

The Regional Nature of Lake Water Quality Across Minnesota: An Analysis for Improving Resource Management

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ABSTRACT—The diversity and number of lakes in Minnesota may be better understood by the use of regional characterizations of lake and watershed information. Recent efforts have utilized the ecoregion approach to define seven regions across Minnesota, four of which contain 98 percent of our lake resources. Typical land use patterns vary regionally as do lake water quality patterns. Understanding these patterns will assist lake managers to develop realistic goals and minimize false expectations. Regional assessments facilitate the definition of reasonable goals, expressed in terms of: average summer nutrient concentrations, probability of nuisance conditions (e.g., estimates of algal bloom frequency), and probability of Secchi transparency ranges for lake resource management—for protective as well as restorative purposes. User perceptions of water quality also may be used to define swimmable conditions to assist in goal setting by lake resource managers.

Introduction

As our license plates attest, Minnesota is a Land of Lakes. The frequently conjured idea of pristine lakes inhabited by loons, bountiful populations of walleyes, and canoe traveling visitors, does not reflect the reality of natural variability of lake types, water quality, and lake ecology across the sizable expanse called Minnesota. This diversity of lakes allows for a wide array of recreational and consumptive uses. However, overall lake management can be a very confusing task if regional patterns and limitations are not recognized.

Previous investigators, such as Moyle (1) recognized distinct regional patterns in lake productivity across Minnesota that were generally considered a function of geology, vegetation, hydrology, and land use. These observations have helped to shape fishery and wildlife management in Minnesota. Assessments of data from over 1,000 lakes reaffirm these regional patterns (2, 3).

The most recent assessment (3) has used the ecoregion approach as a basis for evaluating regional patterns. This approach was developed by the U. S. Environmental Protection Agency (EPA) Research Laboratory at Corvallis, Oregon. Ecoregions are areas of relative homogeneity that were developed from mapped information by Omernik (4, 23) based on land use, soils, land and surface form, and potential natural vegetation. Minnesota is characterized by seven ecoregions as delineated by Omernik (Figure 1). Ninety-eight percent of Minnesota's 12,034 lakes (greater than four ha in size) occur in four of the seven ecoregions: Northern Lakes and Forests, North Central Hardwood Forests, Northern Glaciated Plains, and Western Corn Belt Plains. Typical land use varies regionally (3). The Northern Lakes and Forests ecoregion is dominated by forests with some water and

marsh, while the Northern Glaciated Plains and Western Corn Belt Plains are primarily cultivated with some pasture and open land. The North Central Hardwood Forests ecoregion consists of a mixture of various land uses (Table 1).

The objectives of this paper are to examine regional patterns in the trophic state and morphometry of Minnesota's natural lakes and to discuss the implications of these findings for lake management applications.

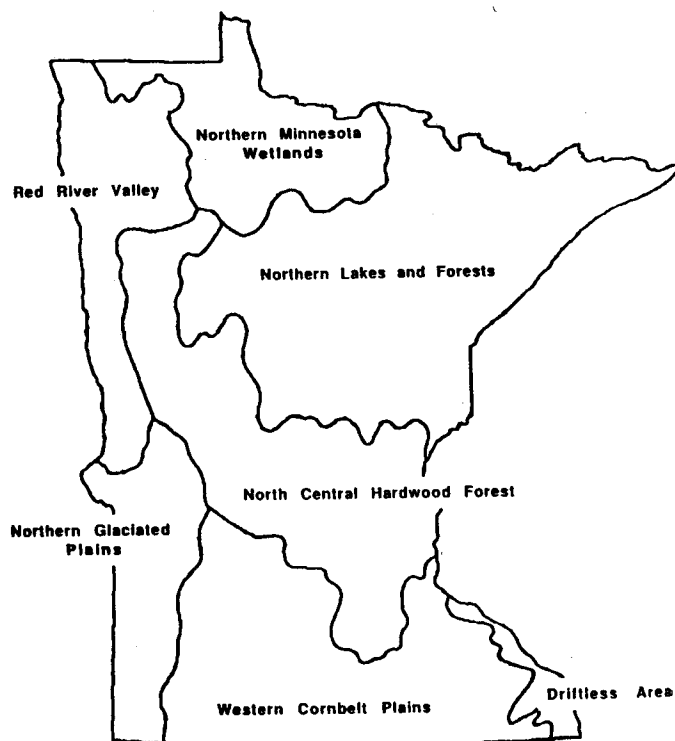


Figure 1. Minnesota's seven ecoregions.

