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EVALUATION OF THE ECOREGION CONCEPT AS AN INLAND LAKE MANAGEMENT TOOL FOR LOWER MICHIGAN

By

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ABSTRACT

EVALUATION OF THE ECOREGION CONCEPT AS AN INLAND LAKE MANAGEMENT TOOL FOR LOWER MICHIGAN

By

Nanette Fae Kelly

There is a need to manage water quality in inland lakes in Michigan to halt cultural eutrophication and/or restore inland lakes. Evaluation of individual lakes is a time consuming and expensive process according to state and national governmental agencies. Ecoregions are becoming accepted as a regional water quality management tool throughout the United States to predict reasonable attainable water quality for geographic areas. This paper analyzes the spatial relationship of chemical and biological attributes of selected inland lakes in Lower Michigan, and evaluates the ecoregion concept as a possible inland lake management tool. Possible lake management regions were defined for lakes on the extreme ends of the trophic scale by combining regions previously defined by two independent methods. Existing ecoregions do not provide the best lake management regions, but if based on water quality parameters this concept could provide useful lake management regions for state water quality managers.

ACKNOWLEDGMENTS

I would like to thank Dr. Niles Kevern, my major professor, for giving me the opportunity to do this project and for being so patient and understanding as I struggled through it. I have gained much knowledge about the workings of lakes and about Lower Michigan.

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INTRODUCTION

There has been increased concern over the quality of the surface water in the United States since the Clean Water Act and it's amendments in the 1970's. Cultural eutrophication of surface waters from additions of fertilizers, animal wastes, detergents and municipal sewage and septic systems, has contributed to the decrease of water quality for inland lakes in Michigan.

Michigan has over 35,000 inland lakes (Pringle 1983), over 11,000 are at least five acres in surface area. There are 712 significant public access lakes in Michigan, according to the Michigan Department of Natural Resources (MDNR), many having relatively complete chemical, biological and physical data stored in STORET, Storage and Retrieval of the United States Environmental Protection Agency's (USEPA) water quality datafile.

According to Dorr (1970), the genesis of the underlying area determines the morphometry and substrate that characterize lakes. Michigan has a history of glaciation that has repeatedly stripped soils from the bedrock, churned them up and randomly deposited them. Outwash plains of sand, gravel and silt provided varying low nutrient subsoil where vegetation was established and contribute to the soil layer. Michigan presently has over 250 soil types that are being mapped (Mokma, pers. comm.) and that are found in seventy eight soil associations for the entire state, most of which occur in Lower Michigan (USDA 1981). There is a division between the Frigid soils in the north which are sandier and have lower concentrations of nutrients, and the Mesic soils in the south which are more productive clays and loams.

The soil types, climate and topography dictate the type of land use for an area. Areas dominated by forest land uses such as timber or recreation tend to be in the northern part of Lower Michigan (Figure 1). Agricultural use dominates the southern part of Lower Michigan and often adds nutrients to surface water in the form of fertilizer.

There are a number of physical attributes, other than soil types, that contribute to the similarities and differences in lakes; latitude (Brylinski and Mann 1973), the proximity of land to large bodies of water (Wetzel 1983), total dissolved solids (Northcote 1956, Ryder 1965, Ryder 1974), morphometry (Richardson 1975, Horne 1975, Fee 1979), the ratio of surface area to mean depth (Rawson 1955) and a number of chemical attributes such as phosphorus and carbon for example (Wetzel 1972).

Total phosphorus was selected for this study because it is usually considered to be the limiting factor in natural surface waters because of it's scarcity (Fee 1979, Richardson 1975, Schaffner and Oglesby 1978, Schindler 1977, Edmondson 1970, Hsiang and Long 1991). Phosphorus can be added to surface

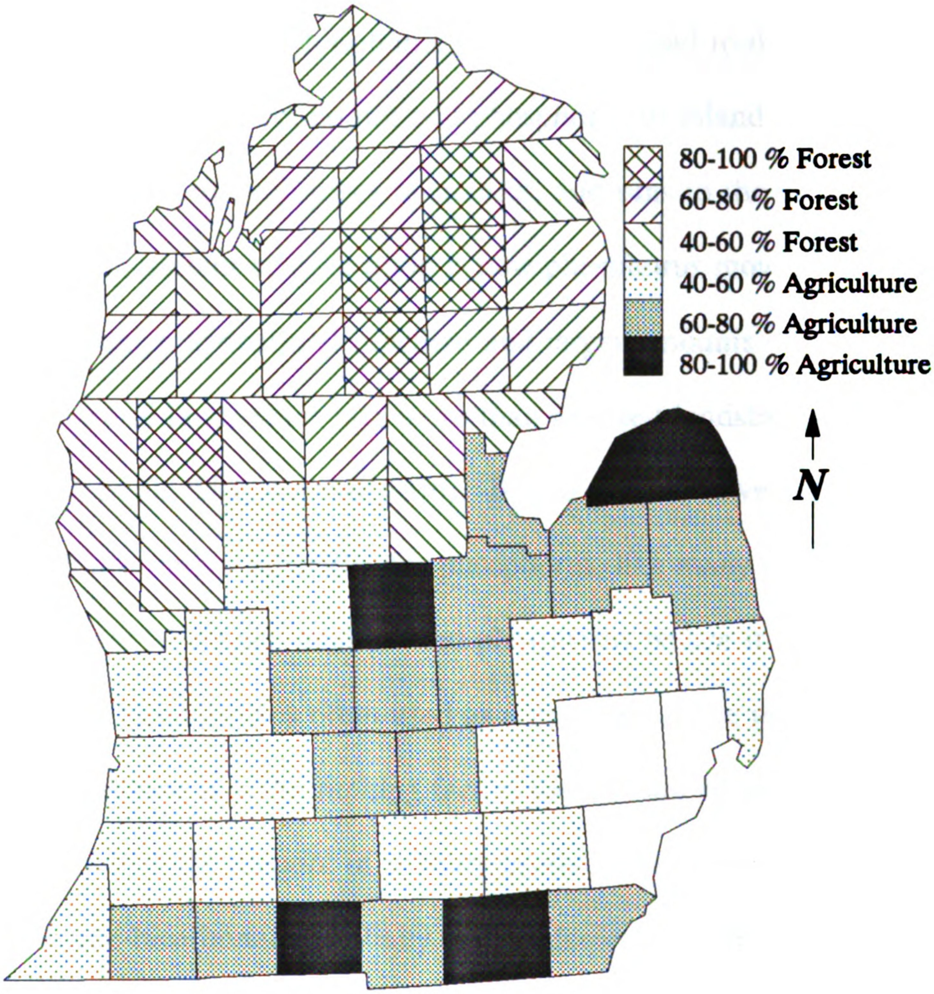

Figure 1. Forest and agriculture land use by county in Lower Michigan (Atlas of Michigan 1978).

waters by a number of human activities (Oglesby and Bouldin 1984, Schaffner and Oglesby 1978). Human populations add phosphorus through sewage wastewater. Homeowners add phosphorus in the form of lawn fertilizers (Taylor 1977), leaky septic systems (Tsatsaros 1993), and in some states, laundry detergents. Agriculture adds phosphate from fertilizers and manures (Harrison 1987). Atmospheric fallout delivers phosphorus to lakes adsorbed to dust particles (Baudo 1990). Urban centers do not add phosphorus to inland lakes because sewage is transported through pipes to streams, and runs to the Great Lakes.

Another important consideration is how phosphorus moves in the environment. Active agricultural practices add larger amounts of nutrients than inactive agricultural land, which add more than forested landscapes (Harrison 1987, Omernik et al. 1981, Borman 1970). Baudo (1990), however, points out that soils with high adsorptive capacities for phosphorus, like many of the glacial tills in southern Lower Michigan, tend to bind phosphorus before it reaches the surface water. Phosphorus is often used as a measure of the productivity of surface water. Where it is the limiting factor, the amount of phosphorus available to plants determines the amount of primary productivity in the water.

Carbonate-bicarbonate alkalinity is a fundamental factor in determining the potential productivity of lakes as well. The drainage basin within which a lake is situated has a particular substrate, soil composition and climate. Carbon dioxide can be consistently made available to plants through the atmosphere in terrestrial systems but not in aquatic systems. These plants must rely on the supply of carbon dioxide from the carbonate-bicarbonate alkalinity system (King 1970). Those lakes of low alkalinity tend to have lower productivity than those having high alkalinity (Barrett 1952, Omernik 1986, Moyle 1956). The alkalinity in lakes is based on the geology of an area and can vary regionally depending on the type of substrate. Areas dominated by limestone bedrock have lakes with high alkalinity. Areas dominated by granite substrate have lakes with low alkalinity.

It could be expected that lakes with similar attributes would occur within an area of similar terrestrial attributes. It could also be expected that lakes in close proximity to one another would have similar attributes such as nutrient levels and biological assemblages compared to lakes spatially removed from one another (Hughes 1987). These expectations are based on the assumption that there is relative spatial homogeneity of attributes, and that there is a gradual change in attributes as physical distance increases between lakes.

The spatial relationship of trophic levels of lakes has relevance to terrestrial regional variation which will be covered in the section of this thesis on ecoregions. Water quality in lakes reflects the conditions in the watershed such as land use, soil type and vegetative cover. Both land uses such as agriculture or forest, and natural characteristics such as soil type or vegetation, vary among watersheds thus the lakes within these watersheds vary as well.

Ecoregions

This thesis compares lakes in Lower Michigan to regional areas that have been defined previously (Omernik 1987, Albert 1986). It considers the possibility of grouping inland lakes in Michigan into areal units, or "ecoregions" based on surface water quality for the purpose of lake management. Ecoregions have been defined by similarities of soil types, land use, climate, physiography, and vegetation types within areas. Chemical conditions of lakes in close proximity to one another could be used to define spatial homogeneity of lakes. This could be used as a guideline for attainable water quality by comparing the water quality of lakes near the lake in question.

There is a need for a general classification system that can be used for more than a single purpose in water quality management. Expensive site specific remedies for problems could be eliminated or reduced using this method of management. There is interest from the Environmental Protection Agency (EPA) for this approach to identify areas for monitoring and assessment; the Environmental Monitoring and Assessment Program (EMAP) (Loehr pers.comm. 1991).

Geographic areas having similar attributes that vary significantly from adjacent areas can be called ecoregions. Several attempts have been made to classify areas into ecoregions for the United States and individual states. R. G. Bailey (1976) produced a map based on climate and vegetation, land surface form, soils, and fauna delineating areas of similar characteristics as an aid to environmental management. The climate descriptions used by Bailey were based on Koppen's classifications and land surface form and work by E. H. Hammond as cited in Bailey (1976). James Omernik (1988) published a map of ecoregions of the United States to assist managers of aquatic and terrestrial resources to understand possible realistic attainable water quality. Omernik (1987) stressed land use (agriculture or forest), soils, land surface form and potential natural vegetation. Dennis Albert (1986) produced a map of ecoregions for the state of Michigan. Albert's districts are based on climate, soil types, physiography and vegetation.

There has been support for Omernik's theory (Hughes and Larsen 1988, Rohm et al. 1987, Whittier et al. 1988, Hughes et al. 1986, Larsen et al. 1988). A number of papers have been published defining the theory, and comparing it to conventional surface water management techniques (Omernik and Gallant 1989, Hughes et al. 1990, and Omernik and Griffith 1991). Work in Michigan, Wisconsin and Minnesota mapped total phosphorus alone, or combined with a number of physical attributes related to lakes (Omernik et al. 1988, Omernik et al. 1991). The purpose of these maps was to clarify patterns of lake trophic states based on total phosphorus concentrations in water, to be used to determine attainable water quality for inland lakes.

Omernik's Ecoregions

The ecoregions defined by James Omernik are areas of relatively homogeneous ecological systems. He stresses soil type, land use, potential natural vegetation and physiography. His ecoregions consist of a core of the most typical conditions and a transitional area surrounding the core. The relatively small central core consists of a homogeneous combination of all of the attributes used for the classification, while in the transitional area one or more of the attributes differed from those in the core. There are parts of five of Omernik's ecoregions within Lower Michigan (Figure 2).

Ecoregion 50 is mostly forest and woodland. Soil types are podzolic (Gray-Brown Podzolic, Podzol, and Brown Podzolic) which have low fertility. Ecoregion 51 is mainly orchards, pasture, woodland, and forest. Soils are Gray-Brown Podzolic which have low fertility. Ecoregion 55 is a small area dominated by cropland. The Soils are Alfisols Gray-Brown Podzolic/Humic Gley and are fertile, productive soils. Ecoregion 56 is row crops, pasture, woodland, and forest. The productive soils of this ecoregion are Gray-Brown Podzolic. Ecoregion 57 is dominated by cropland. The fertile soils of this ecoregion are Humic Gley, Low Humic Gley, Gray-Brown Podzolic/Humic Gley. There are very few lakes in this ecoregion because it is a lake plain from the glacial period. As the glaciers retreated across the large glacial lakes that covered this part of the world, the chunks of ice that fell from the glacier fell into water and melted leaving no evidence of this process. This differs from the glacial retreat on land in which the chunks of ice fell onto rock and were covered with till which melted slowly forming a depression, or kettle lake.

