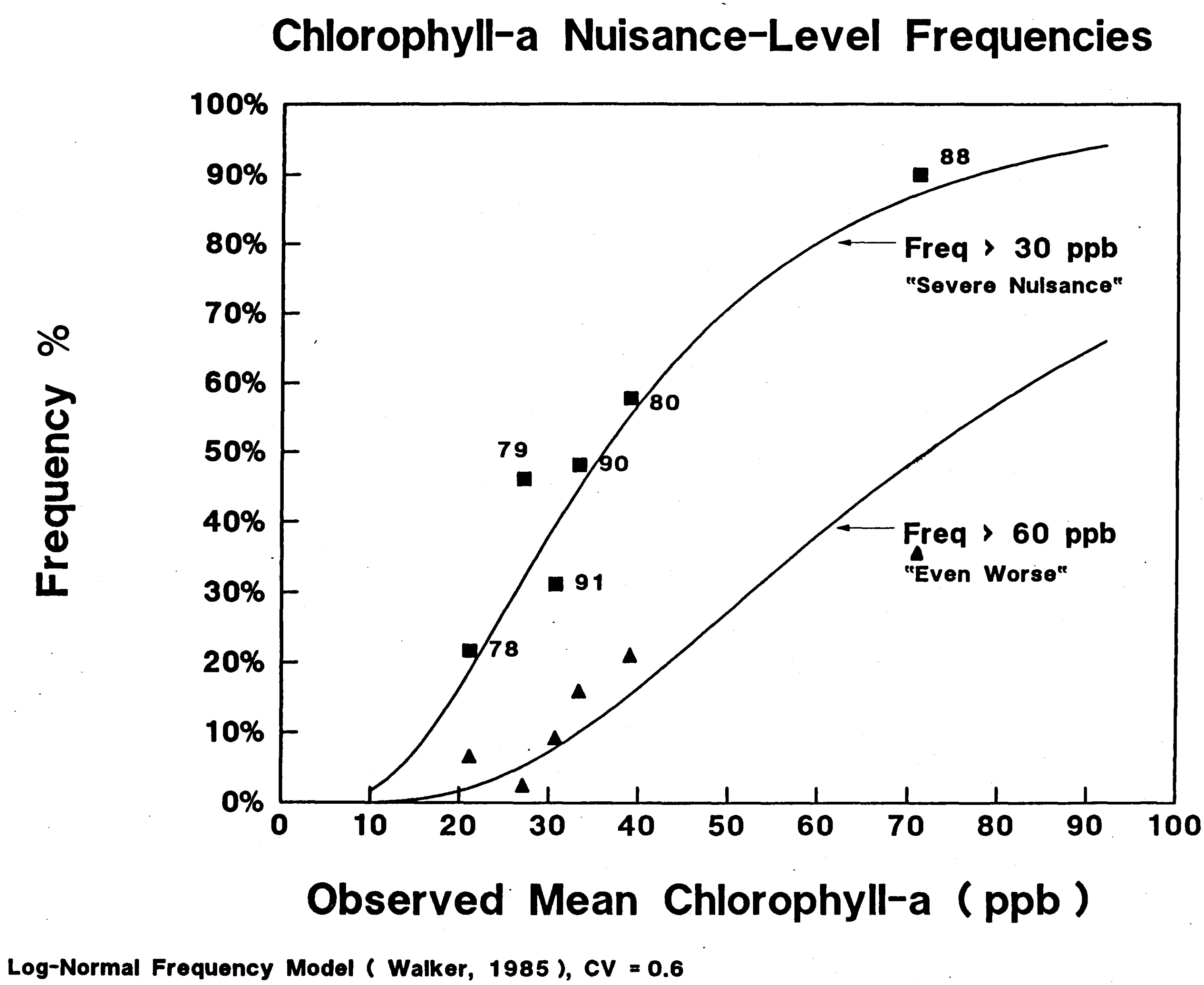
2) They can be related to watershed conditions using nutrient budget models; and

3) They have been widely used in lake assessment and classification.

Walker (1985), however, provides an algorithm for calculating the expected frequency of extreme values (Appendix). Using this methodology, it is possible to estimate the percent of time nuisance levels (e.g. 20, 30, or 40 ug/L) are experienced as a function of the arithmetic mean chlorophyll a. The log-normal frequency model was tested using MPCA Lake Pepin data for the summers of 1978, 1979, 1980, 1988, 1990, and 1991 (Figure 5). This model corresponded closely to the observed data and provides a good means to predict the frequency of chlorophyll a concentrations greater than 30, 40, and 60 ug/L as a function of summer mean chlorophyll a (Figure 5).