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Table 1. Land use patterns by ecoregion. Percent of 40 acre parcels with land use characteristic. Based on 1968-69 land use data from the Planning Information Center. Interquartile range of land use composition for reference lake watersheds in parenthesis.

Land Use (%)	ECOREGION			
	Northern Lakes and Forests	North Central Hardwood Forests	Western Corn Belt Plains	Northern Glaciated Plains
Cultivated	4.6 (0-1)	49.3 (22-50)	82.9 (42-75)	83.7 (60-82)
Forested	75.2 (54-81)	15.9 (6-25)	3.5 (0-15)	0.7 (0-1)
Water and Marsh	10.6 (14-31)	8.1 (14-30)	1.7 (8-26)	2.9 (8-26)
Pasture and Open	7.3 (0-6)	21.4 (11-25)	10.0 (0-7)	11.4 (5-15)
Developed	1.9 (0-7)	5.2 (2-9)	1.8 (0-16)	1.2 (0-2)

Materials and Methods

Eutrophication response variables analyzed in this paper include total phosphorus (TP), chlorophyll *a*, and Secchi transparency. Total nitrogen and total suspended solids are addressed to a lesser degree.

The primary focus of the analysis has been on average summer surface water concentrations of TP because of its central role in lake eutrophication (11, 25). In-lake TP concentration relationships to algal biomass (chlorophyll *a*) and transparency have been well-documented elsewhere (5, 6). Analytical results described in this paper were obtained by generating summary statistics from each lake data set. Methods have been described in greater detail elsewhere (3, 7).

Two data bases will be used to describe the regional patterns in trophic status and morphometry. The first data base consists of data from approximately 1,400 lakes, collected between 1977 to 1987 and accessible through STORET. STORET is U.S. EPA's national water quality data base. The lake data are distributed among the four ecoregions as follows: Northern Lakes and Forests - 793 lakes (56%), North Central Hardwood Forests - 533 lakes (38%), Western Corn Belt Plains - 58 lakes (4%), and Northern Glaciated Plains - 21 lakes (2%). Data included here were obtained by the Minnesota Pollution Control Agency (MPCA), Metropolitan Council and others (7). A majority of the Secchi transparency data was obtained through MPCA's Citizen Lake Monitoring Program (CLMP). This data base will be referred to as the statewide data base.

The second data base consists of approximately 90 reference lakes distributed among the four ecoregions that contain 98 percent of Minnesota's lakes by number. These lakes were sampled between 1985 and 1987. Regional reference sites (lakes) have watersheds characterized by regionally predominant landscapes that are minimally impacted by point and nonpoint sources of pollution (8). Factors such as maximum depth, surface area, fishery classifications, and recommendations from Minnesota Department of Natural Resources (MDNR) area fishery managers were instrumental in selecting these lakes. This data base will be referred to as the reference lakes. Details on sampling, water quality analysis, and data analysis are given in previous publications (3, 7). In addition, CLMP data collected by 176 participants in 1987 were evaluated in order to identify relationships between Secchi transparency and subjective perceptions of the "recreational suitability" and "physical appearance" of the water. Recreational suitability classes ranged from "beautiful" (class 1) to "no recreation possible" (class 5). Physical appearance classes ranged from

"crystal clear water" (class 1) to "severe nuisance algae levels" (class 5). Participants rated these conditions on a survey form (7) when they made their Secchi transparency measurements. This resulted in over 2,200 paired observations of Secchi transparency and user perception measures. Ecoregional patterns in user perception were also evaluated (7).