Albert's Districts

Dennis Albert (1986) divided Lower Michigan into Region I and Region II (Figure 3a). This division was based on differences in climate, physiography, soil,

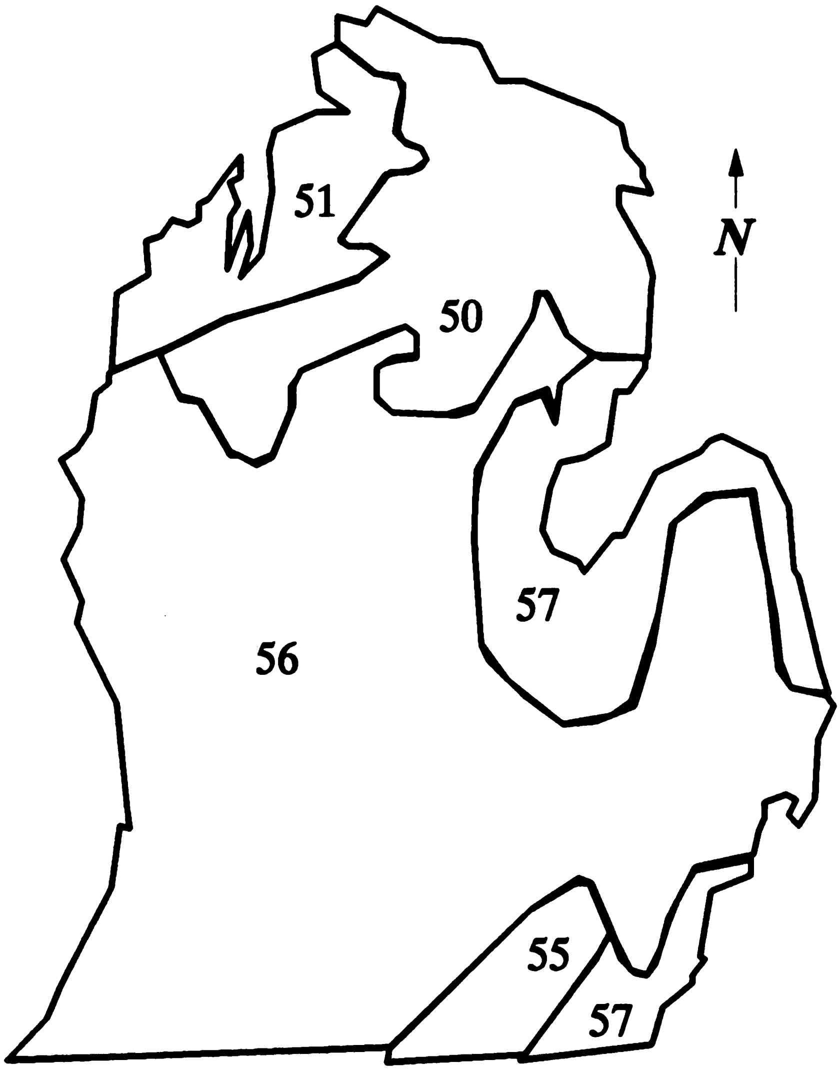

Figure 2. Ecoregions defined by James Omernik are based on soil types, landform, vegetation and land use.

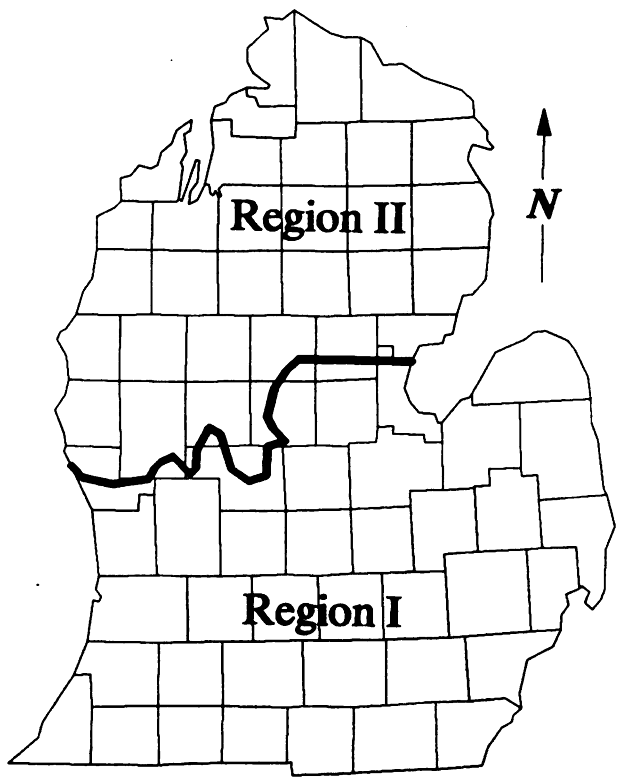

Figure 3a. Two regions used by Dennis Albert to divide northern and southern Lower Michigan.

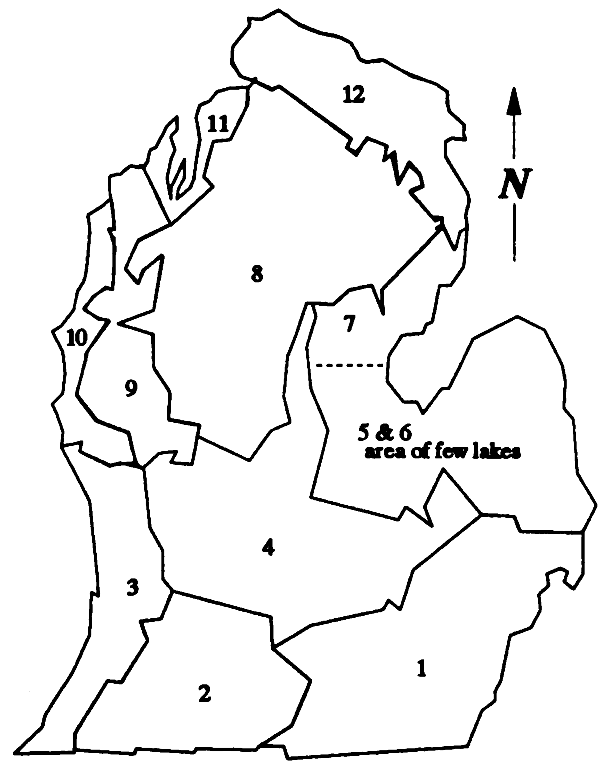

Figure 3b. Districts defined by Dennis Albert based on climate, physiography, soil types and vegetation.

vegetation and land use. He has divided Lower Michigan into twelve ecoregions. Three of which I have combined because they have only two lakes from my data set (Figure 3b).

Region I is southern Lower Michigan where soils are fertile and agriculture dominates land use. The land use in District 1 is dominated by agriculture with some fragmented forest and metropolitan areas. Land use in District 2 is dominated by agriculture with some scattered oak/hickory forest, swamps, marshes and prairies. Land use in District 3 is dominated by agriculture (fruit), with scattered remnants of woodlots. Land use in District 4 is dominated by agriculture and beech/maple forest on uplands and hardwood swamps.

District 5, 6 and 7 surround Saginaw Bay and are combined for this research because they have a very small sample size, only two lakes from my data. Districts 5 and 6 are in region I, district 7 is in region II. Agriculture is the dominant land use in these districts. District 7 is on the northwest shore of Saginaw Bay. Land use is mostly agriculture and is probably the major contributor to phosphorus pollution to surface waters.

Region II is the northern part of Lower Michigan where soils have low natural fertility and agriculture does not dominate land use. In District 8, 9, 10, 11 and 12 land use is dominated by forest of various compositions.

Objectives

1. Many lakes in Lower Michigan exhibit problems associated with accelerated eutrophication from human interferences. The first objective of this thesis is to determine if lakes in Lower Michigan that are being impacted by cultural eutrophication can be identified spatially on a regional scale, and what factor or factors are contributing to, or preventing cultural eutrophication of these lakes.

2. Lake managers in the MDNR are looking for a regional lake management tool that will allow them to predict possible water quality problems without requiring expensive site analysis. The second objective of this thesis is to determine if the ecoregions, that have been defined by James Omernik or Dennis Albert, can be used as a management tool for inland lakes in Lower Michigan. James Omernik initiated his work dealing with ecoregions as a method of determining attainable water quality on a regional scale in response to surface water quality problems due to pollution from various sources.

3. Michigan has an exceptional water resource in the form of inland lakes which needs to be managed to preserve water quality for recreational purposes and ecosystem integrity (Hutchinson 1970, Karr 1991). Is it possible to try to restore all lakes in Lower Michigan to their original form? Should lakes be managed to protect water quality in high quality lakes or to restore water quality

in lakes that have been impacted? The final objective is to determine where we should concentrate our inland lake management efforts in Lower Michigan.

METHODS

The data for this study came from several sources. The majority of the data for my study were EPA quality controlled STORET (Storage and Retrieval) data for significant, public access lakes in Lower Michigan. These data were chemical, physical and biological attributes for about three hundred inland lakes in Lower Michigan. Many of the maps generated for this thesis came from the Atlas of Michigan (1978). Some maps were reproduced directly from the atlas while others were the result of combinations of maps. Other maps used the ecoregions defined by James Omernik or the Districts defined by Dennis Albert.

Lakes that are reservoirs, drowned river mouths or lakes that had significant point source inputs were excluded from the study. Lakes with significant inputs of point source pollution represent exceptional human interferences that often produce abnormally high concentrations of total phosphorus. Reservoirs are the result of stream impoundment, another type of human interference. Drowned river mouths are not natural lakes, but are the shallow waters near the coast of the Great Lakes where streams have become impounded due to a change in water level. These water bodies do not accurately represent natural lakes in Lower Michigan due to their origin or human interference.

Spatial Analysis

Values of total phosphorus from STORET data, for individual lakes were plotted on a basemap using Freelance Graphics software package. The method of assigning trophy of surface water is subjective. Physical, biological or chemical parameters can be used such as Secchi disk depth, chlorophyll *a*, total phosphorus or nitrogen. The chosen parameter could be based on a previous scale or divisions convenient for the purpose at hand. I have used four trophic levels based on total phosphorus for this study (Table 1a) in divisions similar to those used by the MDNR.

Lakes having total phosphorus concentrations within the same trophic level were identified and visually clustered into enclosed regions or polygons by separating lakes of different trophic levels as illustrated in Figure 4a and 4b. Polygons were created in the same way for the alkalinity concentrations for lakes. Four divisions of alkalinity were used (Table 1b).

The shape, sizes and direction of the polygons of these two maps were compared to determine if there was any similarity between the alkalinity polygons and the total phosphorus polygons. Both polygon maps were then compared to a map showing county by county percent of land use in agriculture.

Ecoregions

Previous ecoregion studies by James Omernik (1987), for the conterminous United States, and another by Dennis Albert (1986), for Michigan, were considered as possible models on which to base statistical analyses. Each lake

Table 1a. Trophic states of lakes based on total phosphorus.

Trophic State	mg PO_4/L
Oligotrophic	< 0.01
Mesotrophic	0.01 - 0.03
Eutrophic	0.03 - 0.05
Hypereutrophic	> 0.05

Table 1b. Four classes of alkalinity.

