ANALYSIS OF REGIONAL PATTERNS IN LAKE WATER QUALITY: USING ECOREGIONS FOR LAKE MANAGEMENT IN MINNESOTA

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ABSTRACT

Developing lake management strategies that have utility across diverse geographic areas is difficult. For example, with over 12,000 lakes in Minnesota, determining carrying capacities, restoration goals, and lake protective standards cannot be practically made on a lake-by-lake basis. In light of this, the aquatic ecoregion approach was employed to assess regional patterns in watershed characteristics and inlake parameters such as phosphorus concentration, Secchi transparency, and lake mixing pattern. This approach defined seven distinct ecoregions, of which, the following four contain the majority of lakes in Minnesota: Northern Lakes and Forest (NLF), North Central Hardwood Forests (CHF), Western Corn Belt Plains (WCP) and the Northern Glaciated Plains (NGP). Analysis of total phosphorus data from approximately 1,100 lakes by ecoregion resulted in the following median epilimnetic concentrations: NLF – 23 μg P/L, CHF – 50 μg P/L, WCP – 121 μg P/L, and NGP – 176 μg P/L. Lake mixing patterns may be a further basis for organizing the data. These analyses indicate that the aquatic ecoregion approach is a valid method for grouping lake data and identifying spatial patterns of lake characteristics. Further, for Minnesota, this analysis indicates that no single total phosphorus concentration can be used as a basis for setting standards across Minnesota because of its tremendous diversity of lakes and attainable trophic states. Lake management schemes based on the ecoregion analysis presented.

INTRODUCTION

With over 12,000 lakes in Minnesota, the determination of lake management strategies, such as carrying capacities, restoration goals, and lake protective standards cannot be made practically on a lake-by-lake basis. In light of this limitation, we employed a regional approach to examine spatial patterns in ambient phosphorus levels, Secchi transparency, and lake morphometry. Defining such patterns facilitates the development of lake management strategies across the State of Minnesota. This case provides a good example of a regional aspect of lake management that may prove useful in many regions.

Previous investigators, such as Moyle (1956), 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. A more recent assessment of data from over 1,000 lakes reaffirms these regional patterns (Heiskary, 1985). This assessment revealed a wide spectrum in trophic state for Minnesota lakes, ranging from oligotrophic to hypereutrophic.

The main premise of this paper is that there are regional patterns of lake productivity or trophic status. These productivity levels vary and are a function of the combined interactions of climate, topography, soil, geology, land use, and other factors. In addition, lake morphometric characteristics that tend to have regional patterns may act to modify trophic levels and determine trophic conditions without any significant human influence. Recognition of these regional patterns is essential for effective lake management.

This paper focuses on total phosphorus because of its central role in controlling the lake fertility and availability of data. Also, numerous investigations have defined empirical relationships that relate other measures of trophic state, such as such as Secchi transparency and chlorophyll *a*, to inlake total phosphorus. An analysis of spatial patterns of Secchi transparency was included as an additional basis for relating patterns in trophic status to the layman and lake manager.

DESCRIPTION OF STUDY AREA

Aquatic ecoregions are areas of relative homogeneity that were developed from mapped information by Omernik (1987). The seven ecoregions defined for Minnesota are based on land use, soils, land and surface form, and potential natural vegetation (Fig. 1). The ecoregions provide a means to group various land and surface water characteristics. For example, streams draining watersheds within an ecoregion are believed to exhibit characteristics such as physical habitat, hydrology, water chemistry, and biotic communities more similar to each other than to streams from other ecoregions.

Ninety-eight percent of Minnesota's 12,034 lakes occur in four of the seven ecoregions: Northern Lakes and Forests, North Central Hardwood Forest, Northern Glaciated Plains, and Western Corn Belt Plains. Land use varies regionally. 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 Forest ecoregion consists of a mixture of various land uses (Table 1).

METHODS AND DATA ANALYSIS

Data from approximately 1,100 lakes collected between 1980 and 1985 were used in this assessment. Total phosphorus data were collected by the Minnesota Pollution Control Agency (80 percent), Metropolitan Council (9 percent), U.S. Forest Service (6 percent), and "others" (5 percent). The "others" category generally included persons collecting data in conjunction with Clean Lakes projects. The majority of the Secchi data was obtained through the Pollution Control Agency's Citizen Lake Monitoring Program (Minnesota Pollution Control Agency, 1986).