The next step is to define the "nuisance levels" of concern and select an appropriate summer mean chlorophyll a concentration which will minimize the frequency of "nuisance algal conditions." Given the proximity of the North Central Hardwood Forests and Western Corn Belt Plains ecoregions to Lake Pepin, it is likely that user perceptions in Lake Pepin would be more similar to these regions than the Northern Lakes and Forests ecoregion. The range of summer average Secchi transparency and chlorophyll a measurements for Lake Pepin are plotted on Figure 2. Lake Pepin summer average transparency and chlorophyll a measurements tend to be intermediate between transparency (chlorophyll a) measures associated with "high or severe algae" and "no swimming or no use" perceptions for the North Central Hardwood Forests and Western Corn Belt Plains ecoregion. Thus the "threshold" for nuisance algal conditions and an appropriate chlorophyll a goal for Lake Pepin is likely intermediate between perceived nuisance algal concentrations for these two ecoregions.

Figure 5. LAKE PEPIN CHLOROPHYLL a NUISANCE-LEVEL FREQUENCIES.
Graphic Developed by W.W. Walker, Jr.



Based on user perceptions for Lake Pepin, chlorophyll a concentrations in excess of 25-30 ug/L are associated with "impaired" water quality conditions. As chlorophyll a concentrations exceed approximately 40 ug/L perceptions of "no swimming" and "high algal green" are noted. This is particularly evident on dates when blue-green algae are a prominent portion of the algal community.

Chlorophyll a data and the citizen interviews regarding 1988 serve as an indication of what is undesirable in terms of average and nuisance levels of algae. The 1988 summer average chlorophyll a concentration was 57 ug/L and was characterized by a high frequency of chlorophyll a concentrations > 30, > 40, and > 60 ug/L (Figure 3). In contrast, conditions in 1990 were deemed much better than 1988 based on citizen interviews. Chlorophyll a averaged 33 ug/L and the frequency of chlorophyll a > 30, > 40, and > 60 ug/L were substantially less than in 1988 (e.g., frequency of chlorophyll a > 40 ug/L was > 70 percent in 1988 and < 30 percent in 1990; Figure 3). However, conditions in 1990 were characterized as "swimming impaired" and "algal green" or worse throughout the summer. The perception of "no swimming" and "high algal levels" corresponded to dates with high chlorophyll a (> 40 ug/L) and blue-green algae as a prominent component of the algal community.

Based on all the previous information - Lake Pepin data and user perceptions, citizen interviews, and ecoregion considerations - an appropriate chlorophyll a goal for Lake Pepin should yield an acceptably low frequency of "nuisance algal conditions" throughout the majority of the summer and keep perceptions of "no swimming" to a minimum. Chlorophyll a concentrations > 40 ug/L and > 60 ug/L are appropriate levels to describe "nuisance algal conditions" (> 40 ug/L) and "severe nuisance algal conditions" and "no swimming" (> 60 ug/L) thresholds for

Lake Pepin. Chlorophyll a > 30 ug/L seems appropriate for defining "swimming impaired" and "algal green" conditions for Lake Pepin.

These data suggest that a summer mean chlorophyll a concentration of 30 ug/L is an appropriate goal for Lake Pepin. Using 1991 as an example (summer mean = 31 ug/L), the frequency of chlorophyll a > 40 ug/L would be less than 20 percent and chlorophyll a > 60 ug/L would be less than 10 percent. However, an appreciable percent of the summer (e.g., 30-50 percent based on 1990 and 1991) would be characterized as "swimming impaired" and "algal green."

A slightly higher goal (e.g., 35 or 40 ug/L) is not appropriate. The frequency of nuisance conditions increases rapidly at summer mean chlorophyll a concentrations between 30 and 40 ug/L (Figure 5), i.e., slopes are steep in this portion of the graph. It is appropriate that the frequency of chlorophyll a concentrations < 30 ppb, conditions when water quality is acceptable, represent a majority of time during the summer.

Considering the significance of river flow (water residence time) on the production of algal biomass (chlorophyll a) in Lake Pepin, it is essential to associate a specified (design) flow or range of flows for application of the chlorophyll a goal and evaluating potential strategies (e.g. nutrient reduction) for achieving the goal.

