Comparison of six lakes in Cheboygan and Presque Isle Counties, Michigan

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Abstract

To detect and avoid serious water quality issues, it is imperative to monitor trophic state and nutrient status within a lake. Lake comparisons can serve as a useful tool for understanding the factors affecting lake conditions through an examination of similarities and differences of various parameters within different lakes, as well as the differences in lake conditions affected by these various parameters. In this study, nutrient, light, and chlorophyll a concentrations in six lakes in Cheboygan and Presque Isle Counties, Michigan, were measured and compared. Trophic state was also considered using Carlson's (1977) Trophic State Index (TSI). Differences in productivity and nutrient concentrations were expected based on physical differences between the lakes. Total phosphorus (TP) concentrations, and not light, were expected to limit productivity. Significant differences in these lakes were found based on morphological differences, with larger lakes demonstrating lower chlorophyll a concentrations. TP concentrations were found to limit productivity. TSI values were mainly consistent with past values measured for these lakes.

Introduction

Freshwater lakes provide a myriad of services, from recreation to drinking water (Black Lake Report, 2009). But human presence in and around lakes can have huge impacts on the lake ecosystem (Smith et. al, 1999). Paved surfaces and reduction of vegetation can increase the volume of runoff entering a lake (Smith et. al, 1999). Runoff containing fertilizer and soaps, as well as seepage from septic tanks and waste treatment plants, can all increase nutrient input to lakes (Garg and Garg, 2002, Smith et. al, 1999). The increased nutrient levels in the lake can result in algae and cyanobacteria blooms (Garg and Garg, 2002, Dillon and Rigler, 1974, Smith et. al, 1999), which can decrease water clarity, introduce harmful toxins into the lake, and lead to anoxic conditions in the metalimnion region of the lake (Dillon and Rigler, 1974).

Humans are also responsible for the introduction of many non-native invasive species, which threaten the biodiversity of invaded ecosystems (Higgins and Vander Zanden, 2010, Smith et. al, 1999). One example is the zebra mussel, Dreissena polymorpha, which was introduced to Lake St. Clair in 1986 from the ballast water of ships and is now distributed throughout North America (Griffiths et. al, 1991, Higgins and Vander Zanden, 2010). Zebra mussels can have major impacts on aquatic ecosystems. By removing large quantities of plankton from the water column, zebra mussels improve water clarity, which in turn allows light to penetrate deeper into the water column (Higgins and Vander Zanden, 2010). Zebra mussels can limit primary productivity in the water column by both filtering out large amounts of phytoplankton, and by reduction of phosphorus and particulate-bound nutrient availability in the water column (Higgins and Vander Zanden, 2010). These nutrients removed from the water column are concentrated in the benthos in the form of feces and pseudofeces (Higgins and Vander Zanden, 2010). Greater nutrient availability and deeper light penetration can create more favorable conditions for macrophytes and other benthic organisms, which tend to increase in population, altering community composition within the lake (Higgins and Vander Zanden, 2010).

In light of the many threats to lake ecosystems, it is imperative to understand the current state of the lake in order to recognize any problems currently existing in the system, as well as to detect future changes in conditions so solutions can be found. Lakes are generally divided into three categories based on lake conditions: oligotrophic, mesotrophic, and eutrophic (Carlson 1977). Oligotrophic lakes generally have low nutrient availability, low productivity levels, and good water clarity (Sawyer, 1966, Smith et. al, 1999). Eutrophic lakes tend to have high nutrient availability, high productivity, and poor water clarity (Sawyer, 1966, Smith et. al, 1999). Lakes that fall between these two definitions are considered mesotrophic (Sawyer, 1966, Smith et. al, 1999). The Trophic State Index (TSI) developed by Carlson in 1977 provides a means by which lake conditions can be communicated and compared. The index converts parameters indicative of lake conditions, such as Secchi depth (SD), chlorophyll a (chl a) concentrations, and total phosphorus (TP) concentrations, into a scale from 1 to 100 (Carlson, 1977). Index values provide a consistent method for comparison of conditions within and between lakes.

Although lakes within a region experience similar climatic patterns, differences in nutrient loading, residence time, volume, average depth, and many other factors cause neighboring lakes to experience different conditions. A larger volume of water in a lake can dilute nutrients, leading to lower levels of productivity than might be witnessed in lakes with smaller volumes (Hutchinson, 1957). Shallower lakes also often experience higher productivity levels than deeper lakes, as shallower lakes have a greater area of benthic habitat located within the photic zone (Higgins and Vander Zanden, 2010). Lake comparisons can serve as a useful tool for understanding the factors affecting lake conditions through an examination of similarities and differences of various parameters within different lakes, as well as the differences in lake conditions affected by these various parameters.