Data were generally collected during the open water season (May–November). Sampling stations were located at midlake at the greatest lake depth. Samples were acid preserved at the time of collection (Minn. Pollut. Control Agency) or within six hours of collection (Metropolitan Council and U.S. Forest Service). The most commonly employed methods of analyzing total phosphorus were colorimetric, automated block digester for Minnesota Pollution Control Agency, acid digestion, and modified ascorbic acid reduction method for the Metropolitan Council and U. S. Forest Service (Methods 365.4 and 365.3, respectively, *in* U.S. Environmental Protection Agency, 1979). Detection limits were 10 µg/L for Minnesota Pollution Control Agency and Metropolitan Council and 1 µg/L for U.S. Forest Service. Mean precision for the Minnesota Pollution Control Agency data was 4.9 µg/L based on 10 percent duplicate analysis. Metropolitan Council reported a mean standard deviation of 7 µg/L based on samples collected in

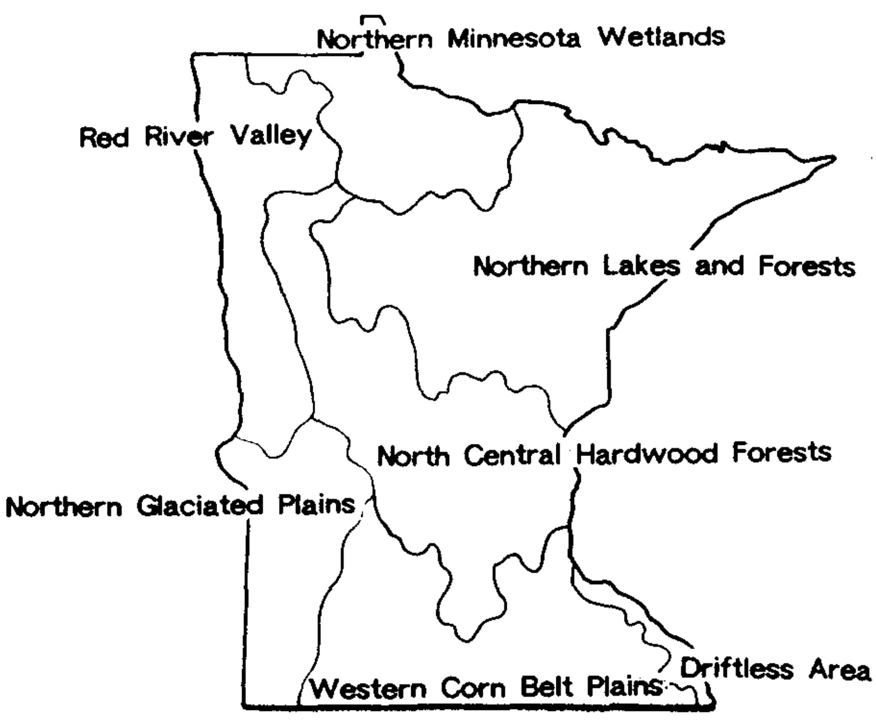

Figure 1.–Aquatic ecoregions of Minnesota.