Class	mg $CaCO_3$/L
Low	< 50
Moderate	51 - 100
Moderately High	101 - 150
High	> 150

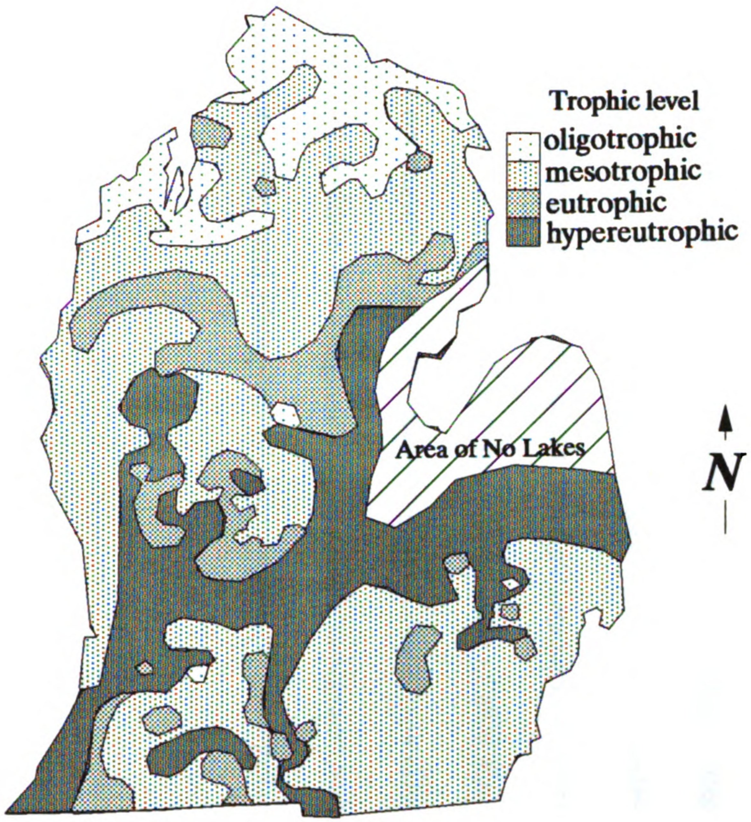

Figure 4a. Polygon maps for total phosphorus in inland lakes in Lower Michigan in mg P/L.

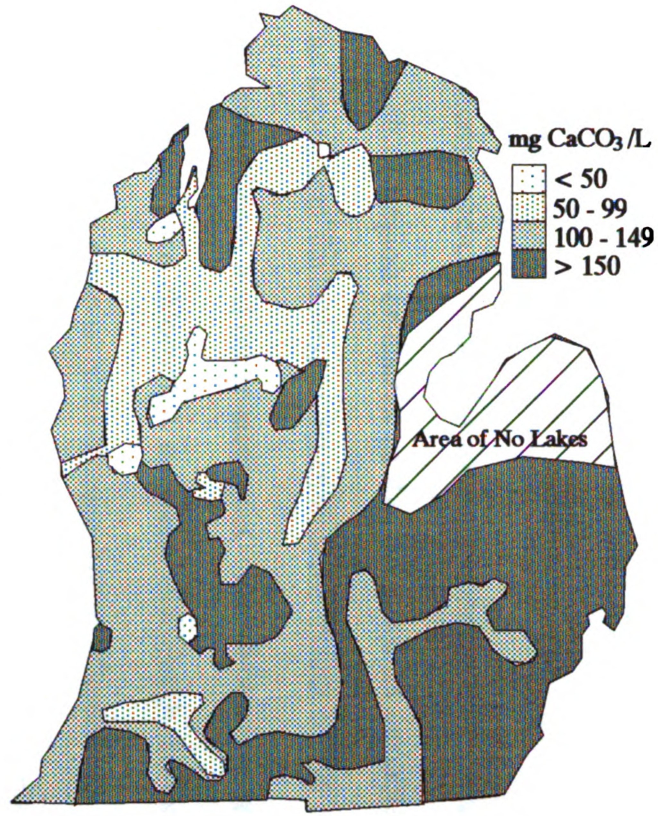

Figure 4b. Polygon maps for alkalinity in inland lakes in Lower Michigan, in mg Calcium Carbonate/L.

was assigned to the appropriate district as defined by Albert or, to ecoregions defined by James Omernik.

Simple Regressions

Regressions were calculated for total phosphorus concentrations for inland lakes within each ecoregion or district as the independent variable, and the other attributes as dependent variables, to determine the extent of the correlation between total phosphorus and other attributes. The dependent variables selected for these correlations were chlorophyll *a*, Secchi disk depth, and alkalinity. Simple regressions were done on the software Lotus 123, version 2.3 for DOS.

The STORET data for total phosphorus values for the inland lakes in Lower Michigan were entered into the spreadsheet software Lotus 123. The data were sorted into subsets by Omernik's ecoregion or Albert's district. Averages, standard deviations, maximum, minimum and the number of lakes in the sample were calculated and included on the spreadsheet. Bar graphs for mean total phosphorus, by ecoregion or district, were plotted. High-Low-Close graphs use the same data but include the range of the standard deviation to see how much variation there was for total phosphorus among the lakes within an ecoregion or district.

Kruskal-Wallis One Way Analysis of Variance

Each of Omernik's ecoregions and Albert's districts, having lakes, was analyzed using the Kruskal-Wallis one way analysis of variance (Howell 1989) (Figure 5a). This nonparametric test does not assume normal distribution. It tests the hypothesis that all samples were drawn from identical populations. It is especially sensitive to differences in central tendency. Total phosphorus, Secchi disk depth, chlorophyll *a*, and alkalinity were tested separately. Then they were divided by ecoregion or district and summed.

The data were analyzed using the Kruskal-Wallis multiple comparison test to determine what was causing the differences among the ecoregions and districts (Miller 1980) (Figure 5b). This test compares each ecoregion or district to each of the other ecoregions or districts, for each of the attributes mentioned in the previous paragraph, to calculate the basis for the differences.

Carlson's Trophic State Index

Carlson's trophic state index (TSI) values for Secchi disk depth (SD), chlorophyll *a* (Chl *a)*, and total phosphorus (TP) were calculated using the mean value for each region, for each of these parameters. These regional TSI values were plotted as bar graphs. The TSI bars for total phosphorus, chlorophyll *a*, and Secchi disk were grouped by region. This index should give TSI values for total phosphorus, chlorophyll *a*, and Secchi disk which are about the same values for a given lake, and for a group of similar lakes.

This method of determining the productivity of lakes is used by many state agencies and citizen monitoring groups throughout the United States. For Secchi

$$H = \frac{12}{N(N+1)} \sum_{j=1}^{k} \frac{R_j^2}{n_{j1}} - 3(N+1)$$

k = the number of groups
n_j = the number of observations in Group j
R_j = the sum of the ranks in Group j
$N = \Sigma n_j$ = total sample size

Figure 5a. The forumula for Kruskal-Wallis One Way Analysis of Variance.

$$|\bar{R}_i - \bar{R}_{i'}| \leq (h^{\alpha}_{k-1})^{½} \left[\frac{N(N+1)}{12}\right]^{½} \left(\frac{1}{n_1} + \frac{1}{n_{1'}}\right)^{½}$$

$\bar{R}_i - \bar{R}_{i'}$ = the rank mean of population tested
N = total sample size
n_1 $n_{1'}$ = the number of observations
h^{α}_{k-1} = X^2

Figure 5b. The formula for Kruskal-Wallis multiple comparison (Miller 1980).

disk depth the equation is:

$$TSI(SD) = 10\ [6 - (\ln SD\ /\ \ln 2)\ ];$$

for chlorophyll *a* (mg/L):

$$TSI(Chl\ a) = 10\ [6 - (2.04 - (0.68\ \ln\ Chl\ a)\ /\ \ln 2)\ ];$$

and for total phosphorus (mg P/L):

$$TSI(TP) = 10\ [6 - (\ln 48/TP)\ /\ (\ln 2)\ ].$$

RESULTS

Spatial Analysis

There was a general east-west trend for the phosphorus polygons, and a general north-south trend for the alkalinity polygons (Figures 4a and 4b). There are some total phosphorus areas that agree with alkalinity areas, such as the band of hypereutrophic lake polygon in the south thumb area and the northern most part of the large high alkalinity polygon in southeastern Lower Michigan. Some other small areas overlap as well. Most of the polygons do not agree however, such as the southern most part of the large high alkalinity polygon which corresponds with the mesotrophic lake polygon in the southeastern part of Lower Michigan. The level of potential productivity indicated by the alkalinity polygons is different from the level of productivity of the total phosphorus polygons.

Comparing the total phosphorus polygons to the county by county percent use in agriculture did show agreement. Where agriculture dominates land use the total phosphorus in lakes tends to be higher (Figure 1).

Ecoregions

Lakes with Omernik's Ecoregions

Oligotrophic lakes fall into ecoregions 50 and 51 in northern Lower Michigan, and there are a few lakes scattered through ecoregion 56 (Figure 6a). Mesotrophic lakes are in every ecoregion except 57 (Figure 6b). Eutrophic lakes

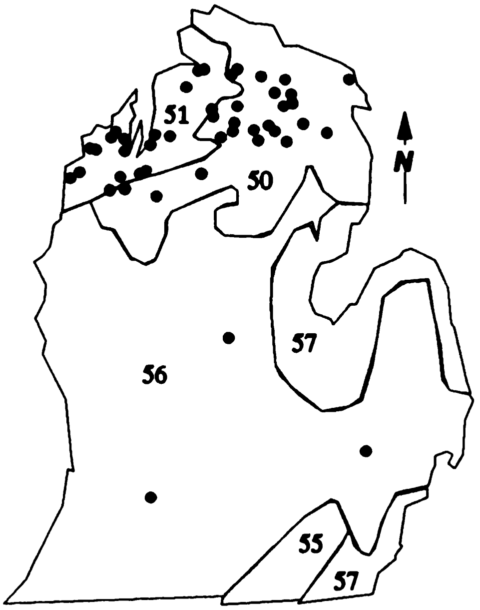

Figure 6a. The location of oligotrophic lakes with respect to the ecoregions defined by James Omernik.

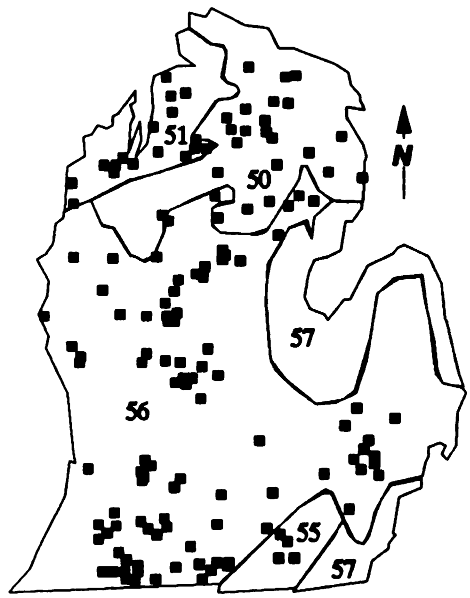

Figure 6b. The location of mesotrophic lakes with respect to the ecoregions defined by James Omernik.

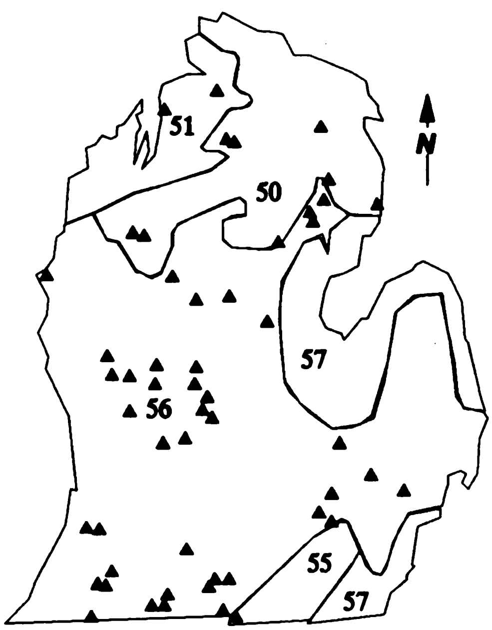

Figure 6c. The location of eutrophic lakes with respect to the ecoregions defined by James Omernik.

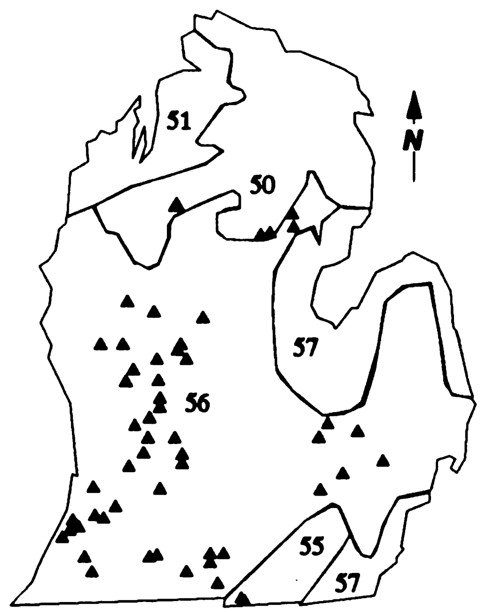

Figure 6d. The location of hypereutrophic lakes with respect to the ecoregions defined by James Omernik.

also are found in all of the ecoregions except ecoregion 57 (Figure 6c). Hypereutrophic lakes are found for the most part in ecoregion 56, the large ecoregion that dominates the central and southwestern part of Lower Michigan (Figure 6d). There are two near the Michigan-Ohio border in ecoregion 55, one just on the edge between ecoregions 57 and 56, and several straddling the border between ecoregions 50 and 56.

