Indiana Lake Water Quality Assessment Report For 1999 - 2003

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Acknowledgments

This report was written by William W. Jones and Selena Medrano, with data analyses and graphics prepared by Selena Medrano, both of Indiana University's School of Public and Environmental Affairs (SPEA). It represents five years of traversing the State of Indiana, reading maps, searching for lake access, extracting stuck trailers, seemingly endless washing of laboratory glassware, and most importantly, having the opportunity to visit and sample the beautiful and varied lakes of Indiana. This work required the dedicated efforts of many people. Therefore, it is with gratitude that we recognize the superb efforts of the following SPEA graduate students who conducted the lake sampling and laboratory analyses of the water samples: Robin Lutton, Brandon Stuery, Nathan Bowden, Jessica Caplinger, Sara Peel, Candice Crutcher, Joel Klumpp, Nick Haxton, Jan Hosier, Mary Wilson, Theresa Wilson, Sean Graham, Emily Williams, Sarah Panter, Wendy Drake, Brad Schroeder, Marisa Shetlar, Joanna Kind, and Liz Zelasko.

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INDIANA CLEAN LAKES PROGRAM

The Indiana Clean Lakes Program was created in 1989 as a program within the Indiana Department of Environmental Management's (IDEM) Office of Water Management. The program is administered through a grant to Indiana University's School of Public and Environmental Affairs (SPEA) in Bloomington. The Indiana Clean Lakes Program is a comprehensive, statewide public lake management program having five components:

1. Public information and education
2. Technical assistance
3. Volunteer lake monitoring
4. Lake water quality assessment
5. Coordination with other state and federal lake programs.

This document is a summary of lake water quality assessment results for 1999-2003.

Lake Water Quality Assessment

The goals of the lake water quality assessment component include: (a) identifying water quality trends in individual lakes, (b) identifying lakes that need special management, and (c) tracking water quality improvements due to industrial discharge and runoff reduction programs (Jones 1996).

Public lakes are defined as those that have navigable inlets or outlets or those that exist on or adjacent to public land. Only public lakes that have boat trailer access from a public right-of-way are generally sampled in this program. Sampling occurs in July and August of each year to coincide with the period of thermal stratification and the period of poorest annual water quality in lakes. Approximately 80 lakes are assessed each summer proceeding geographically through the state to minimize travel costs.

Sampling occurs at one site on each lake and is positioned over the deepest part of the lake. Profile measurements of dissolved oxygen (D.O.) and temperature are taken at 1 meter intervals from the surface to the bottom of the lake. Water samples for chemical analyses are collected from one meter below the water surface and from 1-2 meters above the lake bottom.

Sampling one site at each lake every 5 years is not the ideal frequency for data gathering. However, this protocol allows for gathering data from as many lakes as possible within a reasonable time frame and financial budget. The current protocol also reduces seasonal variability in sampling (Jones 1996).

Water Quality Parameters Included in Lake Assessments

Monitoring lakes requires many different parameters to be sampled. The parameters analyzed in this assessment include:

Phosphorus: Phosphorus is an essential plant nutrient and most often controls aquatic plant (algae and macrophyte) growth in freshwater. It is found in fertilizers, human and animal wastes, and yard waste. There is no atmospheric (vapor) form of phosphorus. Because there are few natural sources of phosphorus and the lack of an atmospheric cycle, phosphorus is often a ***limiting nutrient*** in aquatic systems. This means that the relative scarcity of phosphorus may limit the ultimate growth and production of algae and rooted aquatic plants. Therefore, management efforts often focus on reducing phosphorus input to a receiving waterway because: (a) it can be managed, and (b) reducing phosphorus can reduce algae production. Two common forms of phosphorus are:

> ***Soluble reactive phosphorus (SRP) –*** SRP is dissolved phosphorus readily usable by algae. SRP is often found in very low concentrations in phosphorus-limited systems where the phosphorus is tied up in the algae and cycled very rapidly. Sources of SRP include fertilizers, animal wastes, and septic systems.
>
> ***Total phosphorus (TP) –*** TP includes dissolved and particulate forms of phosphorus. TP concentrations greater than 0.03 mg/L (or 30μg/L) can cause algal blooms in lakes and reservoirs.

Nitrogen: Nitrogen is an essential plant nutrient found in fertilizers, human and animal wastes, yard waste, and the air. About 80% of the atmosphere is nitrogen gas. Nitrogen gas diffuses into water where it can be "fixed" (converted) by blue-green algae to ammonia for algal use. Nitrogen can also enter lakes and streams as inorganic nitrogen and ammonia. Because nitrogen can enter aquatic systems in many forms, there is an abundant supply of available nitrogen in these systems. The three common forms of nitrogen are:

> ***Nitrate (NO_3^-) –*** Nitrate is an oxidized form of dissolved nitrogen that is converted to ammonia by algae under anoxic (low or no oxygen) conditions. It is found in streams and runoff when dissolved oxygen is present, usually in the surface waters.
>
> ***Ammonia (NH_4^+) –*** Ammonia is a form of dissolved nitrogen that is readily used by algae. It is the reduced form of nitrogen and is found in water where dissolved oxygen is lacking such as in a eutrophic hypolimnion. Important sources of ammonia include fertilizers and animal manure. In addition, ammonia is produced as a by-product by bacteria as dead plant and animal matter are decomposed.
>
> ***Organic Nitrogen (Org N) –*** Organic nitrogen includes nitrogen found in plant and animal materials and may be in dissolved or particulate form. In the analytical procedures, total Kjeldahl nitrogen (TKN) was determined. Organic nitrogen is TKN minus ammonia.

Light Transmission: This measurement uses a light meter (photocell) to determine the <u>rate</u> at which light transmission is diminished in the upper portion of the lake's water column. Another important light transmission measurement is determination of the 1% light level. The 1% light level is the water depth to which one percent of the surface light penetrates. The 1% light level is considered the lower limit of algal growth in lakes and this area and above is referred to as the *photic zone.*

Dissolved Oxygen (D.O): D.O. is the dissolved gaseous form of oxygen. It is essential for respiration of fish and other aquatic organisms. D.O. enters water by diffusion from the atmosphere and as a by-product of photosynthesis by algae and plants. Epilimnetic waters continually equilibrate with the concentration of atmospheric oxygen. Excessive algae growth can over-saturate (greater than 100% saturation) the water with D.O when rate of photosynthesis production is greater than the rate of oxygen diffusion to the atmosphere. Hypolimnetic D.O. concentration is typically low as there is no mechanism to replace oxygen that is consumed by respiration and decomposition. Fish need at least 3-5 mg/L of D.O. to survive.

Secchi Disk Transparency: Secchi disk transparency refers to the depth to which the black and white Secchi disk can be seen in the lake water. Water clarity, as determined by a Secchi disk, is affected by two primary factors: algae and suspended particulate matter. Particulates (soil or dead leaves) may be introduced into the water by either runoff or sediments already on the bottom of the lake. Erosion from construction sites, agricultural lands, and riverbanks all lead to increased runoff. Bottom sediments may be resuspended by bottom-feeding fish such as carp, or by motorboats or strong winds in shallow lakes.

Plankton: Plankton are important members of the aquatic food web. Plankton includes algae (microscopic plants) and zooplankton (tiny shrimp-like animals that eat algae). Plankton are collected by filtering water through a very fine mesh net (63-micron openings = 63/1000 millimeter). The plankton net is towed up through the lake's water column from the one percent light level to the surface. Blue-green algae are those that most often form nuisance blooms and their dominance in lakes may indicate poor water conditions.

Chlorophyll *a*: The plant pigments of algae consist of the chlorophylls (green color) and carotenoids (yellow color). Chlorophyll *a* is the most dominant chlorophyll pigment. Thus, chlorophyll *a* is often used as a direct estimate of algal biomass.

LAKE CLASSIFICATION

There are many factors that influence the condition of a lake including physical dimensions (*morphometry)*, nutrient concentrations, oxygen availability, temperature, light, and fish species. In order to simplify the analysis of lakes, there are a variety of lake classifications that are used. Lake classifications serve to aid in the decision-making process, in prioritizing, and in creating public awareness. Lakes can be classified based on their origin, thermal stratification regime, or on trophic status.

Lake Origin Classification

Hutchinson (1957) classified lakes according to how they were formed which resulted in 76 different classifications; the following are important to Indiana.

***Glacial Lakes* –** As the ice sheets moved south and then receded, they created several types of lakes including scour lakes and kettle lakes. **Scour lakes** are formed when the sheet moves over the land creating a groove in the surface of the earth which later fills with meltwater. **Kettle lakes** are formed when large chunks of ice deposited by the glacier leave depressions in the landscape that fill in with water. The majority of lakes in Indiana are kettle lakes including Lake Tippecanoe, the deepest lake (123 feet), and Lake Wawasee, the largest lake (3,410 acres).

Glacial lakes in Indiana are primarily in the north and found between the western Valparaiso Morainal Area and the eastern Steuben Morainal Area (Figure 1).

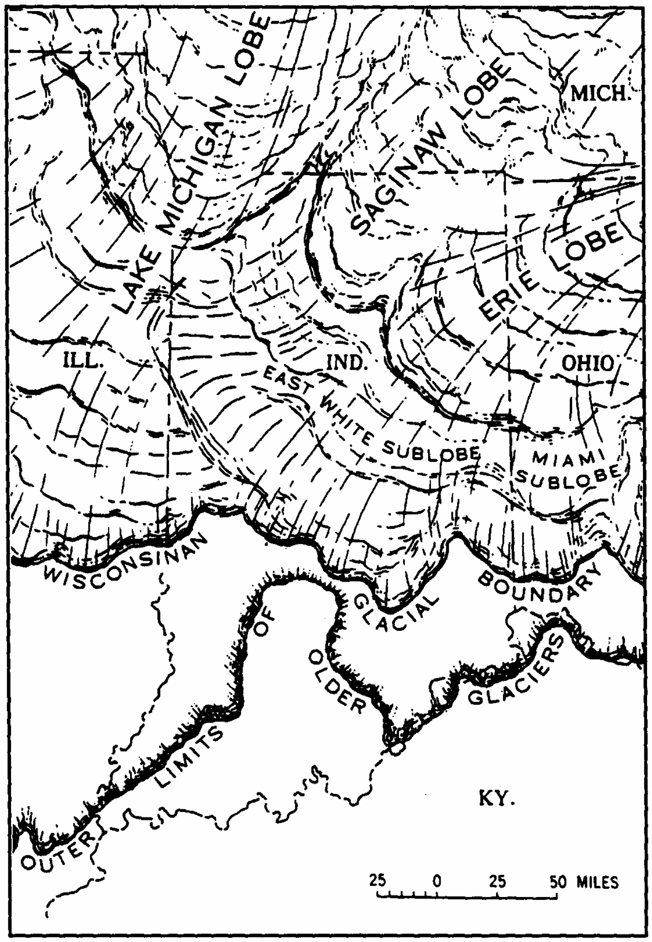


Figure 1. The Lake Michigan, Saginaw, and Erie lobes of the most recent glacial episode affected northern Indiana. Glacial lakes are thus limited to this part of the state.