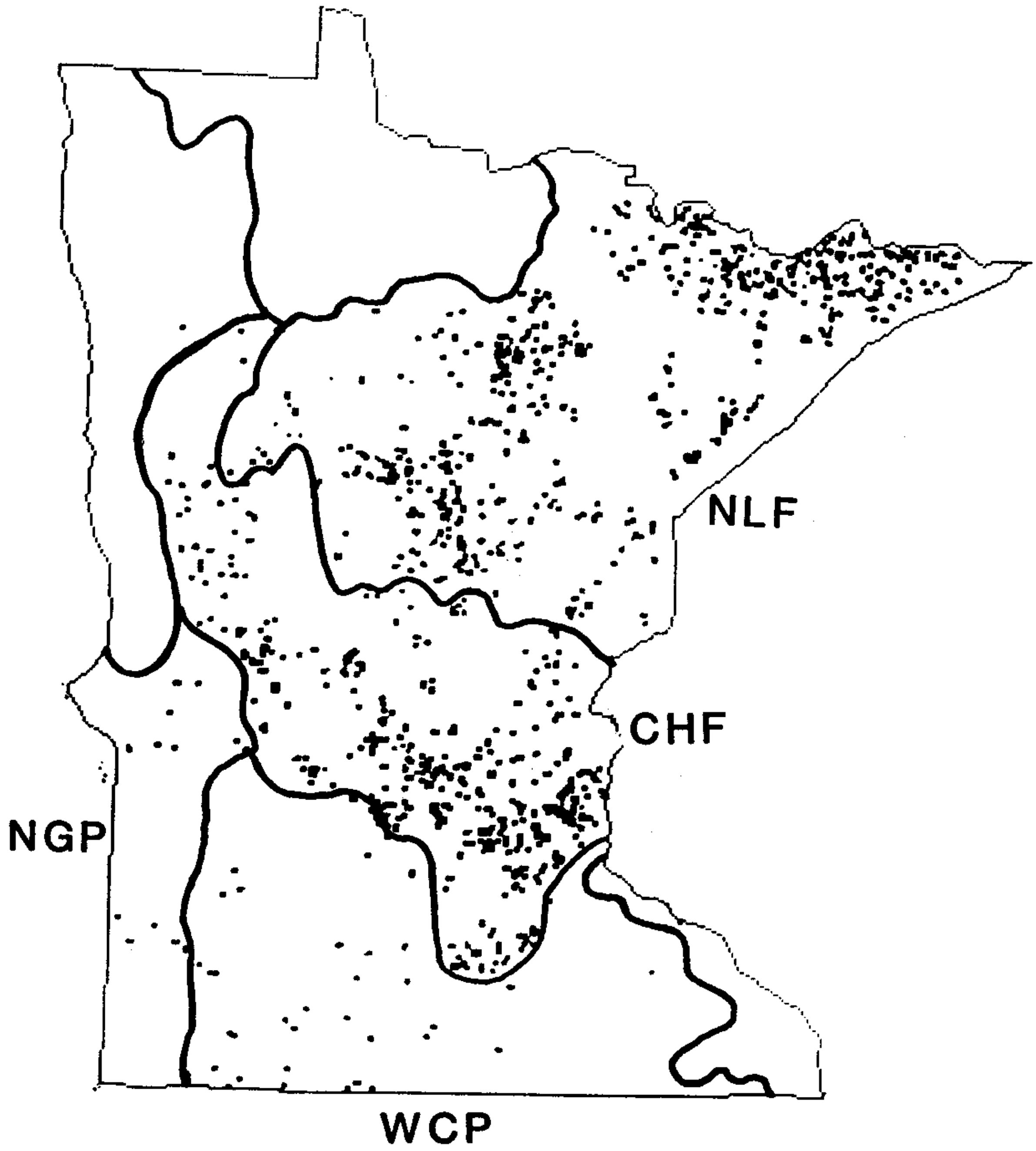

Figure 2.—Statewide availability of total phosphorus data by ecoregion.

interval) (Reckhow and Chapra, 1983). In general, this implies oligo- to mesotrophic conditions for a majority of the lakes in this ecoregion. Although total phosphorus values range up to 96 μg/L in this region, 90 percent of the lakes exhibit concentrations less than 45 μg/L. Median Secchi transparency for lakes in the Northern Lakes and Forests is 2.7 meters, implying mesotrophic conditions. The lakes in this ecoregion are rather deep and small, exhibiting a median Z_{max} of 11 meters and median A_o of 95 ha. Furthermore, the majority of the lakes are thermally stratified during the summer. A comparison of well-mixed to stratified lakes for the Northern Lakes and Forests reveals slightly higher total phosphorus levels in the well-mixed lakes (Table 2).

The ecological classification of a lake describes the type of fish population likely to be present if no fisheries management were undertaken (Scidmore, 1970). The lakes of the Northern Lakes and Forests would typically be classified as bass-panfish-walleye or walleye (Table 3). A small percentage of the lakes in this region support a coldwater fishery.

Table 1. Land use patterns by ecoregion. Percent of 40 acre parcels with land use characteristic. Based on 1968-69 land use data (Plann. Infor. Center, 1986).