By using the total phosphorus values for inland lakes we could combine Omernik's ecoregions 50 and 51 to have a northern lake management region because oligotrophic lakes are found almost exclusively in these ecoregions. The other ecoregions could be a southern lake management region since the hypereutrophic lakes are found in this area. Several of the hypereutrophic lakes are near the edge of these two proposed regions which may be due to drawing error.

Lakes with Albert's Districts (Ecoregions)

The oligotrophic lakes lie within districts 11 and 12, and the northern part of districts 8 and 9. Of the southern oligotrophic lakes, one is in district 1, one is in district 4 and the last is between districts 2 and 4 (Figure 7a). The mesotrophic and eutrophic lakes are in every district (Figures 7b and 7c), however there is only one eutrophic lake in each of districts 10, 11 and 12. The hypereutrophic lakes cover areas in districts 2, 3, and 4 (Figure 7d). There are some along the edges of district 8. There are several in the southern part of

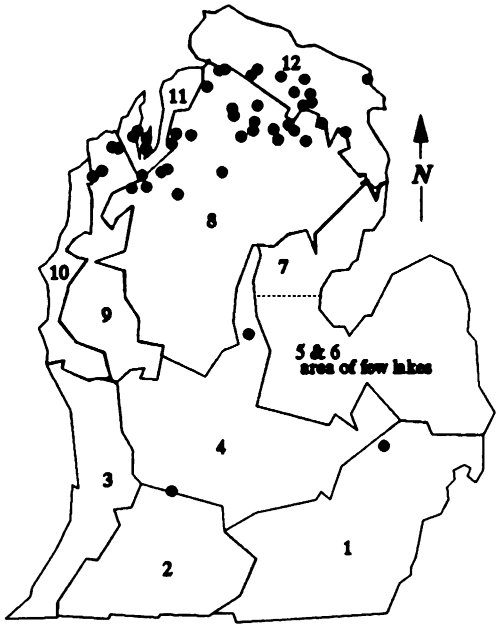

Figure 7a. The location of oligotrophic lakes with respect to the districts defined by Dennis Albert.

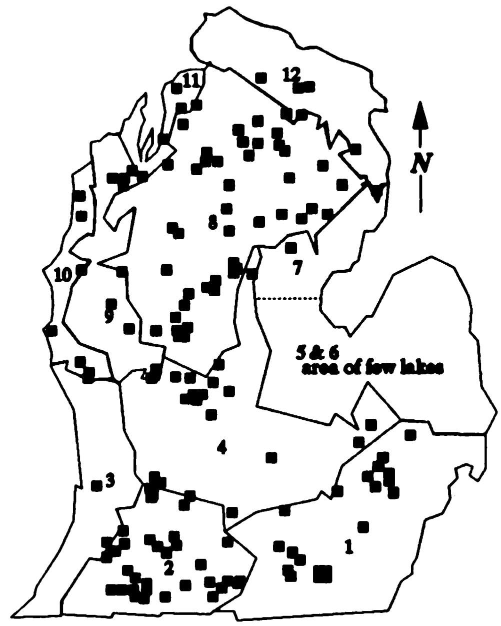

Figure 7b. The location of mesotrophic lakes with respect to the districts defined by Dennis Albert.

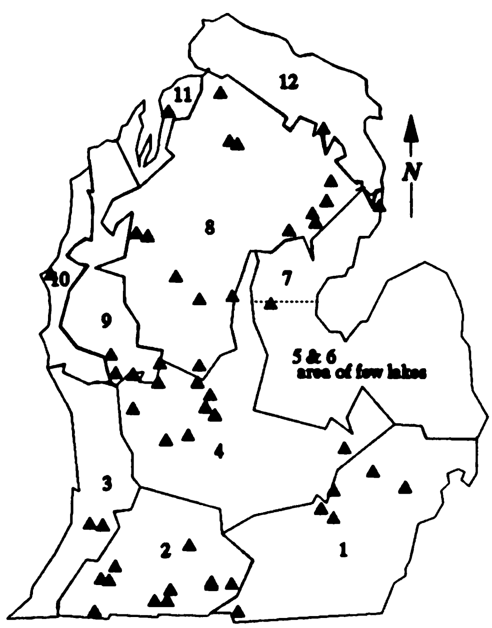

Figure 7c. The location of eutrophic lakes with respect to the districts defined by Dennis Albert.

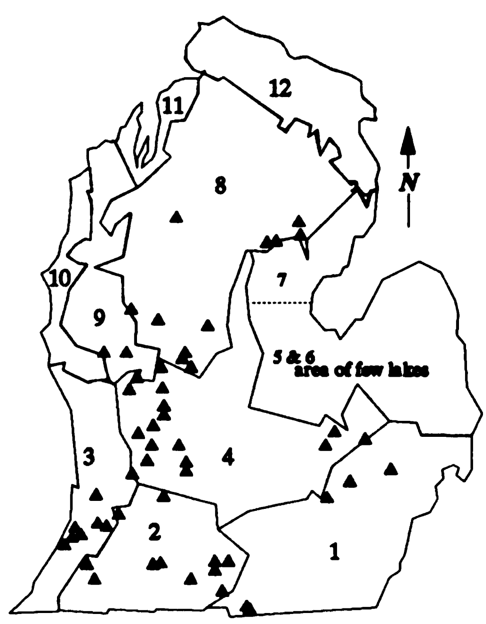

Figure 7d. The location of hypereutrophic lakes with respect to the districts defined by Dennis Albert.

district 9, and several along the north and west edge of district 1. There are no hypereutrophic lakes in districts 10, 11 and 12.

We could almost use Albert's divisions of Region I and Region II for lake management purposes (Figure 3a). Region I would need to extend a little further to the north through Iosco county on the east and Mason or Oceana County on the west side of Lower Michigan. Or we could add District 10 and the northern parts of District 3 and 9 to Omernik's ecoregions 50 and 51.

Statistical Analyses

The lakes were divided into subsets by ecoregions (Omernik) in which they lie. The ecoregions have been ranked according to the average concentration of the total phosphorus in each region (Figure 8a). There are four divisions, because ecoregion 57 has no lakes from my data set. The ecoregions have been ranked from the lowest total phosphorus value to the highest. Ecoregion 51 has the lowest mean value at 0.012 mg P/L, with 31 lakes in the subset. Ecoregion 50 is next with an average of 0.017 mg P/L, with 66 lakes in this subset. These ecoregions have mean total phosphorus values that are within the mesotrophic range as I have defined them. Ecoregion 55 has an average value of 0.027 mg P/L, with a subset of only 7 lakes (also within the mesotrophic range). Ecoregion 56 has the highest average value at 0.044 mg P/L with 156 lakes in the subset (which puts it within the eutrophic range).

There appears to be a difference among mean total phosphorus

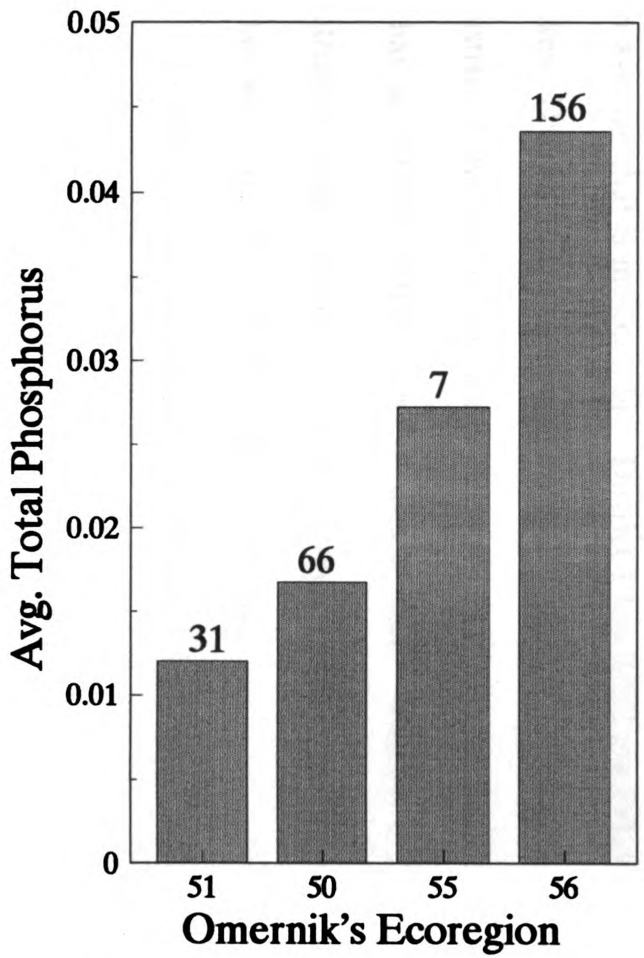

Figure 8a. Averaged total phosphorus, by ecoregion, in mg P/L. (The numbers above the bars are the n values).

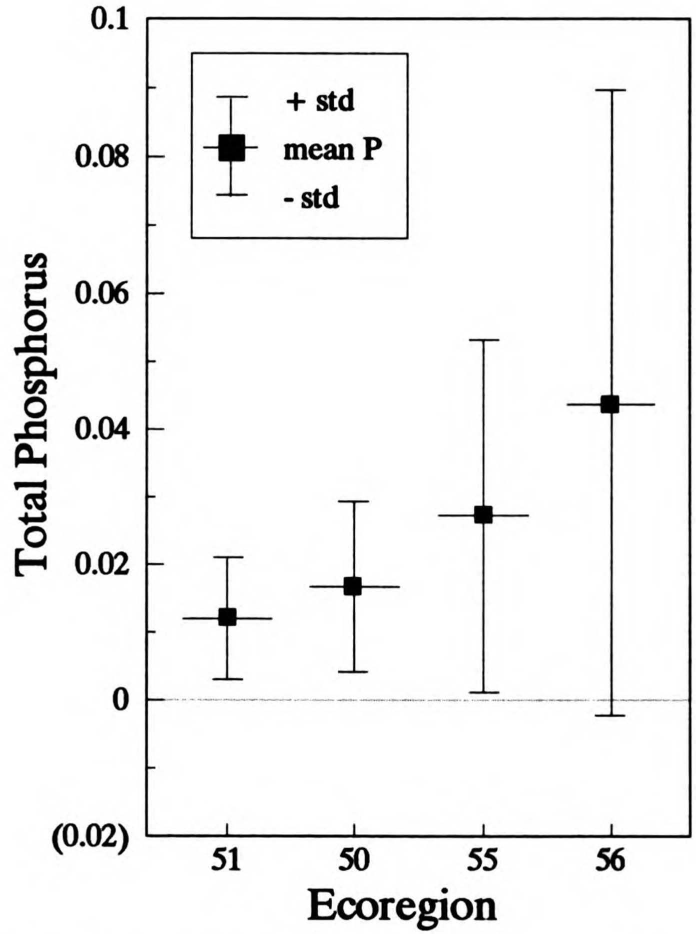

Figure 8b. Mean total phosphorus values in mg P/L, and standard deviation for four ecoregions defined by James Omernik.

concentrations for ecoregions (Figure 8b), but the standard deviation indicates no statistical difference among ecoregions. Lakes fall over a large range of trophic levels from mesotrophic to hypereutrophic in ecoregion 55, and oligotrophic to hypereutrophic in ecoregion 56. For ecoregion 50 the standard deviation is 0.0125, for 51 it is 0.009, for 55 it is 0.026, and for 56 it is 0.046.

There are nine subsets of lakes using Albert's districts. His districts 5, 6 and 7 have only two lakes from my set. The districts have been ranked from low to high, using average total phosphorus concentrations (Figure 9a). District 12 has the lowest average with 0.010 mg P/L, and 19 lakes in the subset (just into the mesotrophic range). District 11 has an average of 0.012 mg P/L with 12 lakes in the subset. District 8 has an average 0.023 mg P/L with 81 lakes. District 9 has an average of 0.025 mg P/L with 16 lakes. Districts 8, 9. 11, and 12 also have an average that is mesotrophic. District 1 has 0.032 mg P/L with a subset of 29 lakes. District 10 has an average of 0.036 mg P/L with a subset of 10 lakes. District 2 also has an average of 0.036 mg P/L with a subset of 46 lakes. District 3 has an average of 0.042 mg P/L with 14 lakes. Districts 1, 2 and 10 are in the eutrophic range. District 4 has an average of 0.065 mg P/L with a subset of 41 lakes which puts it in the hypereutrophic range.