Solution Lakes – Solution lakes form when water collects in basins formed by the solution of limestone found in regions of karst topography. These lakes tend to be circular and are primarily found in the Mitchell Plain of southern Indiana.

Oxbow Lakes – Oxbow lakes are formed from former river channels that have been isolated from the original river channel due to deposition of sedimentation or erosion. Oxbow lakes can be found throughout the State of Indiana.

Artificial Lakes – Artificial lakes are created by humans due to excavation of a site or to damming a stream or river. Artificial lakes include ponds, strip pits, borrow pits, and reservoirs (Jones 1996). Reservoirs are typically elongate with many branches representing the tributaries of the former stream or river. Strip pits are found in southwestern Indiana where coal mines are located. All types of artificial lakes may be found throughout the State of Indiana.

Trophic Classification

Trophic state is an indication of a lake's nutritional level or biological productivity. The following definitions are used to describe the tropic state of a lake:

Oligotrophic – lakes with clear waters, low nutrient levels (total phosphorus < 6 µg/L), supports few algae, hypolimnion has dissolved oxygen, and can support salmonids (trout and salmon).

Mesotrophic – water is less clear, moderate nutrient levels (total phosphorus 10-30 µg/L), support healthy populations of algae, less dissolved oxygen in the hypolimnion, and lack of salmonids.

Eutrophic – water transparency is less than 2 meters, high concentrations of nutrients (total phosphorus > 35 µg/L), abundant algae and weeds, lack of dissolved oxygen in the hypolimnion during the summer.

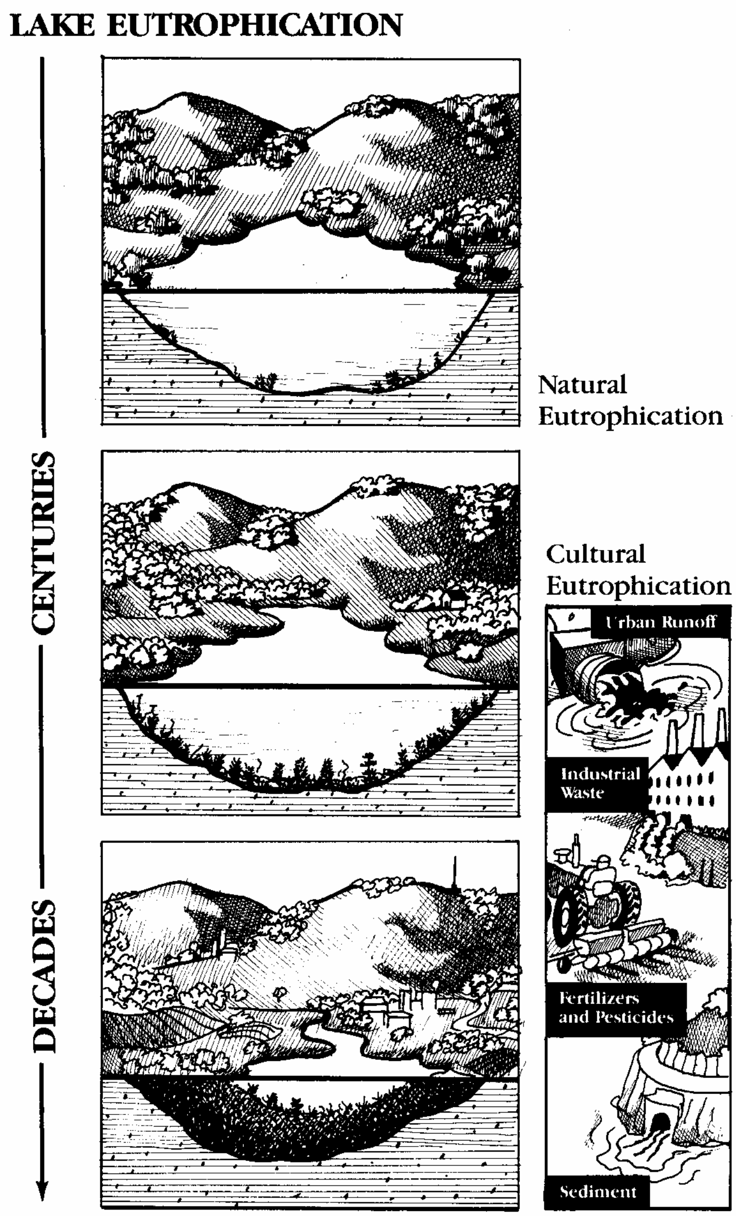
Hypereutrophic – water transparency less than 1 meter, extremely high concentrations of nutrients (total phosphorus > 80 µg/L), thick algal scum, dense weeds.

Eutrophication is the biological response observed in a lake caused by increased nutrients, organic material, and/or silt (Cooke et al., 1993). Nutrients enter the lake through runoff or through eroded soils to which they are attached. Increased nutrient concentrations stimulate the growth of aquatic plants. Sediments and plant remains accumulate at the bottom of the lake decreasing the mean depth of the lake. The filling-in of a lake is a natural process that usually occurs over thousands of years. However, this natural process can be accelerated by human activities such as increased watershed erosion and increased nutrient loss from the land. This ***cultural eutrophication*** can degrade a lake in as little as a few decades (Figure 2).

Although it is widely known that nutrients, especially phosphorus, are responsible for increased productivity, the concentration of nutrients alone cannot determine the trophic state of a lake. Other factors such as the presence of algae and weeds aid in the determination of the trophic status, and other factors such as light and temperature impact the growth of algae and weeds.

Trophic State Indices

Due to the complex nature and variability of water quality data, a trophic state index (TSI) is used to aid in the evaluation of water quality data. In a TSI, points of varying amounts are defined for specific concentrations or parameters. The total of these points represents the standardized trophic status of a lake which can be compared in different years or can be compared to other lakes. When using a TSI for comparison, it is important to consider the actual data. When the data are reduced to a single number for a TSI, the single number itself is not informative.



The natural process by which lakes form, evolve and disappear takes thousands of years. Human activites, however, can change these lakes — for better or worse — in less than a single generation.

Figure 2. Lake eutrophication. Adapted from Freshwater Foundation (1985).

The Indiana Trophic State Index

The original purpose of the Indiana State Tropic Index (ITSI) was to identify lakes with problems and to determine the reasons for complaints from lake users. The ITSI was not used to rank Indiana lakes until the mid 1970's.

The ITSI consists of 10 metrics (Table 1), all of which must be evaluated in order to achieve an accurate score. The metrics include biological, chemical, and physical parameters. Water samples for nitrogen and phosphorus are collected and analyzed from both the epilimnion and the hypolimnion and the mean of the values is assigned a certain number of eutrophy points based on the mean concentration.

TABLE 1. The Indiana Trophic State Index

Parameter and Range			Eutrophy Points
I.	Total Phosphorus (μg/L)		
	A.	At least 30	1
	B.	40 to 50	2
	C.	60 to 190	3
	D.	200 to 990	4
	E.	1000 or more	5
II.	Soluble Phosphorus (μg/L)		
	A.	At least 30	1
	B.	40 to 50	2
	C.	60 to 190	3
	D.	200 to 990	4
	E.	1000 or more	5
III.	Organic Nitrogen (mg/L)		
	A.	At least 0.5	1
	B.	0.6 to 0.8	2
	C.	0.9 to 1.9	3
	D.	2.0 or more	4
IV.	Nitrate (mg/L)		
	A.	At least 0.3	1
	B.	0.4 to 0.8	2
	C.	0.9 to 1.9	3
	D.	2.0 or more	4
V.	Ammonia (mg/L)		
	A.	At least 0.3	1
	B.	0.4 to 0.5	2
	C.	0.6 to 0.9	3
	D.	1.0 or more	4

Indiana Trophic State Index (continued)

VI.	Dissolved Oxygen: Percent Saturation at 5 feet from surface		
	A.	114% or less	0
	B.	115% 50 119%	1
	C.	120% to 129%	2
	D.	130% to 149%	3
	E.	150% or more	4
VII.	Dissolved Oxygen: Percent of measured water column with at least 0.1 ppm dissolved oxygen		
	A.	28% or less	4
	B.	29% to 49%	3
	C.	50% to 65%	2
	D.	66% to 75%	1
	E.	76% 100%	0
VIII.	Light Penetration (Secchi Disk)		
	A.	Five feet or under	6
IX.	Light Transmission (Photocell) Percent of light transmission at a depth of 3 feet		
	A.	0 to 30%	4
	B.	31% to 50%	3
	C.	51% to 70%	2
	D.	71% and up	0
X.	Total Plankton per liter of water sampled from a single vertical tow between the 1% light level and the surface:		
	A.	less than 3,000 natural units/L	0
	B.	3,000 - 6,000 natural units/L	1
	C.	6,001 - 16,000 natural units/L	2
	D.	16,001 - 26,000 natural units/L	3
	E.	26,001 - 36,000 natural units/L	4
	F.	36,001 - 60,000 natural units/L	5
	G.	60,001 - 95,000 natural units/L	10
	H.	95,001 - 150,000 natural units/L	15
	I.	150,001 - 5000,000 natural units/L	20
	J.	greater than 500,000 natural units/L	25
	K.	Blue-Green Dominance: additional points	10

In the Indiana Trophic State Index, the total eutrophy points range from 0 to 75. Oligotrophic conditions are represented with a score of 0 to 15. Mesotrophic conditions score 16 to 30 points. Eutrophic conditions score 31 to 45. Hypereutrophic lakes have ITSI scores greater than 46.