The "design flow" for applying this goal should include the Mississippi River flows of 1976 and 1988 (i.e., about 4,700 cfs or lower as a summer mean). As a frame of reference, the summer 7Q10 at Prescott is about 3,900 cfs. For this purpose, a 120Q 50-year discharge of 4,578 cfs may be appropriate as a "lower design flow." The 120-day period would cover the season of concern (June through September) and a flow of 4,578 cfs would include the recent low flow years of 1976 and 1988. If a summer mean chlorophyll a concentration of 30 ug/L is protective for 1976 and 1988 conditions then summers of higher flow should be protected also based on the interrelationship of flow and chlorophyll a for Lake Pepin (Figure 21 in Section 3 and Figure 3 in this report).

An upper design flow may be desirable for several reasons:

a) An upper flow limit would serve to separate flow regimes associated with very low residence time in Lake Pepin (i.e., river-like conditions) from the "average to low flow" conditions which produce more "lake-like" conditions;

b) At very high flows algal production (chlorophyll a concentration) is regulated more by flow than other factors (e.g., nutrient loading) and chlorophyll a exceedance frequencies (> 30, > 40, > 60 ug/L) decline markedly at higher flows (Figure 6);

c) Blue-green algae, which can influence perceptions of "nuisance algal blooms" are a very small component of the algal population during summers of very high flow (e.g. 1991) in contrast to summers of more moderate flow (e.g. 1990); and

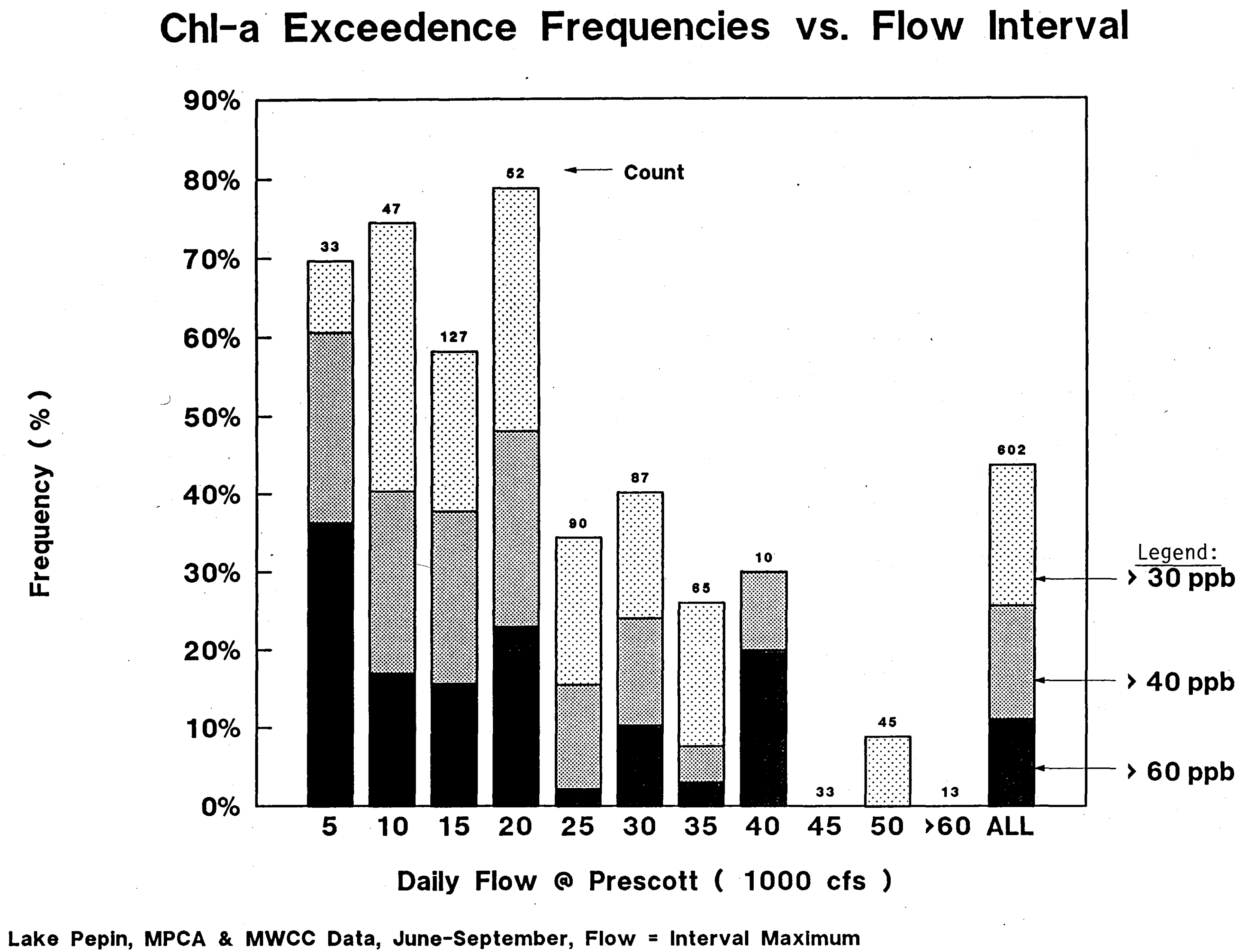
d) An upper flow limit combined with a lower flow limit will help to focus modeling efforts and development of management options on the range of flows over which problems with nuisance algal conditions are most likely to occur.