	ECOREGION			
LAND USE (%)	NORTHERN LAKES FORESTS	NORTH CENTRAL HARDWOOD FORESTS	NORTHERN GLACIATED PLAINS	WESTERN CORN BELT PLAINS
Cultivated	4.6	49.3	83.7	82.9
Forested	75.2	15.9	0.7	3.5
Water and Marsh	10.6	8.1	2.9	1.7
Pasture and Open	7.3	21.4	11.4	10.0
Developed	1.9	5.2	1.2	1.8
Extractive	0.4	0.1	0.1	0.1

triplicate. U.S. Forest Service reported a precision of 3 μg/L. Accuracy, expressed as percent recovery, was 104 percent at a concentration of 20 μg/L and 101 percent at a concentration of 40 μg/L for Minnesota Pollution Control Agency data. The Forest Service reported 98-99 percent recovery. Accuracy was not reported for Metropolitan Council data.

The initial data analysis was conducted in STORET, U.S. Environmental Protection Agency's national water quality data bank. Mean epilimnetic total phosphorus concentrations (surface to a depth of 2 meters) were calculated for each lake. Although no seasonal limitations were placed on the data, the mean phosphorus concentrations reported reflect the open water season because of the aforementioned sampling periods. Mean Secchi measurements were calculated for each lake with available data. The calculations were limited to data collected during the "summer period" defined as June 24 through September 11. Lakes with major point source discharges in their watershed (for example, wastewater treatment plants) were eliminated from the analysis.

Previous investigators recognized that lake morphometry, in addition to watershed factors, plays an important role in determining lake productivity (Rawson, 1955; Ryding and Forsberg, 1980; Riley and Prepas, 1985). An analysis of Minnesota Pollution Control Agency data collected in 1985 indicated, in general, that lakes with a maximum depth less than 10 meters and a ratio of surface area (A_o) to maximum depth (Z_{max}) greater than 5:1 (ha/m) are usually well mixed or weakly stratified. Lakes not meeting these criteria are usually stratified. The criteria, though somewhat arbitrary, were used for further classification in the data base.

RESULTS AND DISCUSSION

Total phosphorus data were available for 1,062 lakes representing about 9 percent of Minnesota's lakes by number or 30 percent by surface area. Mean total phosphorus concentrations ranged from 2 μg/L to 454 μg/L with a statewide median of 31 μg/L. Relatively good geographic coverage was obtained for the state (Fig. 2). The number of lakes and percentage of lakes sampled in each ecoregion were as follows: Northern Lakes and Forests – 623 (11 percent), North Central Hardwood Forest – 382 (8 percent), Western Corn Belt Plains – 40 (7 percent), and Northern Glaciated Plains – 17 (2 percent).

The lakes of the Northern Lakes and Forests are characterized by very low mean total phosphorus concentrations (Fig. 3), exhibiting a median of 23 μg/L ±2 (approximation of 95 percent confidence