The ten districts defined by Albert also have large standard deviations. The standard deviations are as follows; for district 12 it is 0.006, for district 11 it is 0.010, for district 8 it is 0.024, for district 9 it is 0.024, for district 1 it is 0.029, district 10 it is 0.046, for district 2 it is 0.032, for district 3 it is 0.021, and district 4

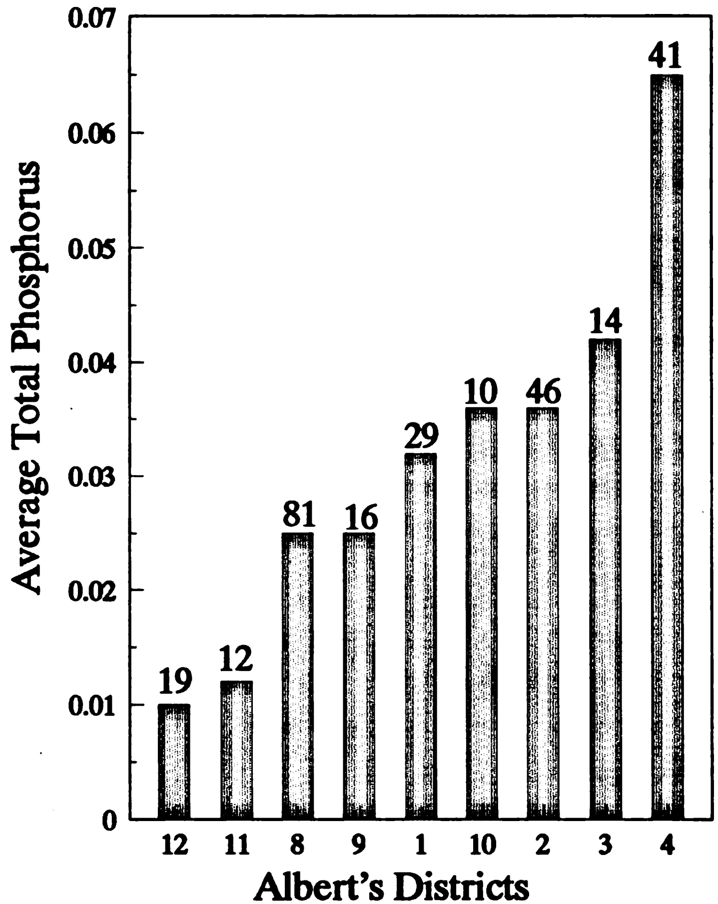

Figure 9a. Averaged total phosphorus values, by district in mg P/L (The numbers above the bar are the n values).

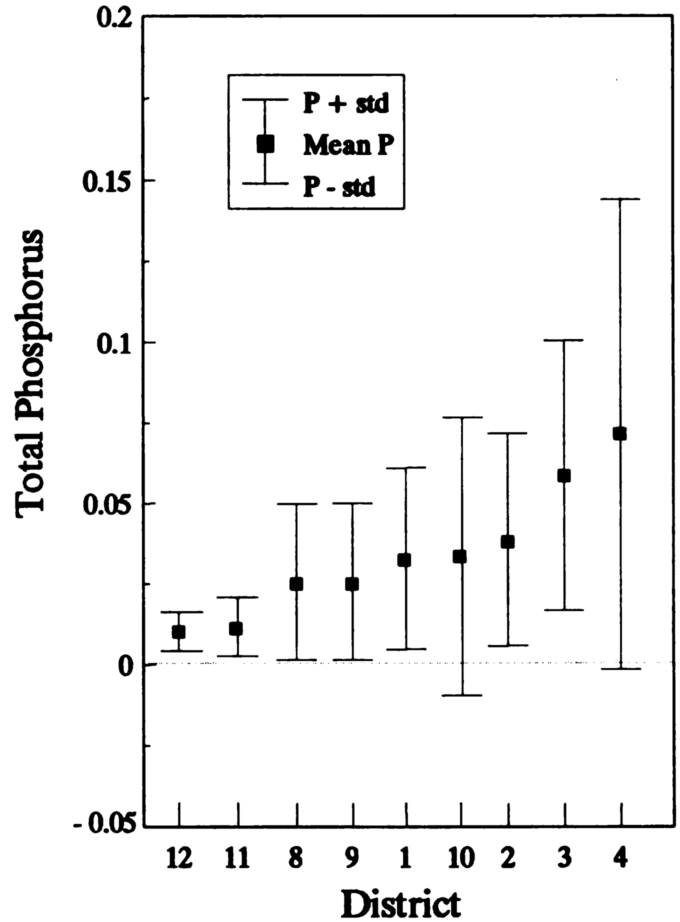

Figure 9b. Mean total phosphorus values in mg P/L, and standard deviation for nine districts defined by Dennis Albert (Districts 5, 6, and 7 have only one lake in the data set).

has a standard deviation of 0.071 (Figure 9b). Again, the large standard deviations show a wide range of trophic levels for all district except 11 and 12. Using visual comparison, the only statistical difference appears to be between districts 3 and 12 where the standard deviations do not overlap.

Simple Regressions

The strongest correlation for Omernik's ecoregions was in ecoregion 55, between total phosphorus and chlorophyll *a* with an r^2 value of 0.863, with total phosphorus as the independent factor and chlorophyll *a* as the dependent factor (Table 2). This is a very small ecoregion with only seven lakes. The other comparisons for Omernik's ecoregions were significantly weaker having r^2 values 0.333 or lower.

For Albert's districts the larger r^2 values were 0.756 in district 9, 0.733 in district 12, and another of 0.614 in district 1, again were for the correlation between total phosphorus and chlorophyll *a*. Total phosphorus and chlorophyll *a* have been shown to be highly correlated (Dillon and Rigler 1974, Brylinski and Mann 1973, Fee 1979). The lack of correlation of chlorophyll *a* to total phosphorus in other ecoregions or districts could indicate that something other than phosphorus is limiting in some of these lakes. Nitrogen or carbon can become limiting when phosphorus is abundant.

Table 2. Results of simple regressions.

Ecoregion (Omernik)	50	51	55	56
Phosphorus and Alkalinity	0.013	0.005	0.301	0.002
Phosphorus and Secchi Disk	0.078	0.004	0.110	0.135
Phosphorus and Chl a	0.333	0.150	0.863	0.202

District (Albert)	1	2	3	4	8	9	10	11	12
Phosphorus and Alkalinity	0.092	0.246	0.263	0.267	0.017	0.093	0.157	0.076	0.022
Phosphorus and Secchi Disk	0.238	0.017	0.004	0.082	0.140	0.279	0.185	0.099	0.115
Phosphorus and Chl a	0.614	0.436	0.181	0.120	0.392	0.765	0.469	0.467	0.733

Table 3. H values for Kruskal-Wallis One Way ANOVA.
All values are significant at $\alpha = 0.01$.

Ranked Parameter	OMERNIK	ALBERT
Total Phosphorus	95.59	104.81
Chlorophyll a	73.56	68.97
Secchi Depth	40.03	37.00
Alkalinity	29.02	60.84

Kruskal-Wallis One Way Analysis of Variance

Using the Kruskal-Wallis one way analysis of variance all of the attributes were found to have significant differences for all of Omernik's ecoregions and Albert's districts ($\alpha = 0.01$) (Table 3). We can conclude that the ecoregions are different based on the parameters used.

The Kruskal-Wallis multiple comparison test determined where the origin of differences were among ecoregions (Table 4a and 4b). For Omernik's ecoregions, there were two differences each, from a possible six combinations, from total phosphorus, chlorophyll *a*, Secchi disk depth, and alkalinity. There were no differences between ecoregions 50 and 51, 51 and 55, or 55 and 56. There were differences in all cases for ecoregions 50 and 56, and three cases for ecoregions 51 and 56. Only one difference was determined between ecoregions 50 and 55.

For Albert's districts there were 24 cases, from a possible 36 combinations of districts, where the differences came from total phosphorus. There were 18 differences due to chlorophyll *a*, 10 due to Secchi disk depth and 14 due to alkalinity. There were differences in all of the 4 of the attributes in two comparisons; between districts 1 and 4, and between districts 4 and 8. There were differences in three of the attributes in 11 comparisons of districts, total phosphorus being one of the comparisons in each of the 11. Eight combinations of districts where there were no differences determined were 1 and 2, 1 and 10, 2 and 3, 3 and 4, 8 and 9, 8 and 10, 9 and 10, and 11 and 12.

Table 4a. Kruskal–Wallis multiple comparison results for Omernik's ecoregions
(259) indicates that there were four missing values for alkalinity.
* after value indicates a source of difference between ecoregions or districts.

		tot Phos	Chl a	Sd	Alk	
					(259)	(259)
R–R	groups	KW	KW	KW	KW	R–R
49.79	50–51	29.55	34.76	0.51	36.81	49.16
92.04	50–55	39.22	10.48	34.52	112.46 *	90.71
33.81	50–56	80.83 *	63.60 *	57.90 *	58.95 *	33.57
96.69	51–55	68.77	24.28	35.03	75.65	95.22
44.94	51–56	110.38 *	98.36 *	58.40 *	22.14	44.33
89.51	55–56	41.62	74.08	23.37	53.51	88.19

Figure 4b. Kruskal–Wallis multiple comparison results for Albert's Districts.
* after value indicates a source of difference betweem ecoregions or districts.

		tot Phos	Chl a	Sd	Alk	
					(259)	(259)
R–R	groups	KW	KW	KW	KW	R–R
33.69	1–2	13.17	20.20	0.47	11.09	33.52
43.97	1–3	42.93	19.86	32.43	49.87 *	43.30
33.69	1–4	49.07 *	47.69 *	41.65 *	40.63 *	33.18
30.13	1–8	25.58	0.04	21.84	90.42 *	29.71
44.99	1–9	33.57	6.43	0.32	96.04 *	44.29
50.63	1–10	34.67	3.94	17.11	67.51	49.85
48.90	1–11	91.99 *	81.84 *	36.26 *	19.45	45.42
42.26	1–12	109.60 *	76.44 *	38.64	49.48 *	42.41
41.47	2–3	29.76	0.34	32.90	38.78	41.11
30.35	2–4	35.90 *	27.49	42.12 *	29.54	30.27
26.34	2–8	38.75 *	20.24	21.36	79.33 *	26.43
42.54	2–9	46.74 *	26.63	0.15	84.94 *	42.16
48.47	2–10	47.84	24.14	16.63	56.41 *	47.97
43.74	2–11	105.17 *	102.03 *	35.79	8.36	43.34
39.64	2–12	122.77 *	96.64 *	38.16	38.39	40.18
41.47	3–4	6.15	27.83	9.22	9.24	40.83
38.63	3–8	68.51 *	19.90	54.26 *	40.55 *	38.08
51.07	3–9	76.50 *	26.29	32.75	46.16	50.29
56.11	3–10	77.60 *	23.80	49.53	17.63	55.25
52.08	3–11	134.92 *	101.69 *	68.69 *	30.42	51.28
48.68	3–12	152.53 *	96.29 *	71.06 *	0.39	48.63
26.34	4–8	74.65 *	47.73 *	63.48 *	49.79 *	25.99
42.54	4–9	82.65 *	54.11 *	41.97	55.40 *	41.89
48.47	4–10	83.75 *	51.63 *	58.76 *	26.88	47.73
43.74	4–11	141.07 *	129.52 *	77.91 *	21.18	43.07
39.64	4–12	158.68 *	124.12 *	80.29 *	8.85	39.89
39.78	8–9	7.99	6.38	21.51	5.62	39.20
46.06	8–10	9.09	3.90	4.73	22.91	45.39
41.06	8–11	66.42 *	81.79 *	14.43	70.97 *	40.47
36.66	8–12	84.02 *	76.39 *	16.80	40.94 *	37.06
56.90	9–10	1.10	2.49	16.79	28.53	56.03
52.93	9–11	58.42 *	75.41 *	35.94	76.58 *	52.12
49.60	9–12	76.03 *	70.01 *	38.32	46.55	49.52
57.81	10–11	57.32 *	77.89 *	19.15	48.05	56.92
54.77	10–12	74.93 *	72.49 *	21.53	18.03	54.55
54.77	11–12	17.61	5.40	2.38	30.03	50.53

tot Phos = total phosphorus, Chl a = chlorophyll a, Sd = Secchi disk depth, Alk = alkalinity.

Carlson's Trophic State Index

TSI values for total phosphorus, Secchi disk and chlorophyll *a* should be relatively close to one another for a lake or group of lakes spatially near to one another (Figure 10). The average TSI values for Omernik's Ecoregion 51 are the lowest overall. The Secchi disk TSI is slightly over 40 and phosphorus and chlorophyll *a* are about 37 and 39 respectively. In ecoregion 50 the TSI's are slightly higher and all three values are very close at about 42. The phosphorus TSI in ecoregion 55 is higher than the other two TSI values in that ecoregion. Ecoregion 56 has the highest total phosphorus TSI, about 55, while Secchi disk and chlorophyll *a* are lower at about 47 and 48 respectively.