The higher the number of eutrophy points assigned to a parameter, the more likely that parameter is to support increased productivity in the lake. In general, eutrophy points range from 1 to 4. However, the scale is weighted based on the amount of plankton in the sample and the dominance of blue-green algae in the sample. Extra weight is given to the presence of algae due to public perception of poor water quality. Eutrophy points for all metrics are then summed to produce the final ITSI score for the lake.

The Carlson Trophic State Index

The Carlson Trophic State Index, developed by Bob Carlson (1977) is the most widely used TSI in the United States (Figure 3). Carlson used mathematical equations developed from the relationships observed between summer measurements of Secchi disk transparency, total phosphorus, and chlorophyll *a* in northern temperate lakes. Through Carlson's TSI, one parameter, Secchi disk transparency, total phosphorus, or chlorophyll *a*, can be used to yield a TSI value for that lake. One parameter can also be used to predict the value of the other parameters. Values for the Carlson's TSI range from 0 to 100 and each TSI division of 10 represents a doubling of algal biomass.

Not all lakes exhibit the same relationship between Secchi disk transparency, total phosphorus, and chlorophyll *a* that Carlson's lakes show; however, Carlson's TSI gives valuable insight into the functioning of a particular lake.

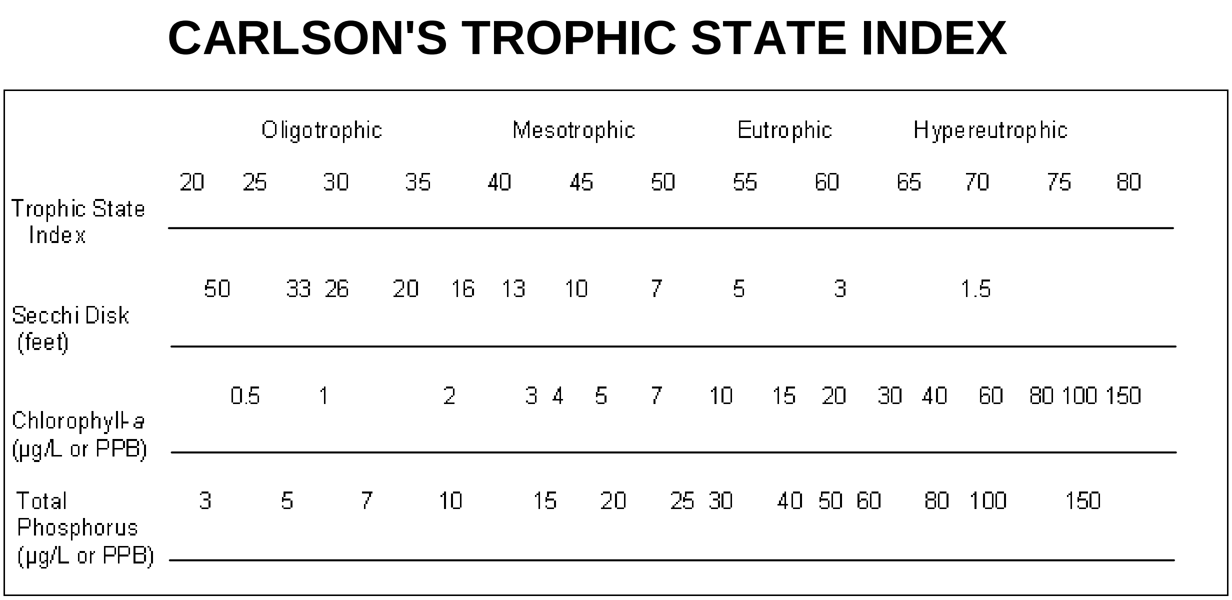


Figure 3. The Carlson Trophic State Index.

Ecoregion Descriptions

When we say that 'lakes are a reflection of their watershed' we refer to not only land use activities within the watershed that may influence lake characteristic, but also soil types, land slope, natural vegetation, climate, and other factors that define the ecological region or *ecoregion*. Omernik and Gallant (1988) defined ecoregions in the Midwest (Figure 4); the boundaries of these ecoregions were determined through the examination of land use, soils, and potential natural vegetation. These ecoregions have similar ecological properties throughout their range and these properties can influence lake water quality characteristics. The six ecoregions present in Indiana are described in Figure 4.

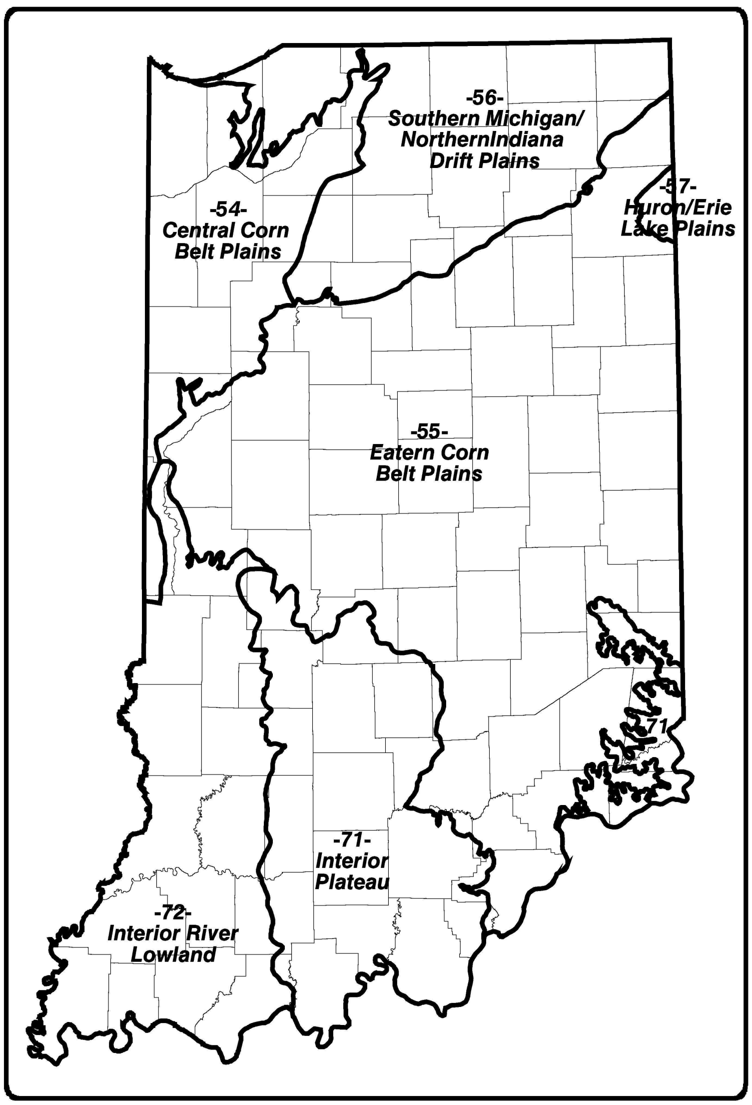


Figure 4. Ecoregions of Indiana.

Central Corn Belt Plains (#54): This ecoregion covers 46,000 square miles of Indiana and Illinois. This ecoregion is primarily cultivated for feed crops, only 5% of the area is woodland. Crops and livestock are responsible for the nonpoint source pollution in this region.

Eastern Corn Belt Plains (#55): This ecoregion covers 31,800 square miles of Indiana, Ohio, and Michigan. Hardwood forests can thrive in this area; 75% of the land is used for crop production. Few natural lakes or reservoirs are in this area.

Southern Michigan/Northern Indiana Till Plain (#56): This region covers 25,800 square miles of Michigan and Indiana. Oak-hickory forests are the dominant vegetation in this area; however, 25% of this area is urbanized.

Huron/Erie Lake plain (#57): This region covers 11,000 square miles of Indiana, Ohio, and Michigan. This area used to be occupied by forested wetlands; however, the primary use is now farming and 10% of this region is urbanized. No lakes in this region were included in this study.
Interior Plateau (71): This area occupies 56,000 square miles from Indiana and Ohio down to Alabama. Land is used for pasture, livestock, and crops. Woodlands and forests remain in this area. There are many quarries and coal mines in this area; however, there are few natural lakes.

Interior River Lowland (#72): This area covers 29,000 square miles in Indiana, Kentucky, Illinois, and Missouri. One third of this area is maintained as oak-hickory forest; other land uses include pasture, livestock, crops, timber, and coal mines. Water quality disturbances come from livestock, crops, and surface mining.

METHODS

In July and August of each year, approximately 80 Indiana lakes are sampled by the Indiana Clean Lakes Program. All of Indiana's boat-accessible, public lakes are sampled on a 5-year rotational basis.

Field Procedures

Water samples are collected from 1 meter below the surface and from 1 meter above the bottom of the lake. Water samples taken for soluble reactive phosphorus (SRP), total phosphorus (TP), nitrate (NO_3^-), ammonia (NH_4^+), and total Kjeldahl nitrogen (TKN) are collected by using a Kemmerer water sampling device. SRP is filtered in the field using a 45-micron filter and a hand pump. Prior to sampling, the TP, nitrate/ammonia, and TKN bottles are acidified with 0.125 ml of sulfuric acid (H_2SO_4).

Dissolved oxygen (D.O.) is measured using a YSI Model 85 Temperature/Dissolved Oxygen/Conductivity Meter. Measurements are taken at 1-meter intervals through the water column to the lake bottom.

Secchi disk transparency measurements are determined by the depth at which the black and white disk is no longer visible in the water column.

Light penetration is measured with a Beckman EV3 Enviroeye meter. The light meter is calibrated at the surface and light penetration is then measured every foot from the surface to where the light is 1% of that at the surface.

Plankton samples are collected with a tow net that is lowered to the 1% light level as determined by the light meter. The water is filtered through a fine-mesh net (63-microns) that concentrates the plankton. The plankton are washed into an opaque bottle with ultra-pure water and Lugol's solution is added to preserve the sample based on the volume of the sample (4 cc/100 ml).

Chlorophyll *a* is collected with an integrated sampler that reaches to a 2-m depth. The apparatus is shut, retrieved, and poured into a pitcher. The sample is shaded and filtered with Whatman GF/C filter paper using a hand pump. The sample is filtered until the flow of water passing through the filter is minimal and the volume of sample filtered is recorded. The filter paper is removed, placed in a bottle, and surrounded by ice.