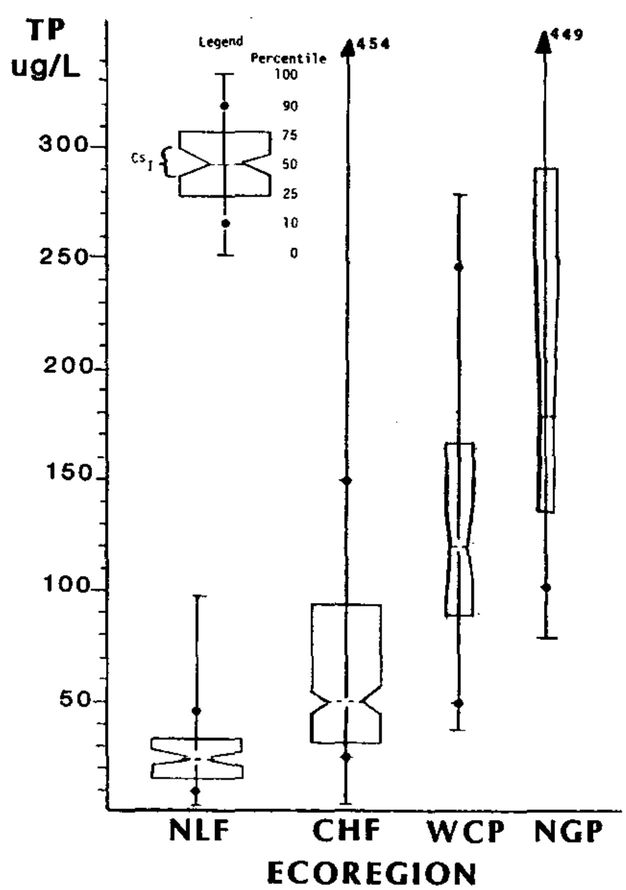

Figure 3.—Box plot of total phosphorus concentrations by ecoregion. Bar width reflects number of lakes (n). Ninety-five percent confidence interval (CsI) of the median is calculated as follows: Cs_I = 1.7 (1.25 I/1.35 n); (Reckhow and Chapra, 1983).

Table 2. Data base summary by ecoregion.

CHARACTERISTICS	ECOREGION NLF	CHF	WCP	NGP
a) Number of lakes total:	5,558	4,765	577	855
b) Number of lakes sampled:	623	382	40	17
c) Median surface area: (ha)				
all	95	107	189	195
well mixed	93	107	209	195
stratified	106	120	108	—
d) Median maximum depth: (m)	11.0	10.4	2.7	3.1
e) Mixing status:				
well mixed (%)	34	39	90	100
stratified (%)	66	61	10	0
f) Median Secchi disk: (m)				
all	2.7	1.5	0.5	0.8
well mixed	1.5	1.0	0.5	0.8
stratified	3.1	1.8	1.4	—
g) Median total phosporus: (ug/L)				
all	23	50	121	177
well mixed	29	77	132	177
stratified	21	43	56	—

The North Central Hardwood Forests lakes are characterized by a very large total phosphorus range with concentrations from 2 μg/L to 454 μg/L (Fig. 3); however, 90 percent of the lakes exhibit concentrations below 150 μg/L. Concentrations above this level are likely a function of extensive urban or agricultural runoff or both. The median total phosphorus concentration is 50 μg/L ±5, suggesting that the majority of the lakes are eutrophic in nature. Median Secchi transparency is 1.5 meters also suggesting eutrophic conditions. These lakes, as with the Northern group lakes, are usually deep and rather small (Table 2) and the majority are considered stratified. A comparison between well-mixed and stratified lakes in the North Central Hardwood Forest ecoregion reveals a large difference in median total phosphorus with concentrations of 77 μg/L and 43 μg/L, respectively. Transparency also followed this pattern with medians of 1.0 meter and 1.8 meters, respectively. The ecological classification of the lakes in the North Central Hardwood Forest is typically bass-panfish-walleye followed by winterkill-roughfish (Table 3).

The lakes of the Western Corn Belt Plains are characterized by significantly higher total phosphorus levels than the North Central Hardwood Forest ecoregion (95 percent level), with a median of 121 μg/L ±19. These total phosphorus levels imply that the majority of lakes in this ecoregion are eutrophic to hypereutrophic in nature. Median Secchi transparency is correspondingly low at 0.5 meters. In general, these lakes are quite shallow (median Z_{max} = 2.7 meters) and have larger surface areas than lakes in the Northern Lakes and Forest and North Central Hardwood Forest ecoregions. These factors account for the well-mixed conditions noted in the majority of these lakes (Table 2).

A comparison of well-mixed to stratified lakes in the Western Corn Belt Plains reveals a large difference in total phosphorus concentrations with median measurements of 132 μg/L and 56 μg/L respectively. Median Secchi transparencies differed markedly also, with values of 0.5 meters and 1.4 meters, respectively. These differences should be viewed with caution, though, as only 4 of the 40 lakes sampled in this region are considered stratified. The predominant ecological classification for lakes in the Western Corn Belt Plains is winterkill-roughfish (Table 3). A smaller percentage are classified as bullhead-panfish or bass-panfish-walleye.

Table 3.—Ecological classification of all lakes greater than 60 hectares (approximately 1,800 lakes) within 4 Minnesota ecoregions. Compiled from data in Borchert et al. 1970.