Results

The statewide data base provides sufficient information to examine general patterns of trophic status and morphometry between the regions. In terms of morphometry the lakes of the Northern Lakes and Forests and North Central Hardwood Forests are rather similar (Figure 2). Typical (defined as the 25th to 75th percentile) surface areas range between 40-280 ha, while maximum depths typically range between 6-17 m with medians, of 11 m and 10 m, respectively (Figure 2). In contrast, the two agricultural ecoregions — Western Corn Belt Plains and Northern Glaciated Plains, exhibit somewhat larger and shallower basins, typically 60-300 ha in size and 2-6 m in depth. The parameters most frequently used to assess the trophic status of lakes are total phosphorus (TP), chlorophyll *a* and Secchi transparency (7, 11). Other variables such as total nitrogen (TN), color and suspended solids are also important (10, 19) for characterizing a lake's condition. Table 2 summarizes average summer TP concentrations and Secchi transparency for each of the four ecoregions based on the statewide data base. The TP and Secchi transparency data reveal overlap in trophic status among these regions. However, if we focus on values in the typical range (25th-75th percentile), we note three rather distinct classes or regions (e.g., Northern Lakes and Forests (forested), North Central Hardwood Forests (transition) and the two agriculture-dominated ecoregions).

Data from the reference lakes are useful for characterizing regional patterns of lake trophic status in more detail. These data also provide insight as to what can reasonably be expected in terms of trophic status for lakes in each of the ecoregions. Boxplots of average summer TP, chlorophyll *a*, Secchi transparency and TN:TP ratios are presented in Figure 3.

Northern Lakes and Forests

Typical average summer trophic conditions can be summarized as follows: TP - 14 to 27 $\mu\text{g/L}$, mean chlorophyll *a* - less than 10 $\mu\text{g/L}$, maximum chlorophyll *a* - less than 15 $\mu\text{g/L}$, and Secchi transparency - 2.5 to 4.5 m. Total suspended solids (TSS) concentrations are low, typically less than 2 mg/L. The lakes are typically phosphorus limited with TN:TP ratios ranging from about 25:1 to 35:1. TN:TP ratios >17:1 are