Lab Procedures

SRP is determined using the ascorbic acid method and measured colormetrically on a spectrophotometer (APHA, et al. 1998). TP samples are digested in hot acid to convert particulate phosphorus to dissolved phosphorus. After pH adjustment, the samples are analyzed as for SRP.

NO_3^- and NH_4^+ samples are filtered in the lab using a 0.45 micron membrane filter and a hand pump. This analysis is run on an Alpkem Flow Solution Model 3570 autoanalyzer (OI Analytical, 2000). TKN samples are first digested in hot acid before being analyzed on the autoanalyzer.

One milliliter of plankton sample is transferred to a Sedgwick-Rafter Cell for identification and enumeration. Fifteen random fields are selected and the genera are identified at 100x magnification. For the *Crustacea*, the entire slide is examined under the 4x objective to count all organisms in the sample. Algae are reported as *natural units*, which records one colonial filament of multiple cells as one natural unit and one cell of a singular alga also as one natural unit. The number of organism per liter is then calculated. Plankton identifications were made according to: Ward and Whipple (1959), Prescott (1982), Whitford and Schumacher (1984), and Wehr and Sheath (2003).

Chlorophyll filters are placed in the freezer upon arriving to the lab. Once frozen, the filters are ground using 90% aqueous acetone to extract the chlorophyll and read on a spectrophotometer. Samples are corrected for pheophyton pigments.

All sampling techniques and laboratory analytical methods were performed in accordance with procedures in *Standard Methods for the Examination of Water and* Wastewater, 20th Edition (APHA, 1998).

RESULTS

Compiled physical, chemical, and biological data of the 425 lakes that were sampled from 1999 to 2003 are presented in the appendices (Appendix A (1999), Appendix B (2000), Appendix C (2001), Appendix D (2002), and Appendix E (2003). *The Indiana Water Resource* (Clark 1980) and the *Indiana Lakes Guide* (IDNR 1993) were the sources of lake areas and depths; however, maximum lake depth was revised based on the maximum depth observed while sampling the lake.

Morphometry

Ecoregion 56 contains 239 lakes, the largest number of lakes sampled in one ecoregion in this study while ecoregion 54 had 21 lakes, the fewest number of lakes sampled in an ecoregion. Ecoregion 55 had the largest median surface area of 81 ha while ecoregion 72 had the smallest median surface area of 4.9 ha (Figure 5). Ecoregions 54 and 56 had similar median lake areas of 26.3 ha and 27.5 ha respectively. Ecoregion 71 had a median lake area of 43 ha. Ecoregion 56 has the deepest median lake depth of 10.1 m (Figure 7). The other ecoregions had median lake depths ranging from 7.3 m to 7.9 m.

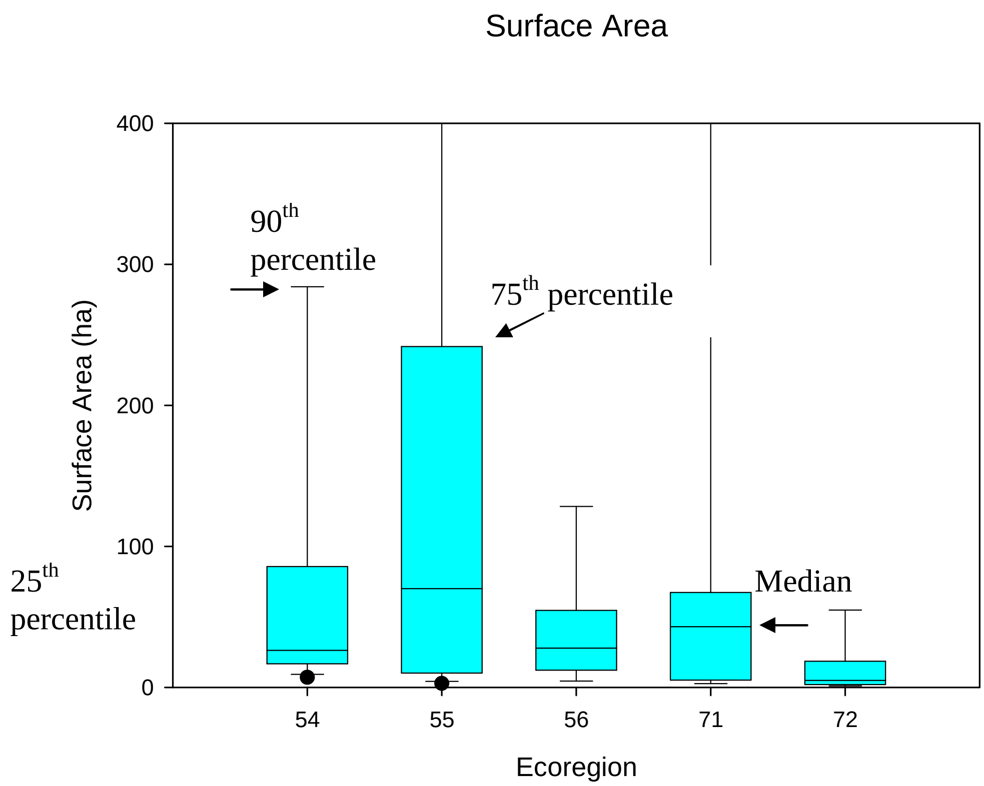


Figure 6: Box and whisker plot showing the distribution of surface areas among lakes by ecoregion. A short box indicates that was little difference in surface area of the sample lakes whereas a long box shows that lakes in the ecoregion varied greatly in size.

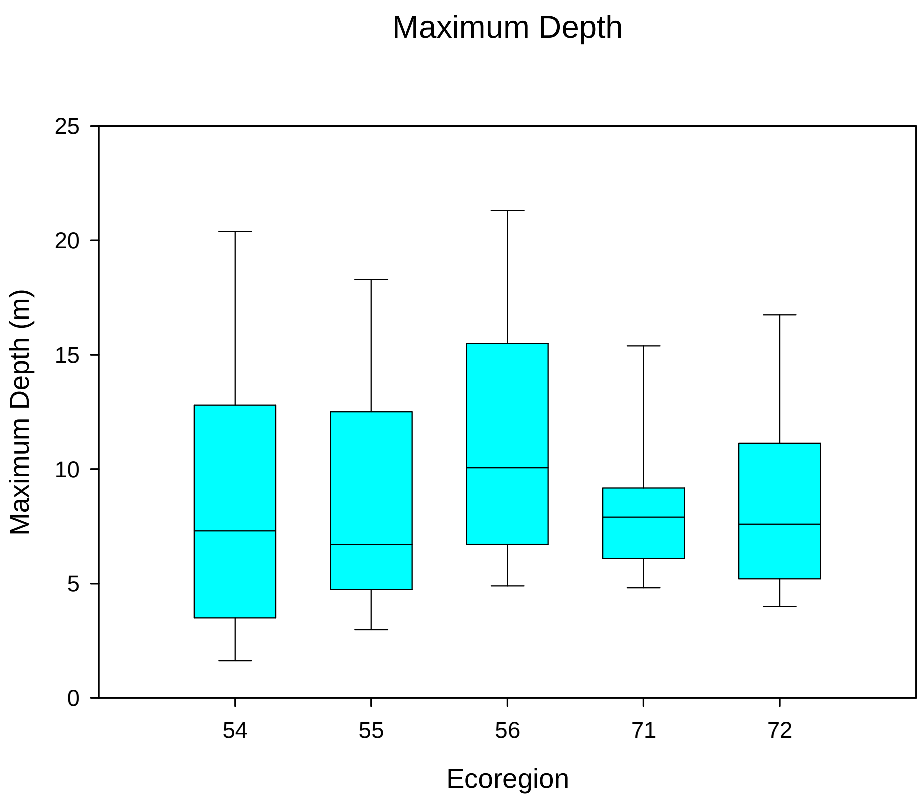


Figure 7: Median maximum depth of lakes by ecoregion

Water Chemistry

Secchi Disk Transparency: Lakes within Ecoregion 71 had the deepest median Secchi disk transparencies of 2.5 m (Figure 8). Ecoregion 72 lakes had the second deepest median Secchi disk transparencies of 2.3 m. Lakes within Ecoregions 56 and 54 had median Secchi disk transparency depths of 1.8 m and 1.6 m respectively. Lakes within Ecoregion 55 had the shallowest median Secchi depth of only 0.7 m.

Total Phosphorus: Lakes within Ecoregion 54 had the highest median phosphorus concentrations of 0.130 mg/L (Figure 9). Ecoregion 55 lakes had a median phosphorus concentration of 0.121 mg/L. Ecoregion 56 lakes had a median phosphorus concentration of 0.079 mg/L. Lakes within Ecoregion 72 had a median phosphorus concentration of 0.70 mg/L while lakes within Ecoregion 71 had the lowest median phosphorus concentration of 0.045 mg/L.

Chlorophyll a: Ecoregion 56 had the highest median chlorophyll *a* concentration of 17.14 mg/m^3 (Figure 10). Ecoregion 55 had a median chlorophyll *a* concentration of 5.34 mg/m^3. Ecoregion 56 had a median chlorophyll *a* concentration of 3.72 mg/m^3. Ecoregion 72 had a median chlorophyll *a* concentration of 1.36 mg/m^3. Ecoregion 71 had the lowest median chlorophyll *a* concentration of 0.86 mg/m^3.