Ecoregion 51 has more lakes in the oligotrophic trophic level than do the other ecoregions, and the total phosphorus TSI is lower than the Secchi disk and chlorophyll *a* TSI values. Ecoregions 55 and 56 have more lakes in the hypereutrophic trophic level and the total phosphorus TSI values are higher than the Secchi disk and chlorophyll *a* TSI values. The TSI values seem to fall within or near the mesotrophic range on the graph. There are differences among them however. There are differences among ecoregions for total phosphorus and chlorophyll *a* (of five TSI points or more) which indicates a difference among some ecoregions.

Albert's district 11 has the lowest TSI values for the three parameters, with the Secchi disk about 42 and total phosphorus and chlorophyll *a* about 36 (Figure 11). District 12 has slightly higher values for all three, and again the Secchi disk

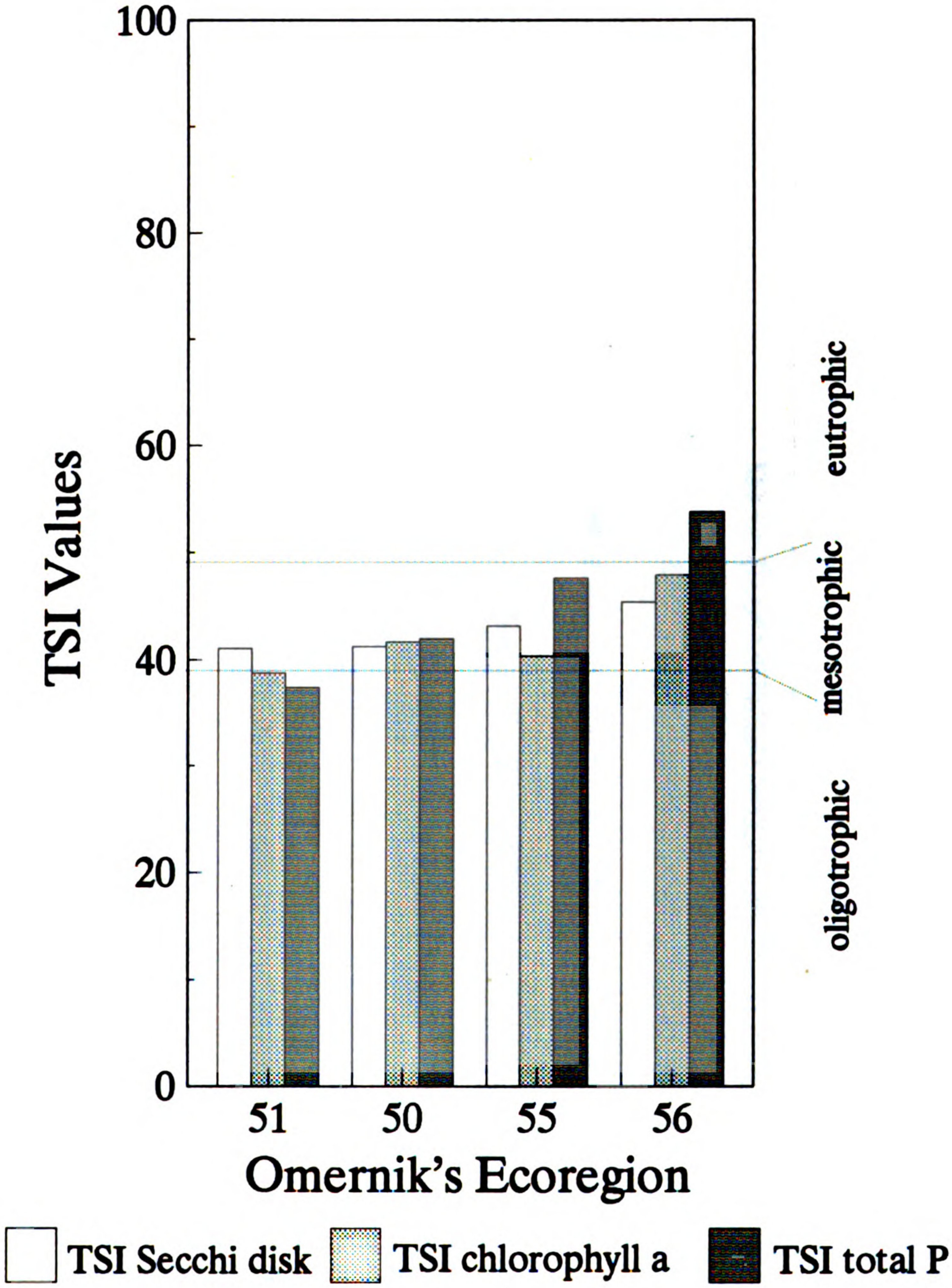

Figure 10. Averaged Carlson's Trophic State Indes values for inland lakes in Lower Michigan, using the ecoregions defined by James Omernik.

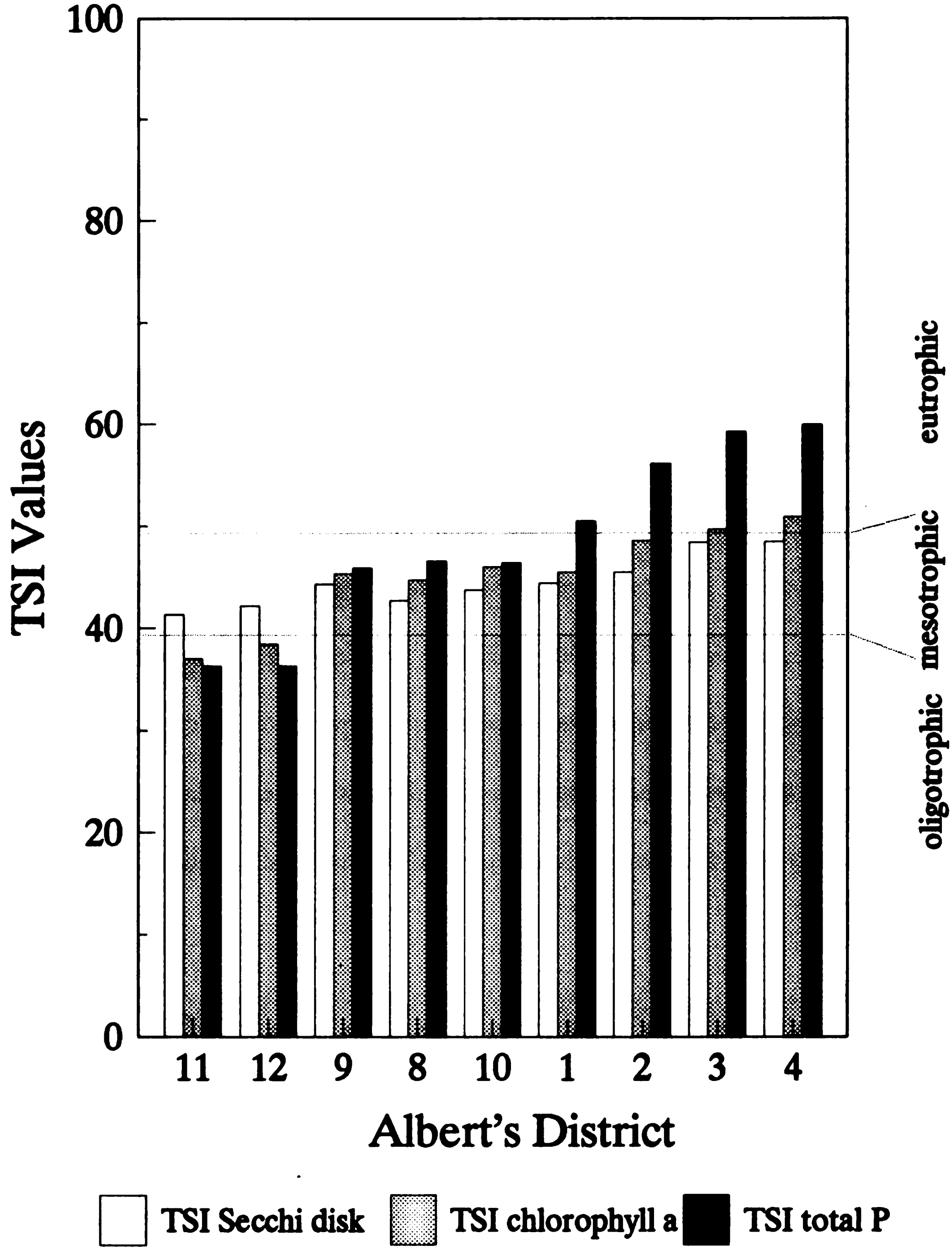

Figure 11. Averaged Carlson's Trophic State Index values for inland lakes in Lower Michigan, using the districts defined by Dennis Albert.

value is higher. District 9 has better agreement among the three TSI values and they are higher overall. District 8 has a higher phosphorus TSI, but the Secchi disk and chlorophyll *a* are lower than district 9. Higher total phosphorus TSI values could indicate that phosphorus is no longer the limiting factor. District 10 has relatively good agreement among the TSI values and is slightly higher than district 8. District 1 has a high phosphorus TSI, over 50, and the others are in the mid 40's. District 2 has slightly higher values in a similar arrangement. District 3 has a very high phosphorus TSI of about 58, the chlorophyll *a* is just below 50 and Secchi disk TSI is about 48. District 4 has the highest overall average values with the phosphorus TSI just at 60 and the others following the pattern of district 3. Districts 11 and 12 with more oligotrophic lakes have total phosphorus TSI values that are lower than the Secchi disk and chlorophyll *a* TSI values. Districts 1, 2, 3, and 4, which have more hypereutrophic, lakes have total phosphorus TSI values that are higher than the Secchi disk and chlorophyll *a* TSI values. Again, as with Omernik's ecoregions there are differences among some of Albert's districts.

DISCUSSION

Ecoregions and Spatial Analysis

Soils are one of the most important factors when considering the productivity of lakes. The soils in Michigan vary widely in color, thickness, texture, chemical composition, biological properties and productivity. Forestry dominates northern Lower Michigan where sandy soils have low fertility. Sandy soils allow leaching of humus, nutrients and other materials. The infiltration rate for these sandy soils is high, water holding capacity is low. Lakes in these areas tend to have low productivity because well washed glacial tills do not have nutrients to add to surface waters.

The oligotrophic lakes, having less than 0.010 mg total P/L, are clustered in the northern tip of Lower Michigan (Figure 12a) where soils are poor and forestry dominates land use. Agriculture is avoided in these areas because of the low fertility of the soils and so the lakes do not receive inputs of phosphorus from agricultural use. Mesotrophic lakes are moderately productive lakes. These lakes are found throughout Lower Michigan. Eutrophic lakes are more productive and are also found throughout Lower Michigan. Both mesotrophic and eutrophic lakes may receive excess nutrients from leaky septic systems of residences around the lake, lawn fertilizers from residences and golf courses, and local agricultural nutrient inputs as well such as from feed lots or crop fields. Lakes in northern Lower Michigan have similarities such as morphometry and sandy soils, but

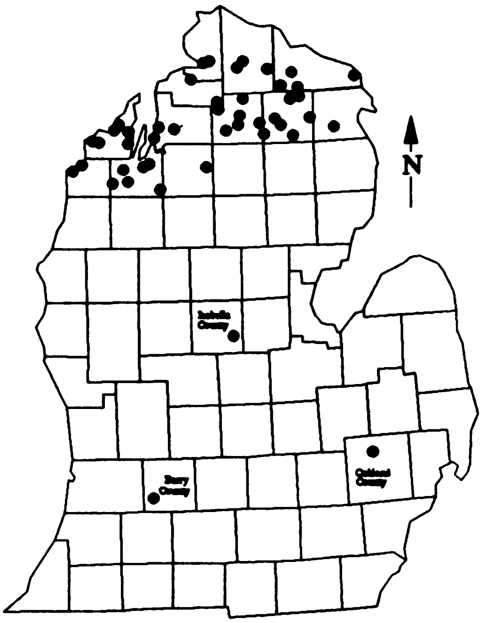

Figure 12a. The location of a subset of oligotrophic lakes in Lower Michigan, having < 0.01 mg P/L.

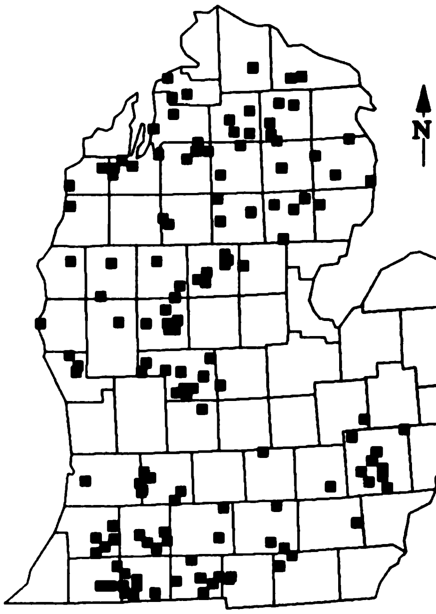

Figure 12b. The location of a subset of mesotrophic lakes in Lower Michigan, having 0.01 to 0.03 mg P/L.