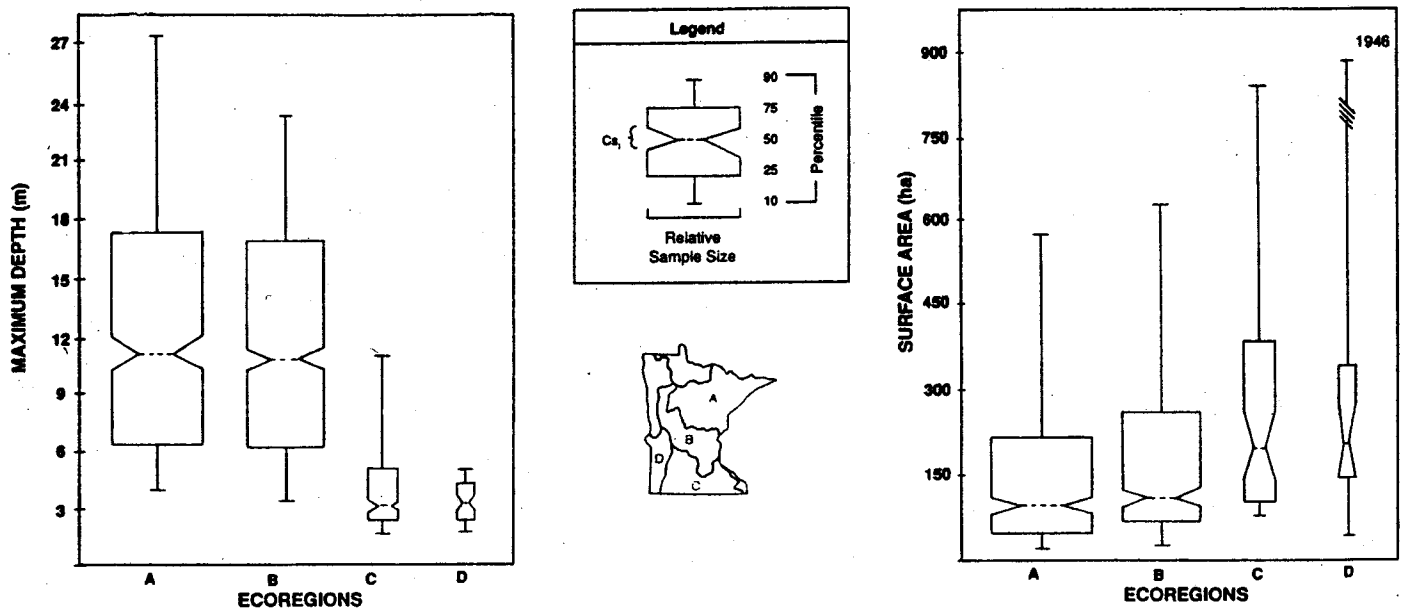


Figure 2. Box plots of surface area and maximum depth by ecoregion. Taken from statewide data base ($n \approx 1,400$ lakes). Ninety-five percent confidence interval (Cs_p) of the median is calculated as follows: $Cs_p = 1.7 (1.25 I / 1.35 n)$ with I = interquartile range and n = number of observations. A = Northern Lakes and Forests, B = North Central Hardwood Forest, C = Western Corn Belt Plains, D = Northern Glaciated Plains.

Table 2. Percentile distribution of summer mean total phosphorus and Secchi transparency by ecoregion. Derived from the statewide data base.

		ECOREGION			
		Northern Lakes and Forests	North Central Hardwood Forests	Western Corn Belt Plains	Northern Glaciated Plains
Percentile					
Total Phosphorus ($\mu\text{g/L}$)	10th	10	22	57	116
	25th	16	35	97	140
	50th	24	60	135	179
	75th	33	118	220	404
	90th	49	253	296	487
	No. of Lakes	621	408	54	19
Secchi (m)	10th	1.1	0.5	0.3	0.3
	25th	1.8	0.8	0.3	0.3
	50th	2.7	1.4	0.5	0.6
	75th	3.9	2.2	0.9	1.2
	90th	4.6	3.1	1.2	1.8
	No. of Lakes	447	491	47	15

generally considered phosphorus limited while ratios less than 10:1 indicate nitrogen limitation (9, 10, 11). Thermal stratification during the summer months is common in many of these lakes. In general, these lakes may be considered mesotrophic to mildly eutrophic in nature based on Carlson's Trophic State Index (7, 24).

North Central Hardwood Forests

A wider range in values is found (Figure 3). Typical average summer values are as follows: TP - 23 to 50 $\mu\text{g/L}$, mean chlorophyll *a* - 5 to 22 $\mu\text{g/L}$, maximum chlorophyll *a* - 7 to 37 $\mu\text{g/L}$ and Secchi transparency - 1.5 to 3.2 m. TSS concentrations are typically less than 4 mg/L. These lakes also tend

to be phosphorus limited with typical average TN:TP ratios from 25:1 to 37:1. Thermal stratification is also common in many of the lakes in this region. In terms of trophic state, these lakes would generally be considered eutrophic (7, 24).

Western Corn Belt Plains

Typical average summer trophic conditions can be summarized as follows: TP - 65 to 150 $\mu\text{g/L}$, mean chlorophyll *a* - 30 to 80 $\mu\text{g/L}$, maximum chlorophyll *a* - 60 to 140 $\mu\text{g/L}$, and Secchi transparency - 0.5 to 1.0 m. Average summer TSS concentrations are higher, typically ranging from 7-18 mg/L. Inorganic suspended solids account for about 40 to 50 percent of the TSS concentrations in these lakes based

on data collected from the reference lakes. The somewhat low TN:TP ratios, 15:1 to 25:1 suggest the potential for nitrogen limitation. Those lakes with total phosphorus concentrations less than 65 $\mu\text{g/L}$ are among the few which are deep enough to maintain stratification throughout the summer. In general, lakes in this region can be characterized as eutrophic to hypereutrophic (7, 24).

Northern Glaciated Plains

Typical average summer trophic conditions can be summarized as follows: TP - 130 to 250 $\mu\text{g/L}$, mean chlorophyll *a* - 30 to 55 $\mu\text{g/L}$, maximum chlorophyll *a* - 40 to 90 $\mu\text{g/L}$, and Secchi transparency - 0.3 to 1.0 m. TSS concentrations are high, typically ranging from about 10 to 30 mg/L. Inorganic suspended solids may account for greater than 50 percent of the TSS concentrations in these lakes. The low TN:TP ratios in these lakes, 5:1 to 15:1, suggest that nitrogen limitation is common in these lakes. No lakes in this ecoregion were found to retain thermal stratification during the summer and all could be considered hypereutrophic (7, 24).