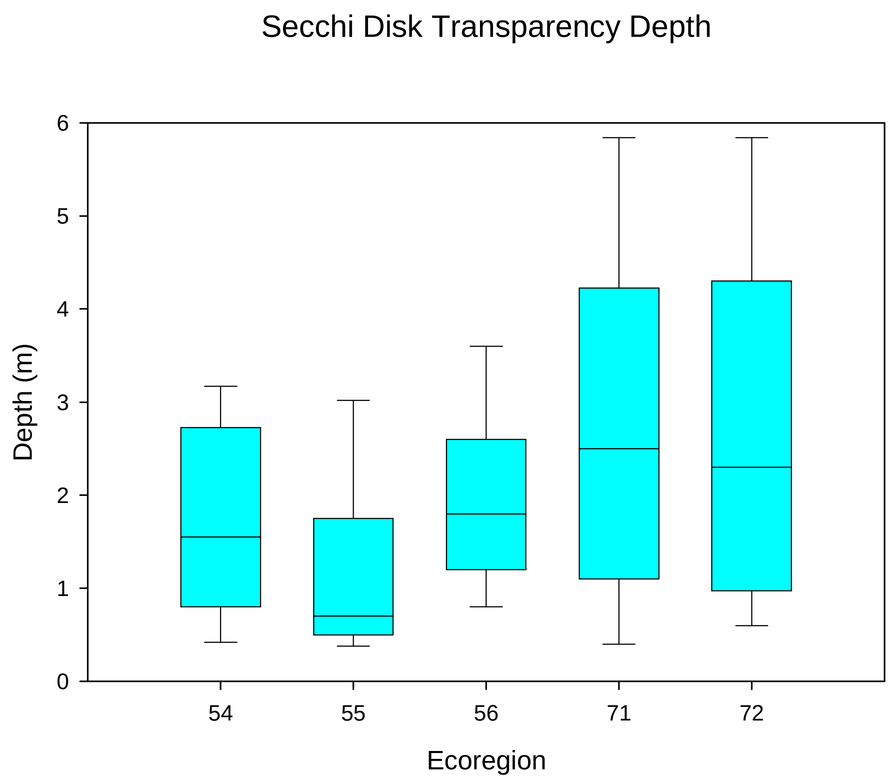


Figure 8: Median Secchi depth by ecoregion

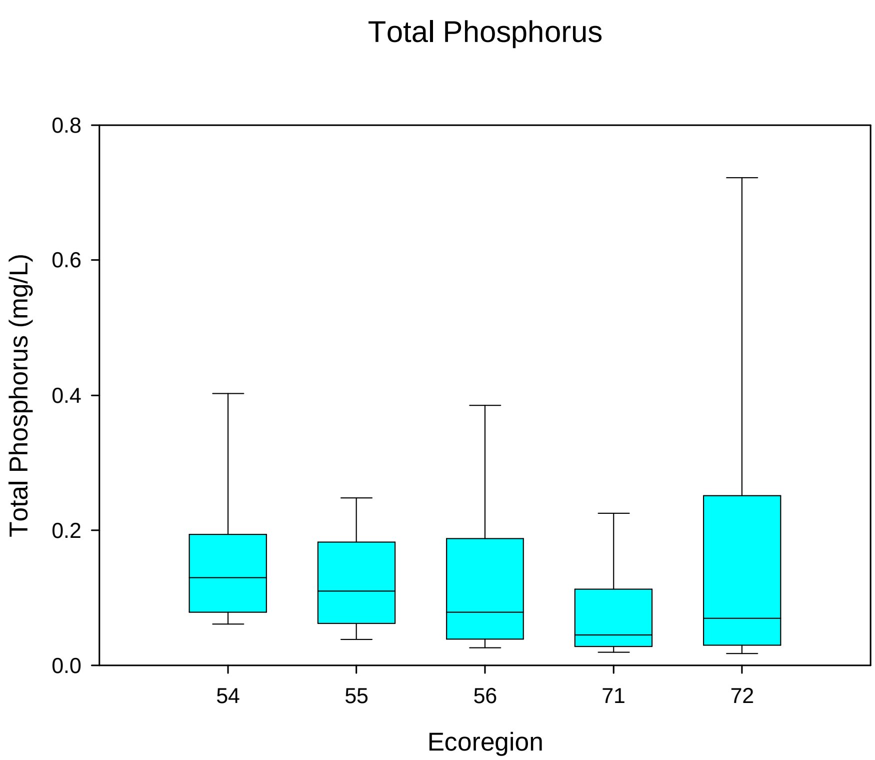


Figure 9: Median total phosphorus concentration by ecoregion

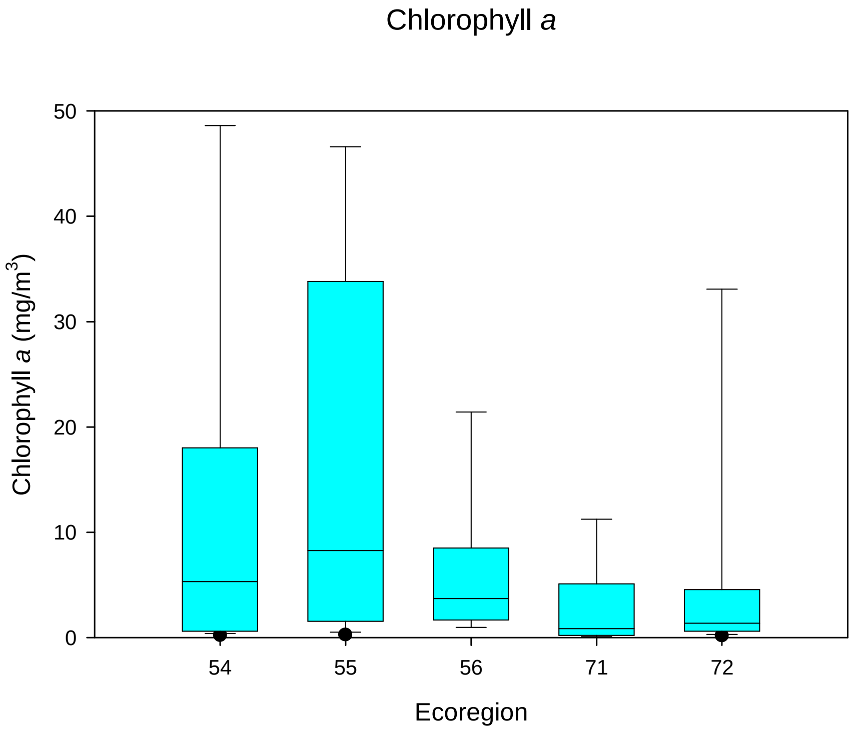


Figure 10: Median chlorophyll *a* concentration by ecoregion

Nitrate: Ecoregion 56 had the highest median nitrate concentration of 0.057 mg/L (Figure 11). Ecoregion 55 had a median nitrate concentration of 0.024 mg/L. Lakes within these two Ecoregions also had a substantial range in nitrate concentrations. Ecoregion 54 had a median concentration of 0.022 mg/L. Ecoregion 72 had a median nitrate concentration of 0.021 mg/L. Ecoregion 71 had the lowest median concentration of 0.013 mg/L. Lakes within Ecoregions 54, 71 and 72 had a very narrow range of nitrate values.

Ammonia: Ecoregion 56 had the highest median ammonia concentration of 0.437 mg/L (Figure 12). Ecoregion 71 had an ammonia concentration of 0.264 mg/L. Ecoregion 72 had a concentration of 0.218 mg/L. Ecoregion 54 had a median concentration of 0.182 mg/L. Ecoregion 55 had a median concentration of 0.163 mg/L.

Total Kjeldahl Nitrogen: Lakes within Ecoregion 54 had the highest median TKN concentration of 1.477 mg/L (Figure 13). Ecoregion 56 had a median concentration of 1.341 mg/L. Ecoregion 55 had a median concentration of 1.181 mg/L. Lakes within Ecoregion 72 had a median concentration of 1.173 mg/L and the largest range in TKN concentrations. Ecoregion 71 had the lowest median concentration for lakes of 0.723 mg/L.

Percent Water Column Oxic: The median percent of the water column oxygenated for lakes in Ecoregion 71 was 63% which was the highest of the ecoregions (Figure 14). Ecoregion 72 had a median percentage of 60 while ecoregion 55 had a median percentage of 58. Ecoregions 54 and 56 both had a median percentage of 50.