For this purpose, an upper flow limit of 20,000 cfs is proposed. A mean summer flow of 20,000 cfs provides a residence time of about 11 days, which is probably a minimum amount of time necessary to allow algae to use available nutrients. This flow could be viewed as a transition between "river-like" to "lake-like" conditions. This flow would include 1990, a summer characterized as having "impaired water quality" as a result of high algal concentrations. Blue-green algae were also prominent in the algal community in late summer 1990, in contrast to 1991 when flows were much higher. Also at flows above 20,000 cfs, chlorophyll a exceedances frequencies (> 30, > 40, > 60 ug/L) decline dramatically (Figure 6).

A flow of 20,000 cfs corresponds to approximately the 40th percentile of summer flows. This implies that 60 percent of the summers have a flow equal to or less than 20,000 cfs. A summer mean (120 day) flow of 20,000 cfs or lower has a recurrence frequency of 1.7 years (120 Q 1.7) or, in simple terms, has a 60 percent likelihood of occurrence in any given year. Thus, the proposed design flows would range from 4,578 cfs (120 Q 50) to 20,000 cfs (120 Q 1.7) encompassing approximately 58 percent of the summer mean flows likely to occur in a given year.

The next logical step in the goal setting process is to evaluate the "achieveability" of the goal for the water body as a function of management options, taking into consideration both current conditions and conditions (factors) which may change in the future. For lakes, this is most frequently done by predictive modeling. In the case of Lake Pepin, we will use the BATHTUB (MPCA) and WASP (MWCC) models as a basis for predicting the necessary reductions

Figure 6. LAKE PEPIN CHLOROPHYLL a EXCEEDANCE
Frequency vs. Flow. Graphic Development by W.W. Walker, Jr.



in inflow and in-lake total phosphorus necessary to achieve a summer mean chlorophyll a goal of 30 ug/L or lower. This modeling will be conducted over a range in river flows. A detailed presentation of modeling results may be found in Section 6 (WASP modeling results) and Section 7 (BATHTUB modeling results).

Summary

Defining what constitutes "nuisance algal blooms" in Lake Pepin is an important aspect of this study. Nuisance algal blooms were defined and a chlorophyll a goal was developed based on Lake Pepin water quality data in conjunction with:

a) Regional patterns in user perception;

b) Interviews of citizens from the Lake Pepin area; and

c) User perceptions as recorded by CLMP volunteers on Lake Pepin in 1990.

Based on this analysis, a chlorophyll a goal of 30 ug/L as a summer mean has been proposed for Lake Pepin. Further, because of the significance of river flow (water residence time) on the production of chlorophyll a in the lake - lower (4,578 cfs) and upper flow (20,000) limits are proposed for application of the goal. This range would include 58 percent of the summer mean flows of record, ranging from 120 Q 50 (98th percentile) to 120 Q 1.7 (40th percentile). This range of flows will help to focus predictive modeling and the evaluation potential management strategies for the lake.

Achievement of a chlorophyll a goal of 30 ug/L during summers of low to average flow in Lake Pepin should reduce the frequency of nuisance algal blooms and provide perceptibly improved conditions. The chlorophyll a goal, combined with the design flows, will also provide a target for predictive modeling to evaluate necessary reductions in nutrient loading or other management strategies for Lake Pepin.

Bibliography

Carlson, R.E. 1977. A trophic state index for lakes. Limnology and Oceanography 22:361-369.