Discussion

Prior to the development of the ecoregion framework, the State was unable to: provide valid yardsticks for evaluating lake water quality, define user perceptions of water quality, develop reasonable criteria for protecting water quality or set attainable goals for improving water quality. The data sets that were developed to evaluate the applicability of the ecoregion framework have allowed the State to address each of these issues.

The development of phosphorus criteria to protect water quality or for use as restoration goals requires a determination of the "most sensitive use" of a lake. As Vighi and Chiaduni (12) note "...the criteria for nutrient reduction should be set according to the intended use of a particular water body and also according to ecological reality." In this context, we have defined the "most sensitive use" of a lake as that use (or uses) which can be impacted or even lost as a result of a change (increase) in the trophic status of the lake. In the case of drinking water supplies, eutrophication can increase water treatment costs and contribute to taste and odor problems

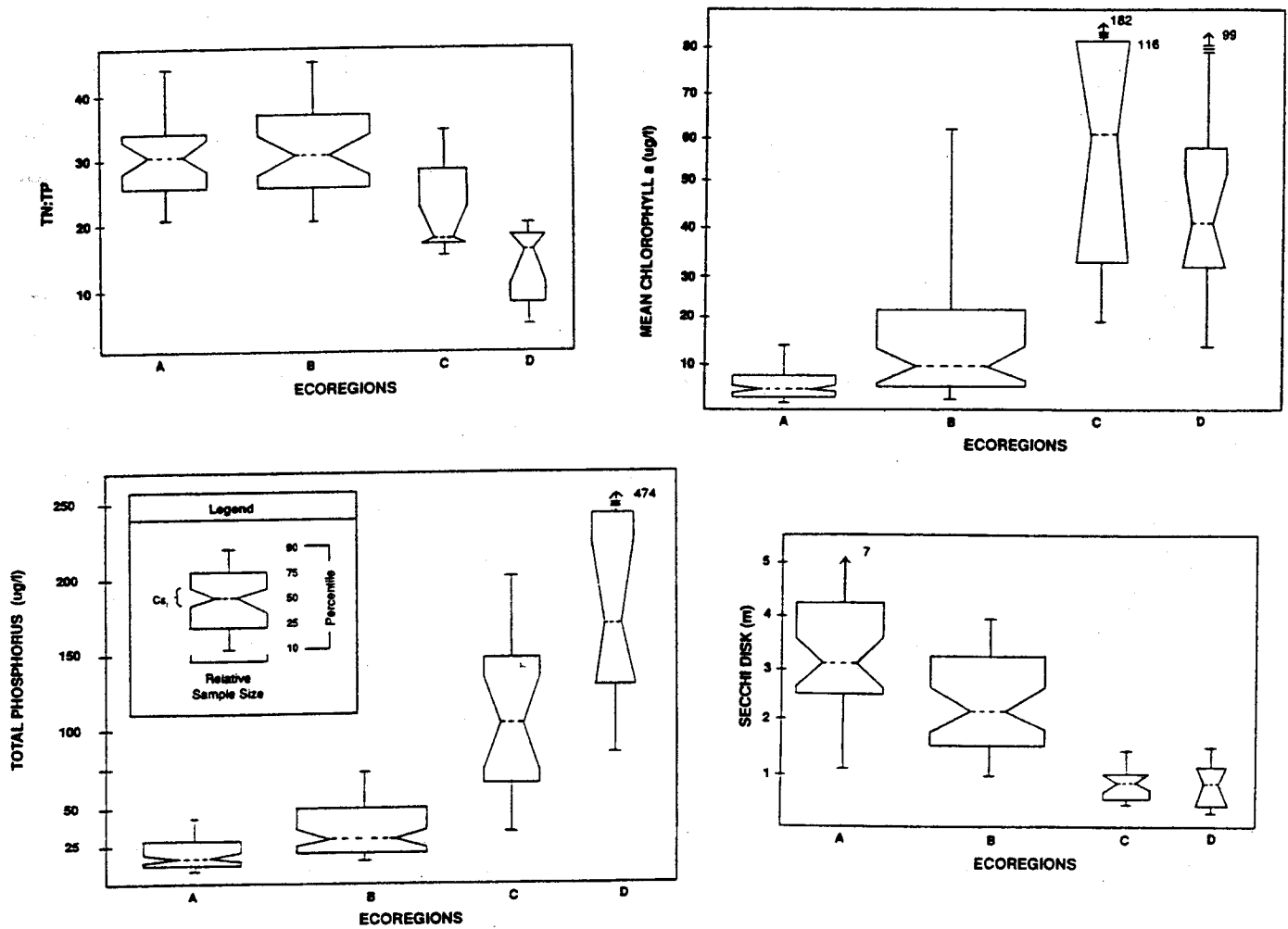


Figure 3. Box plots of total phosphorus, chlorophyll *a*, Secchi transparency, and TN:TP ratios by ecoregion. Based on reference lakes. A = Northern Lakes and Forests, B = North Central Hardwood Forests, C = Western Corn Belt Plains, D = Northern Glaciated Plains.

(13). In the case of a cold water fishery, increased nutrient loading will result in a reduction of oxygen in the hypolimnion (14), and die-offs of cold water species may occur as these populations are driven into warmer surface waters (15).

In this respect, we have used the ecoregion framework as a means for gaining a regional perspective on these issues. Table 3 summarizes the most sensitive uses of lakes by ecoregion. The corresponding phosphorus criteria are intended to protect those uses. The criteria take into account regional differences in values from minimally impacted lakes and citizen (CLMP) user perceptions (7). The emphasis of the discussion has been placed upon protection. For restoration purposes, these criteria can serve as goals. A discussion for each ecoregion follows.

Northern Lakes and Forests