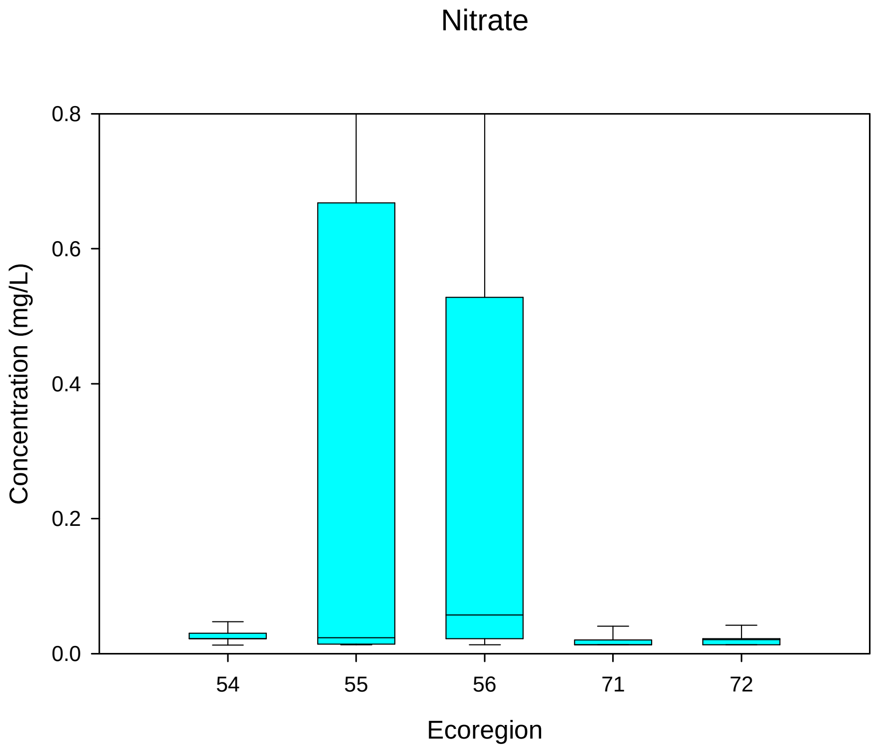


Figure 11: Median nitrate concentration by ecoregion

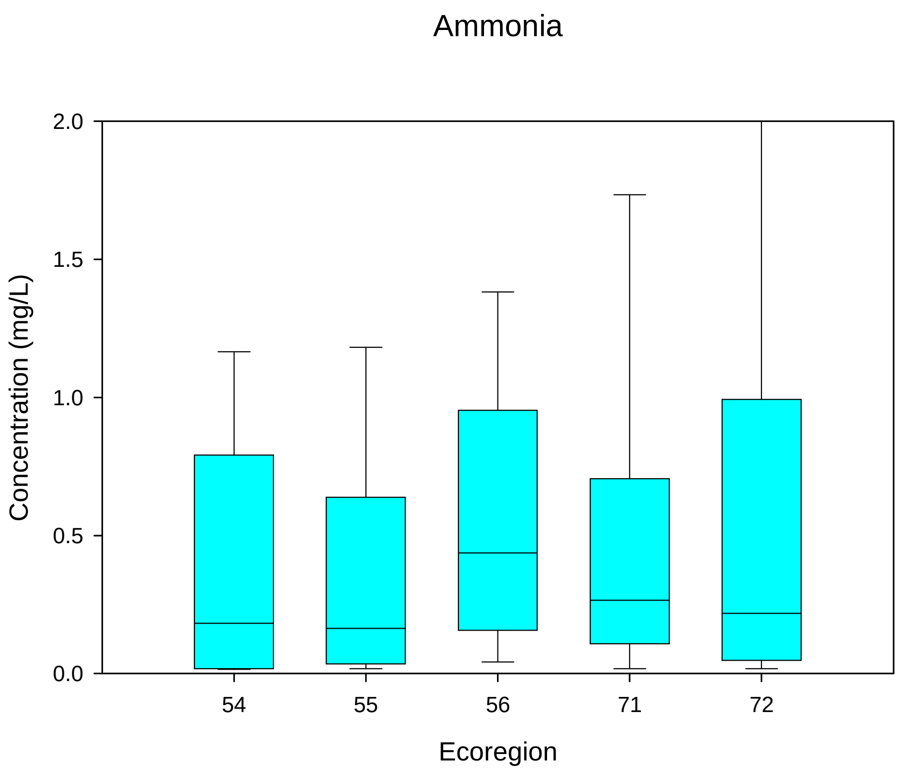


Figure 12: Median ammonia concentration by Ecoregion

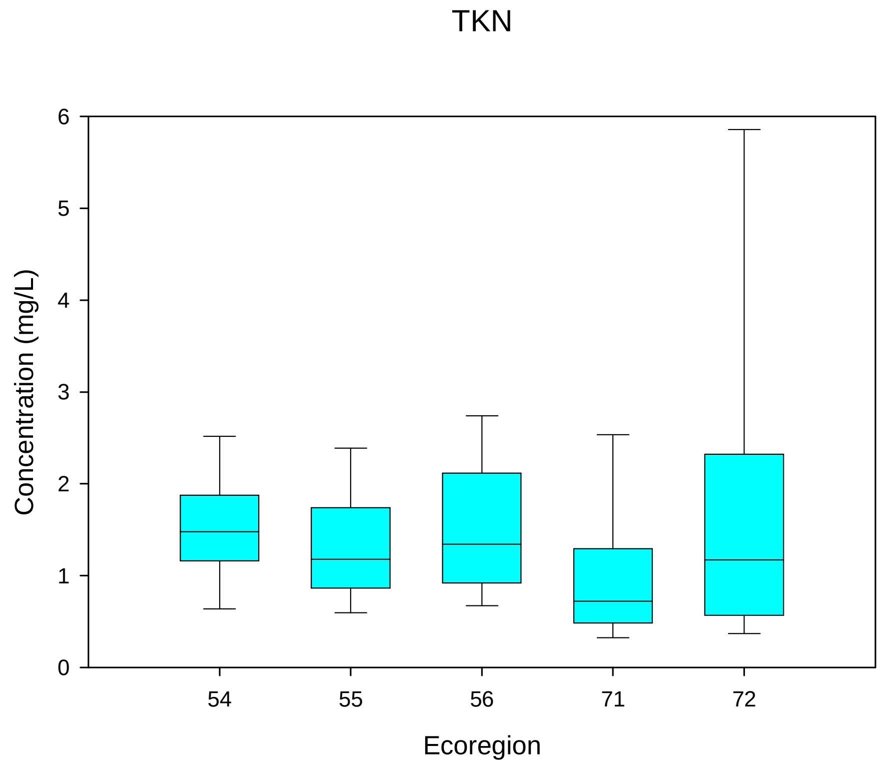


Figure 13. Mean total Kjeldahl nitrogen (TKN) concentration by Ecoregion

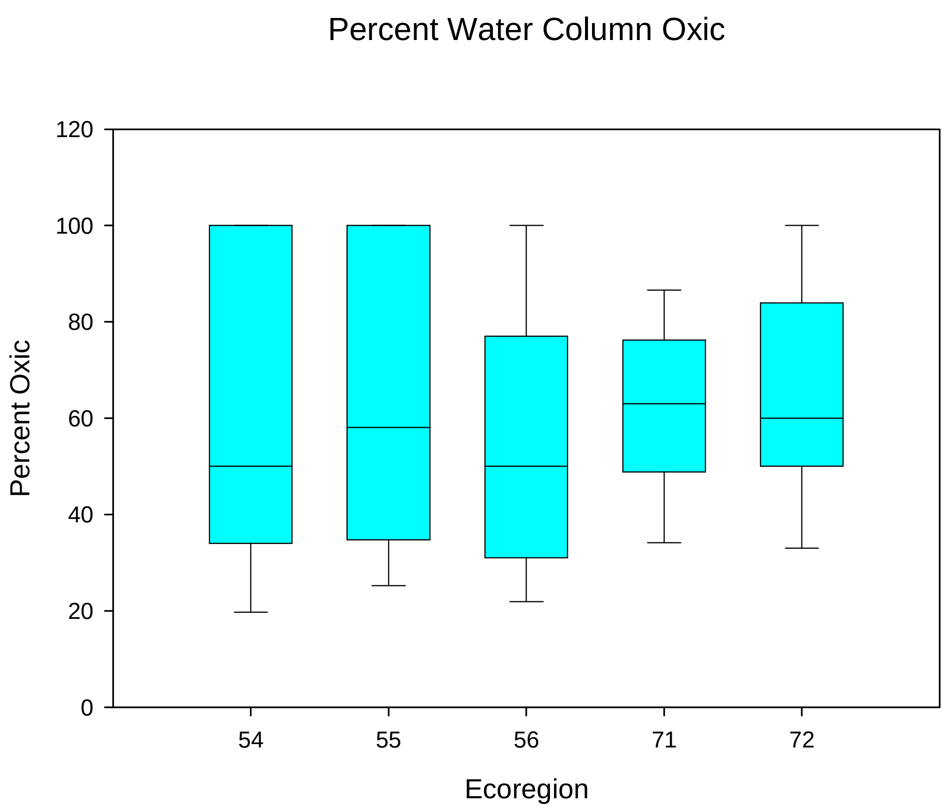


Figure 14. Median percent of the water column containing > 1ppm oxygen, by ecoregion.

Indiana Trophic State Index: The mean trophic state value of all lakes sampled in an ecoregion during a sampling period of 5 years was used as a representative Indiana Trophic State Index (ITSI) value for the ecoregion. There are four sampling periods in this data set: the 1970's, 1989-1993, 1994-1998, and 1999-2003 (Figure 15). Except for Ecoregion 71, the general trend in eutrophication, according to the ITSI scores, tends to be towards improving trophic state.

Lakes within Ecoregion 54 consistently showed the highest mean ITSI values through the years except during the 1989-1993 time period where lakes within Ecoregion 72 had the same ITSI mean of 34. ITSI mean values for lakes within Ecoregion 54 ranged from 48 to 25. The ITSI mean value recorded for the 1999-2003 sampling period represented a transition from eutrophy (all previous scores) to mesotrophy with a score of 25.

ITSI values for lakes within Ecoregion 55 range from 40 to 24. The 1999-2003 sampling period represented a change from eutrophy to mesotrophy with a score of 25. Lakes within Ecoregion 56 had a smaller but similar improvement with ITSI scores that ranged from 34 to 23. The 1999-2003 ITSI score of 23 represents a change from eutrophy (all previous scores) to mesotrophy.

Lakes within Ecoregion 71 did not follow the general trend towards mesotrophy and rather showed a trend towards increasing productivity; however, all of the values for Ecoregion 71 are in the mesotrophic category and ranged from 16 to 22. Lakes within Ecoregion 72 followed the general trend of decreasing productivity. The scores ranged from 35 to 19 in Ecoregion 72. The 1994-1998 ITSI score of 22 represented a change from eutrophy to mesotrophy which continued as the score dropped in the 1999-2003 sampling period to 19.

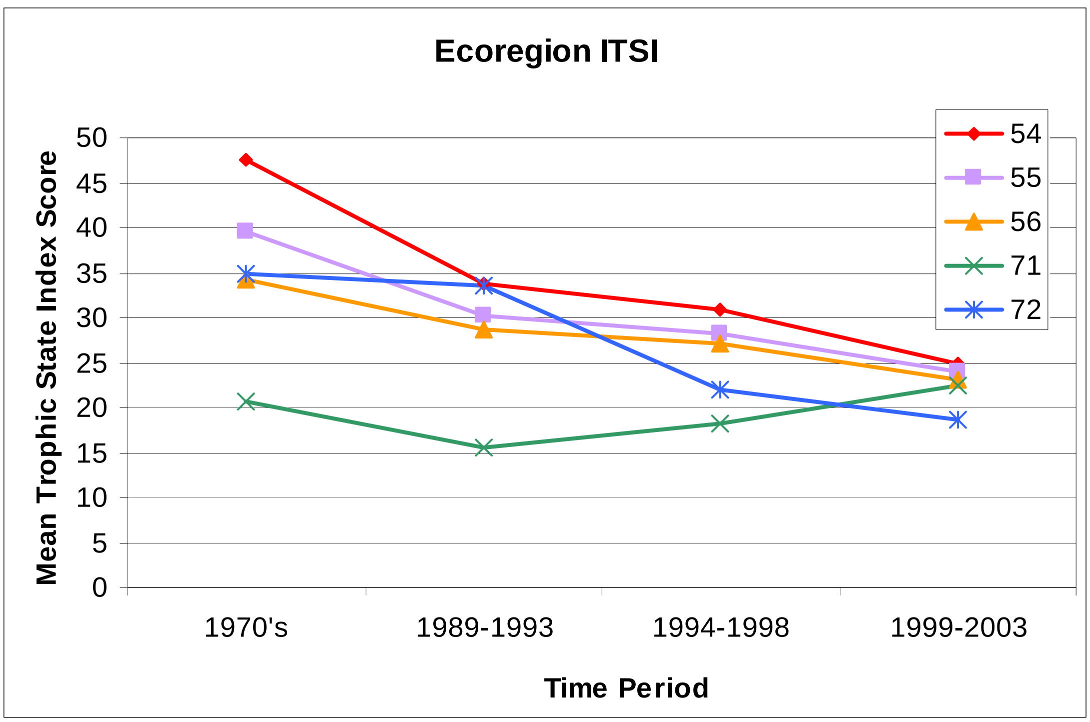


Figure 15: Indiana TSI scores by ecoregion across several sampling periods.