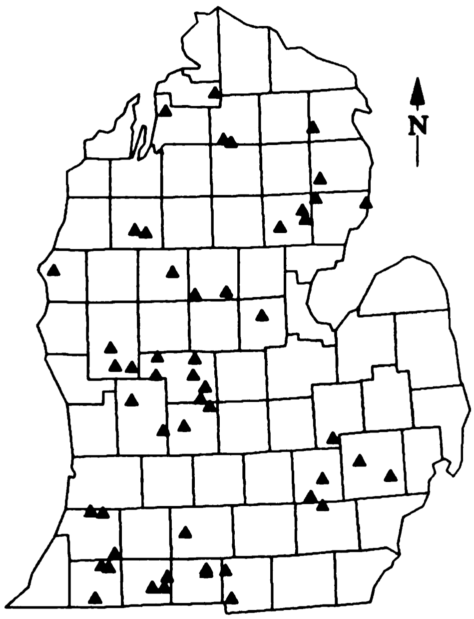

Figure 12c. The location of a subset of eutrophic lakes in Lower Michigan, having 0.03 to 0.05 mg P/L.

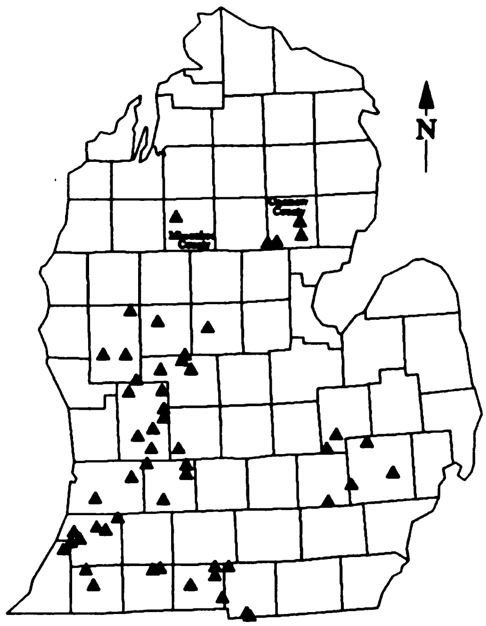

Figure 12d. The location of a subset of hypereutrophic lakes in Lower Michigan, having > 0.05 mg P/L.

nutrients from leaky septic systems, lawn fertilizer runoff and agricultural nutrients will increase productivity because phosphorus does not sorb to the sandy soils. There are a few hypereutrophic (>0.050 mg P/L) lakes in the southern part of northern Lower Michigan, in Ogemaw and Missaukee Counties (Figure 12d).

Lake Missaukee has a high total phosphorus concentration indicating a hypereutrophic condition (Figure 12d.). It is a shallow lake about 27 feet deep at the deepest point and is about 1,880 acres, and alkalinity is somewhat low at 86 mg $CaCO_3$. Lake City borders the lake on the east. Shallow lakes, which do not thermally stratify in the summer, can be very productive (Brylinski and Mann 1974) because nutrients are available during these warm periods (thermal stratification prevents the mixing of nutrients that have settled on the bottom of the lake). If enough phosphorus is provided, as from agriculture or human wastes, these lakes could be quite productive.

Lakes in Ogemaw County are mesotrophic, eutrophic and hypereutrophic. Several lakes in Ogemaw County are hypereutrophic. Soils are a mosaic of clay, sand, loam, and wet sandy and organic soils. Lakes in Ogemaw County are densely populated with houses and summer cottages. Old poorly maintained septic systems leach nutrients into these lakes. Animal waste from feedlots can contribute significant amounts of nutrients to surface waters in these small watersheds. Lake George is 48 feet deep and has a relatively high alkalinity value of 176 mg $CaCO_3$. Tee lake is 62 feet deep and has an alkalinity of 144 mg $CaCO_3$. George lake has a depth of 90 feet and a moderate alkalinity of 119 mg

$CaCO_3$. Hardwood lake is only 35 feet deep and has a moderate alkalinity value of 128 mg $CaCO_3$. The depth and alkalinity concentration for lakes is relevant in considering the possibility of a lake being a marl lake. Lakes that are deeper than neighboring lakes can receive inputs of groundwater that may be supersaturated with CO_2. If this groundwater enters a lake that has relatively high alkalinity (> 150) the CO_2 can cause $CaCO_3$ (marl) to precipitate. Phosphorus can sorb to marl in water and become unavailable for primary production, resulting in an underestimation of phosphorus loading from the watershed.

Agriculture dominates the southern part of Lower Michigan where the soils are more fertile. The infiltration rate for these soils is generally lower and the water holding capacity is greater than for the soils in the upper part of the lower peninsula. In 1969, 595,000 tons of commercial fertilizer was used mostly in the southwest portion and eastern side of the state (Atlas of Michigan 1978). Clearing land for agriculture increases phosphorus loading due to increased overland flow and sedimentation.

Hypereutrophic lakes are found mostly in southern Lower Michigan where soils, climate and topography are good for farming. These lakes occur on the central to southwestern parts of the state because the land has been used for agriculture for many decades and phosphorus from fertilizers has been added to these soils and is washed into the lakes. The mesotrophic and eutrophic lakes in southern Lower Michigan may receive most of their nutrients from agricultural practices rather than residences on the lake as in northern Lower Michigan. The clay soils in the south will bind more of the phosphorus from septic systems and prevent it from leaching into lakes.

There are a few oligotrophic lakes in southern Lower Michigan. Three lakes from my data set that were classified as oligotrophic are Deer lake in Oakland County, Littlefield lake in Isabella County, and Fish Lake in Barry County. These lakes are atypical for their areas. Deer and Fish lakes have moderately high alkalinity values, 213 and 206 mg $CaCO_3$/L while Littlefield has 161 mg $CaCO_3$/L. They are all relatively deep lakes; 63, 66 and 56 feet deep respectively. These two measurements could lead us to believe that these lakes, especially Deer and Fish, may be marl lakes. Again, marl removes phosphorus through adsorption and makes it unavailable for primary productivity.

Lakes on the extreme ends of the trophic scale, oligotrophic and hypereutrophic lakes, are spatially separated. The oligotrophic lakes are in the north and the hypereutrophic lakes are in the south (Figure 13). This results from a change or transition of soil types, land use or other factors that influences total phosphorus concentrations in inland lakes. These two regions could provide the needed lake management regions for highly impacted lakes in the south and relatively unaltered lakes in the north. Combined ecoregions 50 and 51 (Omernik) fit this northern region quite well.

There is a reasonably good fit for the oligotrophic lakes in Omernik's ecoregions 50 and 51 in the north, and for hypereutrophic lakes in ecoregion 56 in the south. The fit is not as good for the mesotrophic lakes or eutrophic lakes

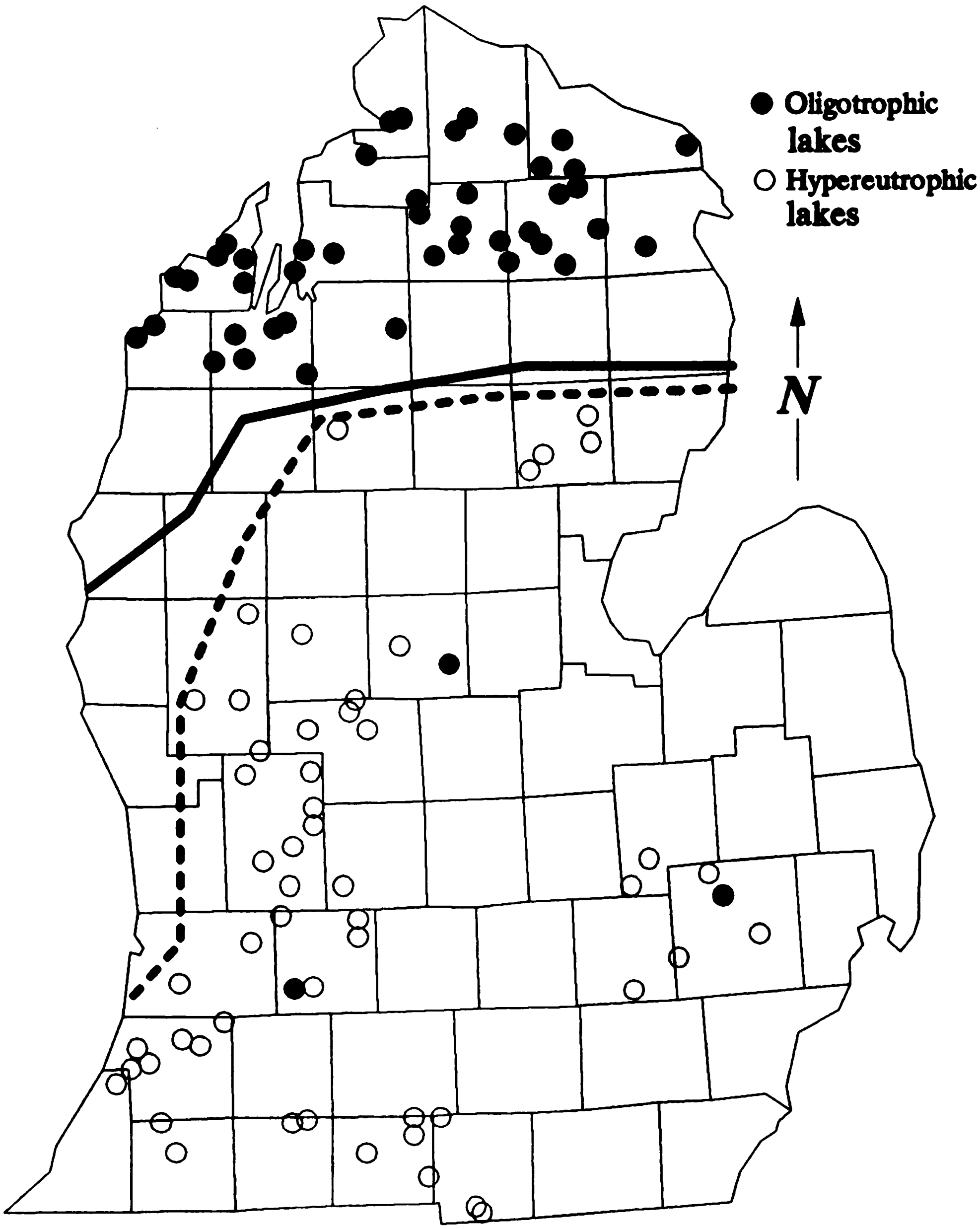

Figure 13. Two lake management regions based on the distribution of oligotrohic lakes in the north and hypereutrophic lakes in the south.

which are in all ecoregions.

Omernik's ecoregion 51 is in the extreme northwestern part of Lower Michigan. There are many oligotrophic and mesotrophic lakes, and few eutrophic or hypereutrophic lakes in this area. The soil types are relatively sandy and low in natural fertility. Thus there are few nutrients to support agriculture or wash into surface waters. Land use in this area is dominated by forest and recreation. Agriculture in this area is dominated by fruit orchards.

Ecoregion 50 is in the extreme northeastern to north central part of Lower Michigan. The physical, biological and chemical influences are similar to ecoregion 51. In my set of lakes there are a few eutrophic lakes in this ecoregion, but only one hypereutrophic lake. Most of the lakes are oligotrophic or mesotrophic. Omernik even had areas that extend from the body of ecoregion 56 that almost include these productive lakes on the edge of ecoregions 50 and 51 (Figures 6c and 6d).

Ecoregion 55 is a small section of Lower Michigan by the Ohio border (Figure 6). The average value of 0.027 mg P/L indicates lakes that are mesotrophic and most of the lakes in ecoregion 55 are mesotrophic. This area is dominated by agriculture which probably has a strong influence on the productivity of these lakes. The soils have more natural fertility than northern soils.

Ecoregion 56 has the highest average values for total phosphorus. The value of 0.044 mg P/L indicates that the area is dominated by eutrophic lakes.

There are only three oligotrophic lakes from my data set but a large number of mesotrophic, eutrophic and hypereutrophic lakes within this large area. This ecoregion covers about two thirds of Lower Michigan including most of the urban centers and agricultural areas of the state. These nutrients are piped into streams and end up in the Great Lakes.

The districts defined by Albert do not work as well for lake management purposes as Omernik's ecoregions. His districts tend to have a north to south orientation due to the his stress on climate and lake effect which will separate shoreline areas from interior sections of Lower Michigan. Albert's Regions I and II (Figure 3a) could be used as lake management regions in Lower Michigan.