Lake protection is the primary goal so that presently low TP levels are maintained. This is very important in lakes that support a cold water fishery and require anoxic hypolimnion. Moyle (1) suggested TP levels below 20 $\mu\text{g/L}$. Recent literature (16) and data from the ecoregion reference lakes (7) indicate that levels less than or equal to 15 $\mu\text{g/L}$ would be feasible and desirable for lakes supporting a cold water fishery. Oligotrophic conditions (TP less than 15 $\mu\text{g/L}$) are also desirable for lakes (including mine pit lakes) used as drinking water supplies in this region. This is particularly important for hypolimnetic water supply withdrawals, because taste and odor problems can result under anoxic conditions.

Lake users in the Northern Lakes and Forests ecoregion generally have high expectations regarding water quality (7, 17). For example, in 75 percent of the observations ranked as "impaired" or "no swimming" the corresponding Secchi transparency was 2 m or less (Figure 4). In general, high transparency and very low algal concentrations are desired by lake users in this region. A TP concentration less than 30 $\mu\text{g/L}$ appears reasonable based on Table 2 and Figure 3. This level should yield transparency above 2 m over 80 percent of the summer and chlorophyll *a* concentrations below 20 $\mu\text{g/L}$ over 90 percent of the summer (8). Chlorophyll *a* concentrations from 10 to 20 $\mu\text{g/L}$ would be considered "mild algal blooms," while concentrations greater than 20 $\mu\text{g/L}$ would be considered "nuisance blooms" (18).

Table 3. Most sensitive lake uses by ecoregion and corresponding phosphorus criteria (7).

Ecoregion	Most Sensitive Uses	P Criteria
Northern Lakes and Forests	● drinking water supply	< 15 $\mu\text{g/L}$
	● cold water fishery	< 15 $\mu\text{g/L}$
	● primary contact recreation and aesthetics	< 30 $\mu\text{g/L}$
North Central Hardwood Forests	● drinking water supply	< 30 $\mu\text{g/L}$
	● primary contact recreation and aesthetics	< 40 $\mu\text{g/L}$
Western Corn Belt Plains	● drinking water supply	< 40 $\mu\text{g/L}$
	● primary contact recreation and aesthetics- (full support)	< 40 $\mu\text{g/L}$
	● recreation and aesthetics (partial support)	< 90 $\mu\text{g/L}$
Northern Glaciated Plains	● recreation and aesthetics (partial support)	< 90 $\mu\text{g/L}$