ECOLOGICAL TYPE	ECOREGION (PERCENT) NLF	CHF	WCP	NGP
Lake trout	2	—	—	—
Walleye	20	5	—	—
Bass-panfish-walleye	48	37	13	7
Bullhead-panfish	4	6	14	4
Winterkill-roughfish	13	34	65	66
No data / other	13	18	8	23

The lakes of the Northern Glaciated Plains exhibit extremely high total phosphorus concentrations with a median of 176 μg/L ±60. Only one lake exhibited a concentration less than 100 μg/L and all lakes in this region are hypereutrophic. Median Secchi transparency is correspondingly low at 0.8 meters. These lakes are all quite shallow (median Z_{max} = 3.1 m) and rather large in size. All lakes in the Northern Glaciated Plains ecoregion were considered well mixed.

As with the lakes of the Western Corn Belt Plains, the predominant ecological classification of the lakes in the Northern Glaciated Plains is winterkill-roughfish. In addition, a small percentage are classified as bass-panfish-walleye or bullhead-panfish.

Regional patterns can also be seen in the total phosphorus–chlorophyll *a* relationship (log–log) based on 1985 data (Fig. 4). A rather small range in untransformed total phosphorus and chlorophyll *a* concentrations can be noted for the Northern Lakes and Forests lakes. These lakes range in trophic state from oligo- to mildly eutrophic. In contrast, the North Central Hardwood Forest lakes exhibit a rather large range in total phosphorus and chlorophyll *a* concentrations. Lakes in the Western Corn Belt Plains and Northern Glaciated Plains lakes are consistently eutrophic to hypereutrophic. Severe nuisance levels of algae, with chlorophyll *a* greater than 30 μg/L (Walmsley, 1984), are common in the Western Corn Belt Plains lakes and Northern Glaciated Plains lakes during the summer period. The regression equation for this data base (mean summer chlorophyll *a* versus mean summer total phosphorus) is quite comparable to that reported by Dillon and Rigler (1974) for summer chlorophyll *a* based on spring total phosphorus:

$$\log_{10}[\text{Chl } a] = 1.449 \log_{10}[\text{P}] - 1.136 \quad (r^2 = 0.75).$$

ECOREGIONS IN MANAGEMENT

These distinct patterns of watershed characteristics, lake trophic status, fisheries composition, and lake mixing pattern offer a holistic framework for managing lakes. Standards or criteria may be necessary to protect or maintain current lake water quality. When lake restoration is needed, (1) realistic restoration goals or attainable levels and (2) the degree of internal loading and recycling must both be considered (Cooke et al. 1986). Readily attainable levels are not the same for the lakes of the Northern Glaciated Plains or Western Corn Belt Plains as they are for the Northern Lakes and Forest, and therefore, no single standard or goal can be reasonably established for the entire state.

The ecoregion analysis suggests specific management schemes for the lakes in these ecoregions. In Northern Lakes and Forests, lake protection is the primary goal so that currently low total phosphorus levels can be maintained. This protection will be very important in lakes that support a coldwater fishery and require an oxic hypolimnion. Moyle (1956) suggested total phosphorus levels below 20 μg/L and more likely a level at or below 15 μg/L (Nordin, 1986) would be desirable for lakes supporting coldwater fisheries. Small reductions in total phosphorus levels can yield reductions in chlorophyll *a* concentrations and improvements in Secchi transparency (Fig. 4). Lakes with total phosphorus levels above the median and exhibiting water quality problems (such as algal blooms or extensive weed growth) should benefit from reductions in external total phosphorus loading, given that the internal load is small relative to the external load. A total phosphorus concentration of less than 23 μg/L would appear as a reasonable goal for an average summer inlake concentration. Highly colored lakes will deviate from the expected total phosphorus – chlorophyll *a* – Secchi models (Brezonik, 1978) and water clarity is unlikely to improve substantially with reduced total phosphorus loading in these cases.

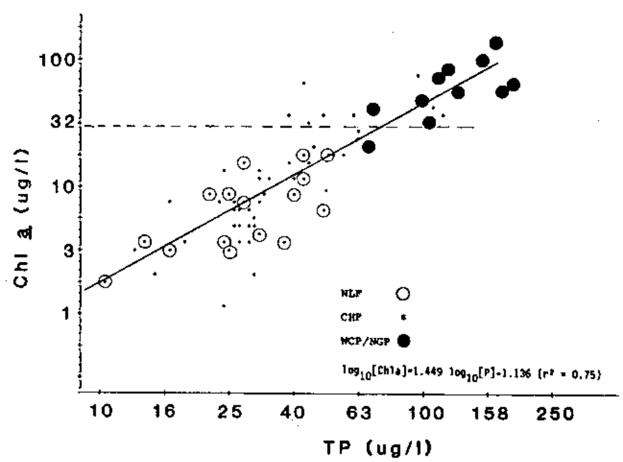

Figure 4.–Mean summer chlorophyll a versus total phosphorus for Minnesota lakes based on 1985 MPCA data. Dashed line delineates severe nuisance concentrations of algae.