Carlson's Trophic State Index: The median and ranges of trophic state scores were calculated for each of the Carlson's TSI parameters for each lake sampled. The results were organized by ecoregion.

Secchi Disk TSI: Lakes within Ecoregion 55 had the highest median Carlson's TSI based on Secchi depth transparency (Figure 16). The median score was 61 indicating that the average lake in this region is eutrophic. Lakes within Ecoregions 54 and 56 also had median Carlson's TSI scores within the eutrophic category. Lakes within Ecoregions 71 and 72 had the lowest median Carlson's TSI scores, which were within the mesotrophic category.

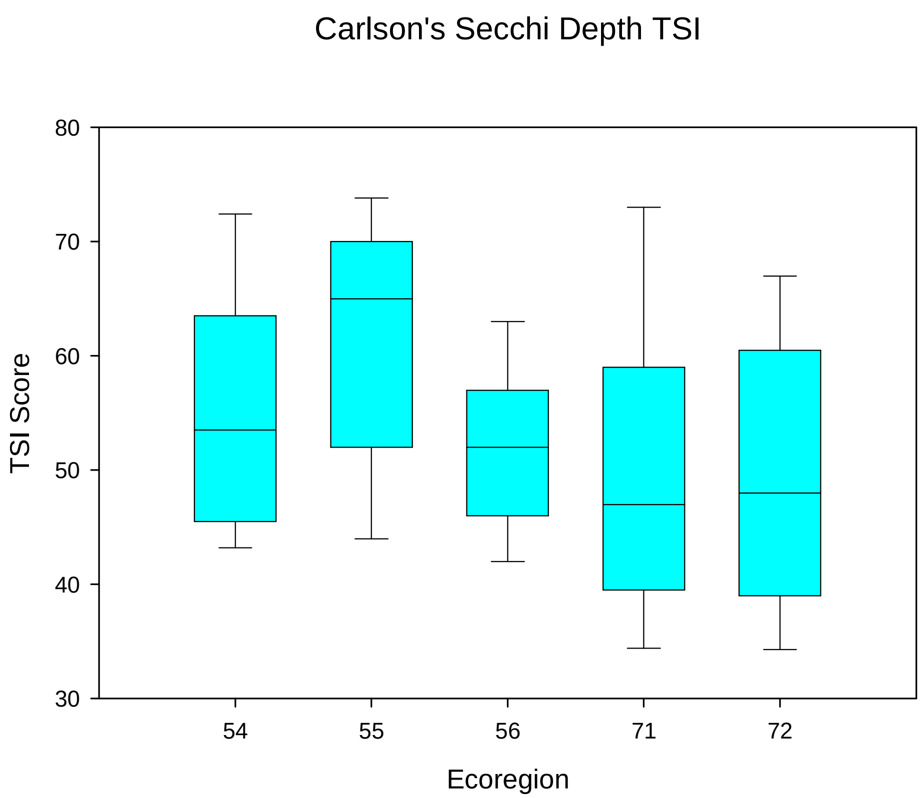


Figure 16. Carlson's Secchi Disk TSI distribution.

Chlorophyll *a*: The distribution of Carlson's chlorophyll *a* TSI scores for the five Indiana ecoregions was similar in order to the Secchi disk distributions (Figure 17). Lakes within Ecoregions 54, 55, and 56 were the highest, all within the eutrophic category. While the median chlorophyll TSI for lakes within Ecoregion 72 was lower, it still fell within the eutrophic category. Only the median chlorophyll TSI for lakes within Ecoregion 71 was within the mesotrophic range.

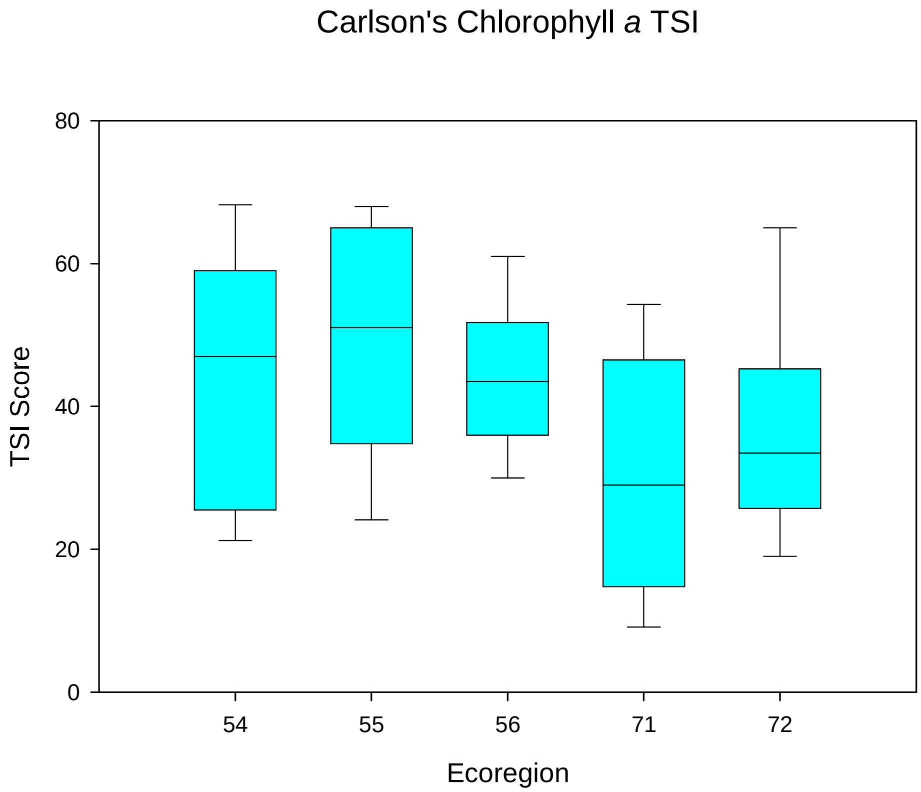


Figure 17. Distribution of Carlson Chlorophyll TSI scores by ecoregion.

Total Phosphorus: Lakes within Ecoregion 54 had the highest median Carlson TSI score based on total phosphorus concentration (Figure 18). As with the Secchi disk and chlorophyll *a* TSI distributions, Ecoregions 55 and 56 followed with the next highest median values. The median total phosphorus TSI scores for Ecoregions 54, 55, 56, and 72 were all within the hypereutrophic category. Lakes within Ecoregion 71 had the lowest median Carlson's TSI score of 62, and this value is representative of eutrophic conditions.

DISCUSSION

Secchi Disk Transparency: Algae and suspended sediments decrease water clarity in lakes. A deeper Secchi disk reading indicates higher water clarity. Although Ecoregion 71 is becoming more eutrophic, it has the deepest median Secchi disk reading indicating that lakes in this ecoregion have generally higher water clarity. According to the ITSI, lakes within Ecoregion 55 are moving from mesotrophy to oligotrophy; however, Ecoregion 55 has the shallowest median Secchi disk reading indicating lower water clarity.

Total Phosphorus: Phosphorus is often the limiting nutrient in lakes; however, small concentrations of phosphorus can cause eutrophication in lakes. Vollenweider (1975) suggests that 0.10 mg/L or more of total phosphorus in a system can stimulate algal growth, causing reduced oxygen content, organism death, and eutrophication (EPA 2003). However, a total phosphorus concentration of only 30 µg/L (0.03 mg/L) is used commonly as the lower limit

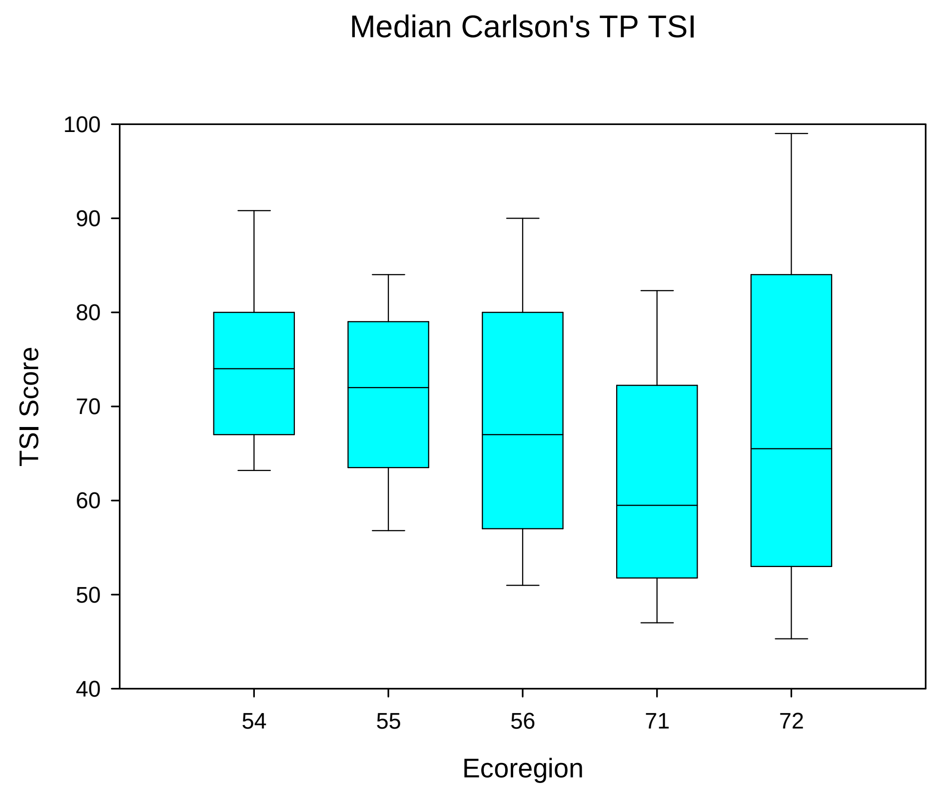


Figure 18. Distribution of Carlson Total Phosphorus TSI Scores by Ecoregion.

necessary to promote excessive algal growth and eutrophic conditions. The median values of total phosphorus for all ecoregions are well within the eutrophic range. Lakes within Ecoregions 54 and 55 have higher median total phosphorus values than Vollenweider's suggested upper limit of 0.10 mg/L. In the 1999-2003 sampling season, lakes in both of these ecoregions had median ITSI scores indicating that the lakes were oligotrophic despite the high total phosphorus median of the lakes. Based on Carlson's TSI for total phosphorus, median scores for lakes in both Ecoregions 54 and 55 are considered hypereutrophic.