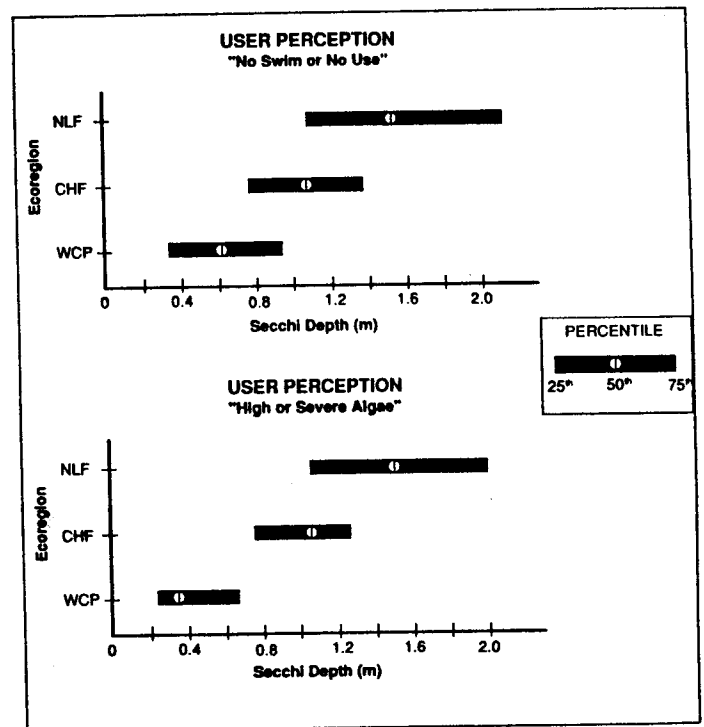


Figure 4. 1987 Citizens Lake Monitoring Program user perceptions of recreational suitability and physical appearance classes. Plots are presentations of typical (25th-75th percentile, and median) user perceptions for recreation suitability classes 4 and 5 ("no swim or no use") and physical appearance classes 4 and 5 ("high or severe algae") for Northern Lakes and Forests (NLF), North Central Hardwood Forests (CHF), and Western Corn Belt Plains (WCP).

In general, lakes in this ecoregion can be expected to exhibit noticeable changes in transparency and chlorophyll *a* concentrations with small changes in in-lake phosphorus concentrations. A notable exception will be highly colored lakes (>50 platinum-cobalt units based on the reference lakes) which will deviate from expected TP/chlorophyll *a*/Secchi disk models (19).

North Central Hardwood Forest

A wide range in trophic status can be expected in this region (Table 2). In terms of TP concentrations, this region has a much more diverse population of lakes than the Northern Lakes and Forests ecoregion. The lakes of the North Central Hardwood Forests are highly used recreationally, both for fishing and primary contact recreation.

Lake users in this region generally have high expectations regarding lake water quality (7, 17). In 75 percent of the CLMP observations ranked as "impaired" or "no swimming" the corresponding Secchi transparency was 1.5 m or less (Figure 4). Thus, to maintain swimmable conditions in lakes of this region, it will be desirable to keep transparency above 1.5 m and minimize algal blooms for a majority of the summer.

Based on the "typical" TP concentrations in the reference lakes and the perceptions of lake users, a TP criteria level of 40 $\mu\text{g/L}$ is suggested. At or below this concentration, transparency should remain above 1.5 m over 70 percent of

the summer and "nuisance" algal blooms (chlorophyll *a* L. It will be important to protect the water quality of these lakes as they are the focus of much recreational activity. They may be viewed as having good water quality relative to other lakes in this region, considering the wide range in TP concentrations (Table 2). Increases in average summer TP concentrations in lakes currently supporting swimmable uses should be avoided. In particular, lakes used for drinking water supply should maintain the lowest in-lake TP concentration reasonable for lakes in this region. For the North Central Hardwood Forests, this corresponds to 25 to 30 $\mu\text{g/L}$. At concentrations above this range the severity and frequency of nuisance algal blooms can be expected to increase dramatically (7).