For North Central Hardwood Forests, protection of current total phosphorus levels for those lakes below or at the median of 50 μg/L is highly desirable. In general, repeated summer nuisance algal blooms will likely be avoided at/or below this level (Allan, 1980). For lakes with concentrations greater than 50 μg/L, the median would appear a reasonable goal except for the region's shallow lakes because of internal phosphorus loading (Rast et al. 1983; Riley and Prepas, 1985). As future studies in this region identify specific causes of intraregional variation, to refine the goal to perhaps less than 35 μg/L (25th percentile) may be reasonable. This lower total phosphorus level would reduce the potential for nuisance algal bloom conditions. Implementation of best management practices to reduce total phosphorus export should benefit this region and yield water quality improvements in many instances. In-lake remedial measures may be necessary, in addition to implementing best management practices in the watershed, to achieve and maintain acceptable total phosphorus levels in the well-mixed lakes of this region. Lakes with high inorganic turbidities, such as those lakes receiving large amounts of stormwater, may yield lower chlorophyll *a* per unit total phosphorus than those with lesser turbidities (Jones and Bachman, 1976). In those lakes with high inorganic turbidities, clarity may not improve substantially with reductions in total phosphorus loading.

In Western Corn Belt Plains and Northern Glaciated Plains, the median total phosphorus concentration is 121 μg/L and 176 μg/L, respectively. These high total phosphorus levels are frequently associated with severe nuisance algae conditions (Fig. 4) and/or extensive weed growth (Sawyer, 1947). Blue-green algae frequently dominate the algal community. For these two regions a goal of 100 μg/L based on their total phosphorus concentrations at the 25th percentile of 90 μg/L and 135 μg/L, respectively, may be reasonable. Because of the shallowness of these lakes, natural fertility of the soils, and high percentage of agricultural land use in their watersheds (Tables 1 and 2), a reasonably attainable nutrient level may not be substantially less than 100 μg/L. A detailed examination of those watersheds with lakes having the lowest phosphorus concentration (lower 25 percent) in these regions may allow for a refinement of the attainable goals.

Reducing inlake total phosphorus levels below 300 μg/L may lead to a reduction in maximum chlorophyll *a* levels (Allan, 1980). Reducing inlake total phosphorus below 100 μg/L is often necessary, however, before phosphorus can become the limiting nutrient and further reductions can lead to increases in transparency (Forsberg and Ryding, 1980). Reductions below this level may also serve to reduce the frequency of blue-green algal blooms (Sawyer, 1947) and the potential health hazards associated with them (Carmichael et al. 1985). Total phosphorus reductions that yield increases in the nitrogen to phosphorus ratio may also shift algae from blue-green to green forms (Schindler, 1977). While concentrations of 100 μg/L phosphorus or lower may be a reasonable goal (and achievable) for some lakes in the Western Corn Belt Plains, in particular those that are deep enough to stratify, it may be a difficult goal to achieve for the shallow lakes of the Northern Glaciated Plains. In those lakes that cannot achieve total phosphorus levels less than 100 μg/L, primary contact recreation will be severely reduced and might be unacceptable for most of the open water season because of algal blooms, extensive macrophyte growth, and transparencies less than 1 meter. Management emphasis for these shallow lakes might be best directed towards maintaining fishery or wildlife habitat (as determined by Minnesota Department of Natural Resources classification) through inlake measures and, whenever possible, reducing sedimentation.

CONCLUSIONS

This analysis indicates that aquatic ecoregion can be used effectively for identifying patterns in lake nutrient status and associated characteristics. Aquatic ecoregions can also serve as a basis for developing strategies for water quality management for lakes on a regional basis. Furthermore, no single total phosphorus level should be used as a basis for setting inlake nutrient standards, either for protection or for restoration goals; standards or criteria by ecoregions may be a viable approach.

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