An alternate approach for lake management regions would combine Omernik's ecoregions 50 and 51 and Albert's district 10 and the northern parts of districts 3 and 9. Districts 10 and 3 follow the western coast of Lower Michigan along the Lake Michigan coast. This area is dominated by sand dunes. These sandy soils, as mentioned before, have few nutrients to leach into lakes. This suggested area is indicated by the dashed line on Figure 13. There is only one eutrophic lake in district 10, and 5 in the parts of ecoregions 50 and 51 included in this lake management region. No hypereutrophic lakes from my data are within this area.

The polygon map (Figure 5b) based on the total phosphorus values of inland lakes in Lower Michigan has regions having shape, location and orientation similar to the county by county percentage of agriculture (Figure 1). The total phosphorus polygons may agree because the soil types are fertile and reflect natural fertility in inland lakes. The fertile soils contribute nutrients directly to the surface water providing sufficient nutrients for mesotrophic conditions in inland lakes. However when this fertile land is deforested for agriculture inputs of nutrients increase significantly due to increased overland flow and erosion, resulting in eutrophic and hypereutrophic conditions in inland lakes. Thus total phosphorus concentrations in inland lakes also reflect the degree of cultural eutrophication imposed upon lakes.

The total phosphorus concentrations of the lakes increase from their original levels when humans add phosphorus through agriculture or inefficient septic systems for houses around lakes. Lakes that have total phosphorus in the eutrophic or hypereutrophic ranges in southern Lower Michigan, where soils are fertile, are also receiving phosphorus from agricultural runoff. This study did not consider whether or not farms used conservation practices. In addition these lakes have significant residential development and may be receiving nutrients from lawn fertilizers.

Lakes that have total phosphorus concentrations in the mesotrophic or eutrophic range in northern Lower Michigan are not receiving as much phosphorus from agricultural runoff because of limited agricultural practices in areas where infertile sandy soils do not support agriculture. These lakes receive additional phosphorus from old, poorly maintained septic systems, fertilizer from lawns and golf courses, and some from local agriculture. Urban centers and smaller developed communities with sewer systems do not add nutrients to lakes. These wastewater treatment plants usually discharge effluent into streams that empty into one of the Great Lakes.

The polygon map based on the alkalinity of water in the inland lakes in Lower Michigan does not have as good agreement as the total phosphorus polygon map. Alkalinity reflects the base character of the watershed and lake while the total phosphorus reflects human influences such as agriculture. Human influences have masked similarities between alkalinity and total phosphorus.

Carlson's Trophic State Index

Robert Carlson published a paper in 1977, outlining a numerical lake classification method that could be used to determine the trophic status of lakes, the Trophic State Index (TSI). Total phosphorus, chlorophyll *a*, and Secchi disk depth readings are manipulated to fit within a 0-100 ranking. TSI values below 39 are considered to be lakes that are oligotrophic, those between 39 and 49 are mesotrophic and those with TSI values greater than 49 are eutrophic. Carlson's trophic state index was used because it has been suggested that there is a relationship between algal biomass and Secchi disk transparency, total phosphorus concentrations and chlorophyll *a*. This index was designed to provide a continuum of trophic levels rather that three or four separate groupings. This is a useful method of evaluating the trophic status of lakes when dealing with citizen monitoring groups.

The values for the three parameters for an individual lake should generally agree. That is, if the TSI for Secchi disk depth and chlorophyll *a* are both 37 and the TSI for total phosphorus is 60, there is something causing this discrepancy that needs to be investigated. There was general agreement in TSI values for Omernik's ecoregions except for the high phosphorus values in ecoregion 55 and 56. This could indicate that phosphorus may no longer be limiting in these systems, and that nitrogen or carbon may now be the limiting factor for primary productivity. Albert's districts 1, 2, 3, 4 also had high phosphorus TSI values. Districts 1, 2, 3 and 4 cover much of the same area as Omernik's ecoregion 55 and 56 (Figures 1 and 3). Districts 11 and 12 had high Secchi disk TSI values. These could be reflecting sediment or water highly colored from humic acids, rather than the presence of algae. Districts 11 and 12 correspond with the northern most parts of Omernik's ecoregions 50 and 51.

It should be noted that there are differences in the total phosphorus TSI value compared to the Secchi disk and chlorophyll *a* TSI values where either oligotrophic or hypereutrophic lakes are found. In Omernik's ecoregion 50 and 51, and Albert's districts 11 and 12, where we find the oligotrophic lakes, the total phosphorus TSI is lower than the Secchi disk and chlorophyll *a* TSI values. Water can become stained by humic acids in areas dominated by poor sandy soils or suspended sediments can reduce visibility. For Omernik's ecoregions 55 and 56, and Albert's districts 1, 2, 3, and 4, where hypereutrophic lakes are found in abundance, the total phosphorus TSI values are higher than the TSI values for

Secchi disk and chlorophyll *a*. Phosphorus has probably been replaced by nitrogen or carbon as the limiting factor in these cases. This could indicate a problem with Carlson's index when it is used on oligotrophic or hypereutrophic lakes.

Carlson's method was developed using a relatively small set of inland lake in Minnesota and there is some concern that lakes in other states may not have the same associations. Lillie et al. (1993) have adjusted Carlson's TSI equations for use in Wisconsin lakes. Carlson's equations have been altered to consider whether lakes are stratified seepage, stratified drainage, mixed seepage, mixed drainage in the south, central and northern parts of the state. They have twelve equations for each of total phosphorus, Secchi disk and chlorophyll *a*. Because the oligotrophic lakes are in northern Lower Michigan and the hypereutrophic lakes are in the southern Lower Michigan we might need to consider either adopting Wisconsin's method of calculating TSI values or developing our own set of equations. This may not be the way to compensate for high total phosphorus TSI values when phosphorus is no longer limiting however. We could use the Secchi disk and chlorophyll *a* TSI values without the total phosphorus TSI value because they are in closer agreement with each other. Alternately, we could use a TSI formula based on nitrogen when phosphorus is suspected of not being limiting, in eutrophic and hypereutrophic lakes. Used as is, a high phosphorus TSI, using Carlson's equations, may simply indicates phosphorus exceeds a limiting concentration (is no longer limiting).

Simple Regressions

While the mean values for total phosphorus concentrations in inland lakes show apparent differences among ecoregions, the large standard deviation indicates that there is a great amount of variation in the total phosphorus values within a region. This means that there is a wide range of total phosphorus values within regions. There are lakes with high or low total phosphorus values that create these large ranges and standard deviations in total phosphorus. These may be due to a local difference such as a small watershed of a very different soil type or an unusually deep or shallow lake. We need to be aware of these differences to be able to base management practices on realistic goals. There are general trends of similarity that may allow using a regional type of system for a guideline for inland lake management.

Regressions determine the strength of relationship between two variables. The good r^2 values of total phosphorus and chlorophyll *a* for ecoregion 55 for Omernik, and for districts 1, 10 and 12 for Albert support the idea that total phosphorus and chlorophyll *a* are highly correlated. However this was only four of the comparisons analyzed. The other correlations for total phosphorus and chlorophyll *a* were lower meaning that these total phosphorus values do not strongly influence the concentration of algae (chlorophyll *a*) in the water beyond certain other limits. There could be a problem with the chlorophyll fluorescence or phosphorus may not be the limiting factor in these lakes.

Kruskal-Wallis One Way Analysis of Variance

The first step in the Kruskal-Wallis analysis determined that there were differences among the ecoregions (Omernik) or districts (Albert) for alkalinity, total phosphorus, chlorophyll *a*, and Secchi disk depth (While alkalinity, total phosphorus, chlorophyll *a*, and Secchi disk depth were used in this test only total phosphorus will be discussed because of it's relevance to this thesis). This is a relatively conservative test which means that it will not detect subtle differences, but will detect moderate differences among populations.

This test indicates a difference among districts and ecoregions, which appears to be the opposite of the results of simple regressions which shows few strong correlations. Simple regressions indicate the degree of difference between attributes rather than a simple presence or absence of difference as in the Kruskal-Wallis test. The variation in soil types, land use, other physical, chemical and biological factors, and the definitions of areas called ecoregions or districts are supported by the Kruskal-Wallis test.

The second part of the Kruskal-Wallis test, the multiple comparison test, determines which attributes are the source of differences between two areas. In the case of Omernik's ecoregions most of the differences are between ecoregion 56 and 50, and 56 and 51. Differences in productivity indicated by total phosphorus vary between ecoregions in the north (50 and 51) and those in the south (55 and 56).

There are 24 differences between Albert's districts based on total phosphorus from a possible 36. Again most of the differences are between north-south rather than east-west spatial relationships. This indicates a north-south difference in the productivity of inland lakes based on the concentration of total phosphorus in inland lakes. These north-south differences support the use of a northern and southern lake management region in Lower Michigan (Figure 13).

Both Omernik's and Albert's regions indicate a spatial difference in the base character of the surface water based on Secchi disk depth, chlorophyll *a* and alkalinity. These could be useful attributes on which to base regional inland lake management regions when there is a question about whether phosphorus is the best attribute to use because it is no longer limiting.

SUMMARY

Lakes in Lower Michigan that have been impacted by cultural eutrophication can be identified spatially. Hypereutrophic and many eutrophic lakes are in the southern part of Lower Michigan where agriculture is the dominant land use, thus the primary contributor to cultural eutrophication. Excess phosphorus fertilizers applied to agricultural fields will be washed into lakes increasing the total phosphorus concentration of the water. Oligotrophic lakes are in the extreme northern part of Lower Michigan. This is an area where forest, rather than agriculture, dominates land use due to the nature of the sandy soils dominating the area. Mesotrophic and the few eutrophic lakes in northern Lower Michigan have increased nutrients possibly from poorly maintained septic systems for residences around lakes or lawn fertilizers from residences or golf courses, rather than from agriculture because the sandy soils do not support agriculture.

Oligotrophic and hypereutrophic lakes fit quite well into ecoregions defined by James Omernik. The oligotrophic lakes are in northern Lower Michigan, ecoregions 50 and 51. The hypereutrophic and most of the eutrophic lakes fit into ecoregion 56. The mesotrophic lakes did not fit exclusively into any one or two ecoregions, but rather covered all of Lower Michigan. Combining Albert's district 10 and the northern parts of districts 3 and 9 with Omernik's ecoregions 50 and 51 makes a logical northern lake management region for regional inland lake management. This region is dominated by sand dunes on the west coast of Lower Michigan and sandy soils in the norther fourth of Lower Michigan. A southern lake management region covers the remainder of Lower Michigan, ecoregions 55 and 56..

While ecoregions and districts can be combined to define general areas that coincide with lakes of various trophic levels, lake management regions should be based on water quality parameters rather than broad general terrestrial parameters. Total phosphorus, alkalinity, Secchi disk depth, chlorophyll *a*, or physical parameters that contribute directly to water quality such as soil type and land use could be used. Watershed analysis could provide nonpoint source pollution (phosphorus) information regarding land use or septic system inputs of phosphorus (Tsatsaros 1993). Lake management regions should include the entire Great Lakes Basin, resulting in a regional Lake Management tool for Michigan, Wisconsin, Minnesota, northern Ohio and Ontario. These lake management regions provide a reasonable first step in determining attainable water quality for inland lakes in Lower Michigan. It could be a useful tool for national or state water quality managers such as the EPA or MDNR.

We should concentrate our lake management efforts in Lower Michigan to those lakes that have been impacted the least, the oligotrophic lakes. These lakes are found mainly in northern Lower Michigan where soils tend to be sandy and forest dominates land use. As people move north when they retire, and year round lake use increases due to our increasing mobility, we need to monitor these lakes. The sandy soils that have not supported agriculture in the north also makes these lakes vulnerable to other sources of phosphorus pollution, such as poorly maintained septic systems or fertilizers from lawns of riparian residences or golf courses. Sandy soils do not have the cation exchange capacity that clay soils have, and so phosphorus will percolate through the soils and run into the groundwater and lakes.

Mesotrophic lakes are a second priority for management efforts. The mesotrophic lakes have potential for maintenance of good water quality. Mesotrophic lakes in southern Lower Michigan might benefit from watershed analysis to determine the source of nutrient inputs, and Best Management Practices by agriculture. Mesotrophic lakes in the north would benefit from a reduction of lawn fertilizer, more frequent septic system maintenance and prudent placement of new septic systems.

It would have been interesting to see what the inland lakes were like fifty or sixty years ago, before the impacts of humans. We have to be content with making assumptions about what these lakes were like before agricultural activity dominated the landscape. The lakes in southern Lower Michigan may not have been the clear, blue lakes of the north because of the soils types that dominate the south. What ever condition the lakes were in and are in now, we should use preventative methods to conserve this resource.

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