Chlorophyll a: Havens and Nürnberg (2004) suggest that with increasing total phosphorus concentrations, chlorophyll *a* concentrations increase. Using our results (Figures 9 & 10), we see that the highest ecoregion median total phosphorus concentration occurs in Ecoregion 54 but the highest chlorophyll *a* median value is in Ecoregion 55. Other limiting factors such as light can affect the growth of algae, as reflected in the chlorophyll values. For example, Carlson (1977) found that lakes with high non-algal turbidity (from eroded soil for example) do not produce as much algae as their phosphorus concentrations might suggest. The presence of macrophytes (aquatic plants) in a lake decreases the validity of total phosphorus as a predictor of chlorophyll *a* concentration (Rooney and Kalff 2003). The higher the concentration of macrophytes in a lake, the lower the concentration of chlorophyll *a* based on total phosphorus concentration, which is especially true during the summer months when the most macrophyte growth has occurred in the lakes (Rooney and Kalff 2003) and when sampling occurred. So the interplay between nutrients, light availability, and macrophytes all can influence the amount of algal production in lakes.

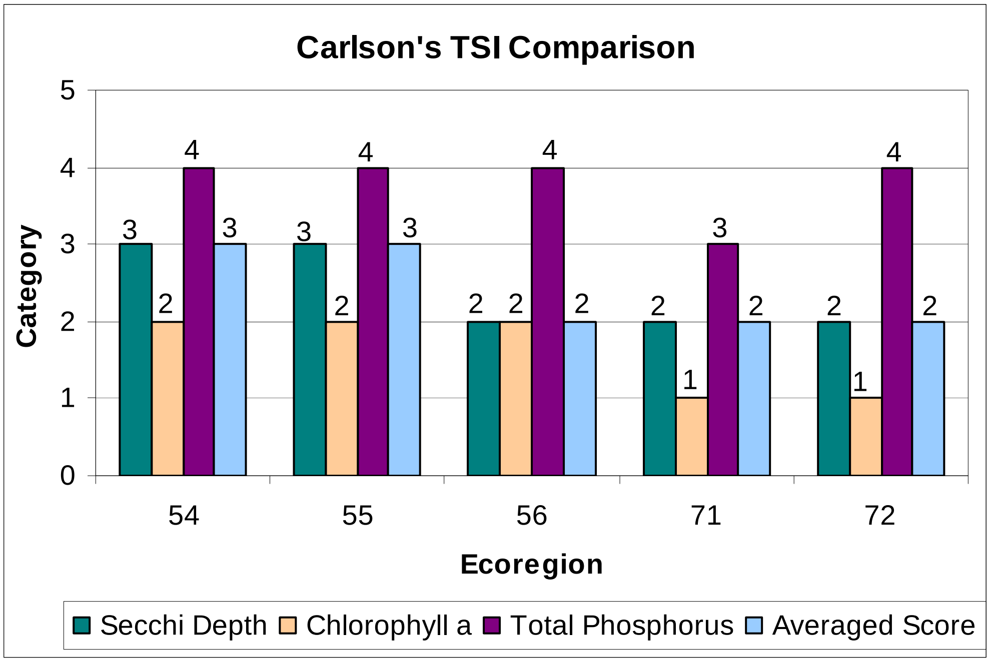


Figure 19. Mean Carlson TSI for lakes within the Indiana ecoregions.
1 = oligotrophic; 2 = mesotrophic; 3 = eutrophic; 4 = hypereutrophic

Figure 19 offers a good comparison of this interplay between Secchi disk transparency, chlorophyll *a*, and total phosphorus. Carlson's original TSI model was calibrated so that the TSI score for Secchi disk transparency, chlorophyll *a*, and total phosphorus would be equivalent for a particular lake, i.e., all bars in Figure 19 would be level for the same population of lakes or ecoregion. Figure 19 illustrates that Indiana lakes produce less chlorophyll than would be otherwise predicted from the phosphorus concentration (the phosphorus bar is higher than the chlorophyll bar). This is likely due to a high amount of non-algal turbidity in Indiana lakes that limits light needed for algal growth. Figure 19 also illustrates this in that the mean Secchi disk transparency scores are also higher (worse) than the mean chlorophyll scores.

Nitrogen: Nitrogen can enter aquatic systems through fertilizers, wastewater, septic tanks, and through the atmosphere. Due to the atmospheric component, nitrogen is almost never a limiting nutrient in aquatic systems and can contribute, along with phosphorus, to increased productivity in a lake causing eutrophication. Nitrate and ammonia concentrations in water bodies are typically less than 1 mg/L (EPA 2003). Nitrogenous compounds can become toxic to organisms at concentrations of 10 mg/L or above (EPA 2003). Excess nitrogen in a system can also contribute to the depletion of oxygen in a system that reduces the percent of the water column that is oxic and causes anoxia. The median nitrate and ammonia concentrations for all of the ecoregions were below the 1 mg/L concentration of natural waters indicating that nitrogen is not contributing greatly to eutrophication in these lakes.

Percent Water Column Oxic: A higher percentage of the water column being oxic indicates that a greater portion of the water column has oxygen (>1 mg/L) that can support aquatic biota. For example, most fish require 5 mg/L of dissolved oxygen to thrive. The median percentage of oxygenated water in all of the ecoregions is at least 50% if not greater.

Comparison of ITSI and Carlson's TSI: Figure 20 compares results from the two trophic state indices. Fifteen of 425 lakes did not have a complete ITSI score and 13 did not have a complete Carlson's TSI score, due to data gaps. The ITSI indicates that there are 220 oligotrophic lakes in Indiana while the Carlson's index indicates that there are only 51 oligotrophic lakes in Indiana. The ITSI shows that there are 161 mesotrophic lakes in Indiana while Carlson's TSI shows that there are 212 mesotrophic lakes in Indiana. The ITSI shows that there are 29 eutrophic lakes in Indiana while the Carlson's TSI shows that there are 97 eutrophic lakes in Indiana. The Carlson's TSI also shows that there are 52 hypereutrophic lakes, a classification that the ITSI does not have.

The ITSI designates 169 more lakes as being oligotrophic than the Carlson's TSI indicates. The ITSI designates 51 fewer lakes as being mesotrophic than does the Carlson's TSI and 68 fewer lakes as eutrophic than does the Carlson's TSI. The Carlson's TSI also designates 52 lakes as hypereutrophic, a classification that the ITSI does not have. The ITSI gives a more positive outlook on Indiana's lakes as it classifies 54% of Indiana's lakes as being oligotrophic whereas the Carlson's TSI classifies only 12% of Indiana's lakes as oligotrophic.

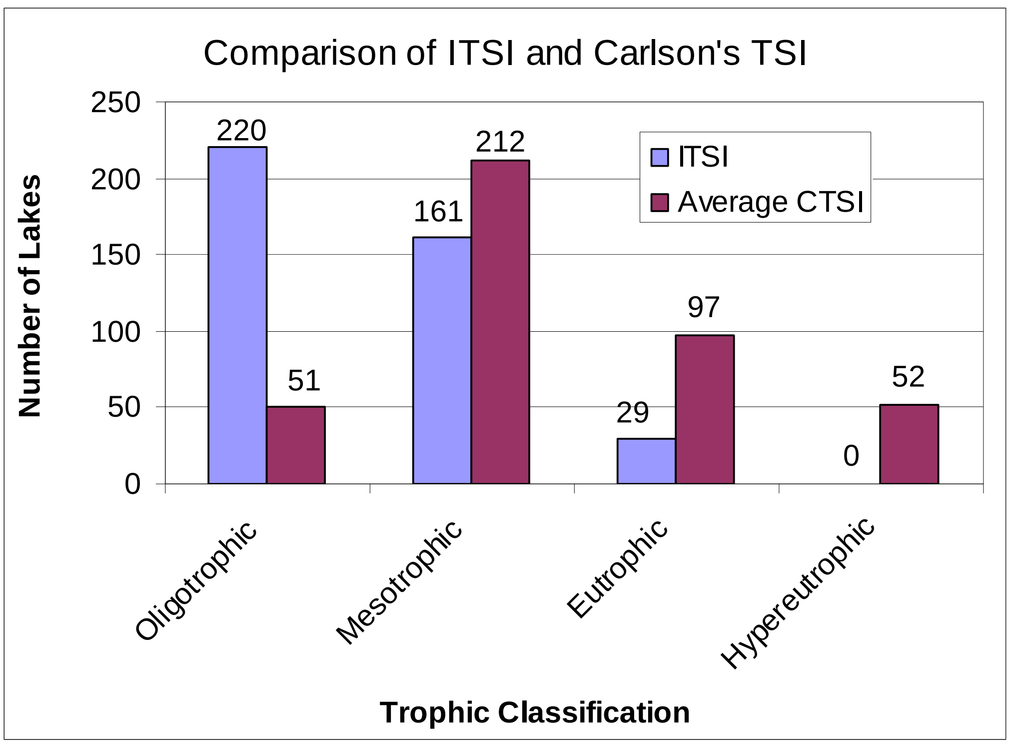


Figure 20. Comparison of Indiana TSI and Carlson TSI Scores.

CONCLUSIONS

Indiana's lakes have been impacted by runoff from agriculture and industry. Lakes within the Central Corn Belt Plains and Eastern Corn Belt Plains Ecoregions as a whole were more productive and had more problems with eutrophication than did lakes in other regions of the state. The bulk of Indiana's glacial lakes are within the Northern Indiana Till Plains Ecoregion and these lakes had better water quality indicators than did lakes within the Corn Belt Plains. Lakes in the southernmost ecoregions had the best water quality indicators. These lakes are primarily reservoirs but there is less farmland and more forests within their watersheds.

When we compared Indiana TSI scores from the 1970s; early 1990s, mid-1990, and early 2000s, there is a trend of improving water quality. This, without question, is a good trend, and one that likely reflects significant improvements in land use practices due to the T-By-2000 and other conservation programs.

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