Harrison, J. 1992. Section 11. Survey of the effects of poor water quality on the economic and community benefits and recreational, sporting and tourism users of the Mississippi River, including Lake Pepin from Red Wing to Alma MN-WI Boundary Area Commission.

Heiskary, S.A. and W.W. Walker, Jr. 1988. Developing phosphorus criteria for Minnesota lakes. Lake and Reserv. Manage. 4:1-10.

Heiskary, S.A. and C.B. Wilson. 1989. The regional nature of lake water quality across Minnesota: an analysis for improving resource management. Minn. Jour. Acad. Sci. 55(1):71-77.

Heiskary, S.A. and C.B. Wilson. 1990. Minnesota Lake Water Quality Assessment Report. MPCA, St. Paul, MN.

Heiskary, S.A. and M. Vavricka. 1993. Section 3: Description of Study Area - Lake Pepin Water Quality, 1976-1991. MPCA. St. Paul, MN.

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

NALMS. 1992. Developing eutrophication standards for lakes and reservoirs. Prepared by Lake Standards Subcommittee. North American Lake Management Society, Alachua, FL. 51 pp.

Walker, W.W. Jr. 1985. Statistical bases for mean chlorophyll a criteria. Lake and Reserv. Manage. 1:57-62.

Appendix

Algorithm for Calculating Chlorophyll a Frequency Distribution as a Function of the Mean Concentration (taken from Walker, 1985).

Table 2.—Statistical models for chlorophyll a variability.

Model Number 1

References:	Walker, 1983b, 1984
Water Bodies:	Vermont Lakes
Data Set:	148 Station-Years
Sampling Freq.:	Weekly
Averaging Period:	June-August
Model:	$SA = .29\ MA^{1.21}$ Based upon log-scale regression of SA on MA ($r^2 = .84$, $SE^2 = .026$, $\log_{10}$ scales)

Model Number 2

References:	Walker, 1980, 1981
Water Bodies:	U.S. Army Corps of Engineer Reservoirs (Nationwide)
Data Set:	258 Station-Years
Sampling Freq.:	3–4 Samples/station-year
Averaging Period:	April–October
Model:	$SL = .62$ Based upon among date variance component of reservoir-mean chlorophyll a values, log scales

Model Number 3

Reference:	Walmsley, 1984
Water Bodies	South African Reservoirs
Data Set:	34 Reservoir-Years
Sampling Freq.:	Weekly, Biweekly, Monthly
Averaging Period:	annual
Model:	$SA = .95\ MA - 1.68$ Based upon regression of SA on MA, linear scales ($r^2 = .85$)

Symbols Defined in Table 3

Table 3.—Algorithm for calculating chlorophyll a frequency distributions.

SYMBOLS:

MA,SA	= arithmetic mean and standard deviation of chlorophyll a (mg/m^3)
ML,SL	= mean and standard deviation of $\log_e$ (chlorophyll a, mg/m^3)
Z	= standard normal deviate (mean = 0, standard deviation = 1)
F(Z)	= integral under standard normal curve from Z to infinity
C	= instantaneous chlorophyll a value (mg/m^3)
V,W,X	= variables used in calculating cumulative distribution function

ALGORITHM:

For a log-normal distribution, the following equations estimate arithmetic moments (MA,SA) from log-scale moments (ML,SL) (Aitchison and Brown, 1963):

$$MA = \exp(ML + .5\ SL^2)$$
$$SA^2 = MA^2\,[\exp(SL^2) - 1]$$

or vice-versa:

$$ML = \log_e(MA) - .5\ SL^2$$
$$SL^2 = \log_e[1 + (SA/MA)^2]$$

The percent of the chlorophyll a distribution exceeding a given chlorophyll a criterion (C^*) can be calculated from:

$$Z = [\log_e(C^*) - ML]/SL$$

$\text{Prob}(C > C^*) = F(Z) \times 100\%$ = percent of samples exceeding C^*

F(Z) can be derived from statistical tables (Snedecor and Cochran, 1972), or estimated from the following empirical equation for the normal distribution:

$$V = \exp(-Z^2/2)/2.507$$
$$W = (1 + .33267\,|Z|)^{-1}$$
$$X = V\,(.4361684\ W - .1201676\ W^2 + .937298\ W^3)$$

If ($Z > 0$) then: $F(Z) = X$
else: $F(Z) = 1 - X$