Reducing the external TP load to lakes in the North Central Hardwood Forests should be beneficial for a majority of the lakes, in particular, those with $\text{TN:TP} > 17$ and those that do not experience substantial internal recycling of nutrients during the growing season. Based upon citizen perceptions of water quality, it appears that attaining a TP concentration of less than 50 $\mu\text{g/L}$ may be necessary to achieve perceptible changes in water quality and to achieve at least "partial support" of swimmable use (7). Lakes that thermally stratify during the summer will tend to be more responsive to reductions in the external TP load in terms of reduced algal abundance (as measured by chlorophyll) and improved transparency. However, additional remedial measures may be necessary to achieve TP levels approaching 50 $\mu\text{g/L}$ in shallow (e.g., maximum depth less than 8 m and a mean depth less than 4 m), well-mixed lakes because of internal nutrient recycling processes (26). However, there will be lakes, particularly shallow lakes, that will likely have TP concentrations that remain above 50 $\mu\text{g/L}$ because of background conditions (e.g. average inflow TP concentrations, water flow quantities, and lake morphometry). In view of the diversity of TP concentrations in this region, analysis of subregional patterns as noted by Omernik *et al.* (25) would be a logical next step and may allow for refinement of the criteria.

Western Corn Belt Plains and Northern Glaciated Plains

The lakes in these two regions range from mildly eutrophic to hypereutrophic, with the majority being hypereutrophic. The lakes in the Western Corn Belt Plains with TP concentrations less than 50 $\mu\text{g/L}$ tended to be among the few deep enough to thermally stratify. No monitored lakes in the Northern Glaciated Plains were deep enough to retain thermal stratification during the summer. The predominant uses of lakes in these regions are related to fishing and wildlife habitat.

The high levels of TP in these regions commonly are associated with severe nuisance algal conditions and/or extensive weed growth. In some instances, high TSS concentrations may control the amount of algae or weed growth. Blue-green algae frequently dominate the algal community. Reasonable management goals for these lakes should focus on reduction of severe nuisance bloom conditions. The literature suggests that reducing TP concentrations below 100 $\mu\text{g/L}$ may serve to reduce the frequency of algal blooms (20, 21). Also, TP reductions which lead to increases in the TN:TP ratio may shift algae from blue-green to green forms (22).

Based on limited 1987 CLMP data from the Western Corn Belt, 50 to 60 $\mu\text{g/L}$ would be necessary. This concentration range is likely achieved by less than 10 percent of the lakes in the Western Corn Belt Plains (Table 2). A more reasonable goal is in the 70 to 90 $\mu\text{g/L}$ range. TP concentrations in this range should result in transparency greater than 0.5 m over 80 percent of the summer, and very severe algal blooms (chlorophyll *a* > 60 $\mu\text{g/L}$) should occur less than 25 percent of the summer (7).

Lakes in these two regions with TP concentrations less than 90 $\mu\text{g/L}$ should be protected from further increases in phosphorus loading. It is likely that less than 10 percent of the lakes in these two regions exhibit TP concentrations in this range (Table 2). These lakes are valuable resources and should be managed as such. In particular, those with TP concentrations less than 50 $\mu\text{g/L}$ provide opportunities for primary contact recreation not realized in most Western Corn Belt Plains or Northern Glaciated Plains lakes.

Because of the shallowness of the lakes, natural fertility of the soils, and high percentage of agricultural land use within their watersheds, reasonably attainable TP (average summer) levels may not be substantially less than 100 $\mu\text{g/L}$ in many of the lakes in these two regions. Unless average TP concentrations can be driven below about 100 $\mu\text{g/L}$, it may be difficult to see improvements in water quality in terms of improved transparency, reduced chlorophyll *a* concentrations, or reductions in the frequency of nuisance blooms (18).

Reducing the external phosphorus load to these lakes may be effective if the external load is large relative to the internal nutrient recycling process. However, the low TN:TP ratios in these lakes suggest that very large reductions in TP may be necessary.

Conclusions

The concept that lake and land resources vary regionally has been used for some time in resource management activities in Minnesota. Regional patterns in lake water quality, morphometry, and watershed characteristics have been redefined for Minnesota based on the ecoregion approach. These regional assessments facilitate the definition of reasonable goals expressed in terms of average summer nutrient concentrations, probability of nuisance conditions (e.g., estimates of algal bloom frequency), and probability of Secchi transparency ranges for lake resource management—for protective as well as restorative purposes. User perceptions of water quality may also be used to define swimmable conditions to assist in goal setting by lake resource managers. A logical next step in these regional assessments is to examine lake trophic status within subregions, particularly the North Central Hardwood Forests. This may allow for a refinement in the regional TP criteria.

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