In this study, six inland lakes in Michigan's northern lower peninsula were studied and compared. Lakes included in the study were Burt Lake, Douglas Lake, Long Lake, Mullett Lake, and Munro Lake, all located in Cheboygan County, Mi, and Black Lake, located in Cheboygan and Presque Isle Counties (Gannon and Paddock, 1978). These lakes range in volume and average depth from 3,114,853 to 757,082,357 m^3 and 1.44 to 12 m respectively (Table 1). With the exception of Lake Munro, all the lakes included in our study have been colonized by zebra mussels. For our comparison of the six lakes we hypothesized:

1) Differences in light attenuation, TN and TP concentrations, and Chl a concentrations among the six lakes based on differences in lake morphology and volume, with the largest lakes, Mullett and Burt Lakes, experiencing the lowest nutrient concentrations, lowest productivity, and lowest light extinction coefficient and the smallest lake, Lake Munro, experiencing the greatest nutrient levels and productivity and the greatest light attenuation.

2) Productivity will be limited by P, with higher TP concentrations corresponding to higher concentrations of chl a. Productivity will not be limited by light; light extinction coefficients will be greatest in areas of high productivity where concentrations of phytoplankton shade out the water column below.
3) Lakes colonized by zebra mussels will experience greater variability in TSI values, with all parameters (chlorophyll a, TP, and Secchi depth) demonstrating lower values compared to index values calculated for these lakes before the introduction of zebra mussels.

Methods

Sample Sites and Conditions:

Six lakes were measured for our study. Measurements were taken at three sample sites on each lake, and all measurements were performed in the afternoon between noon and 4:00 PM. GPS coordinates for each sample site are given in table 2.

Douglas Lake was the fourth largest lake included in the study (table 1) and the first lake measured (July 2, 2010). Douglas Lake is a kettle lake containing seven distinct depressions; measurements were taken in three of these seven deeper areas (Appendix 2 Figure 1). Weather was clear and sunny with a few small waves when measurements were taken.

Black Lake was measured on July 9, 2010, and the third largest lake included in the study (table 1). Black Lake is generally oval in shape, with a shallow northern portion increasing in depth toward the south. The deepest depression in Black Lake is in the southern lobe of the lake, reaching a depth of about 13 to 15 m. Measurements were taken at three sites throughout this deeper depression (Appendix 2 Figure 2). Waves on Black Lake were choppy with an occasional whitecap, and the weather was sunny with very few clouds while measurements were taken.

Burt Lake is the second largest lake included in the study (Table 1). It is linear in shape oriented north to south, with a short lobe extending out the middle of the western side. The deepest region of the lake is in the middle and southern portion, approximately 12 to 15 m deep. Sample sites in this lake spanned from south to north centered in this deeper area (appendix 2 Figure 3). On the day measurements were performed (July 13,2010), the sky was clear with a few clouds on the horizon and the only waves were caused by boat traffic.

Munro Lake is the smallest lake in the study (table 1). It was sampled on July 16, 2010. Munro Lake is ovate with is deepest portion near the center of the lake, about 4.6 m deep. Munro Lake also has two additional very small areas of about 4.6 m depth, one along the northern and one along the eastern shore. Sample sites in this lake were taken south to north within the center deep portion of the lake (appendix 2 figure 4) The weather on Munro Lake was sunny with a few whispy clouds. There was a strong southerly wind and waves were low and choppy.

Long Lake is the second smallest lake included in the study in terms of volume (table 1). It is a long narrow lake oriented northwest to southeast, with its deepest area located towards the northwestern end of the lake, with a smaller area of deep water located in the lake’s southeastern end (Appendix 2 Figure 5). Two sample sites were located in the northwest section of this lake, and the third sample site was located in the southeastern section. Measurements were taken on July 23, 2010, and the weather was overcast with a light wind.

Mullett Lake was the final Lake sampled for our study (July 27, 2010). It is also the largest lake included in the study (table 1). Mullet Lake is generally oval in shape, with a shallower northeastern end deepening towards the south west portion of the lake. Two sample sites on Mullett Lake were located in the deeper south west portion, and one site was ;located in the north east portion of the lake. The sky was cloudy and the waves were a light chop with an occasional light swell the day Mullett Lake was sampled.

Calibrations:

We used a Hydrolab® Quanta to measure temperature, specific conductance, dissolved oxygen (DO), and pH at each site. The Hydrolab® was calibrated each morning before measurements were taken. We calibrated barometric pressure based on readings from a YSI® 6920. We then proceeded to calibrate DO by filling the Hydrolab® with water up to just below the DO sensor. The Hydrolab® was then lightly capped and given time for the water to reach equilibrium with the surrounding air. DO was then calibrated to 100% humidity.

We calibrated pH using a three point curve with buffered standard solutions of pH 7, 10, and 4. For each buffered standard solution, we rinsed the probes three times, then filled the Hydrolab® with the buffered standard pH solution so that the pH probe was submersed in the solution. The Hydrolab® was then calibrated to the appropriate pH.

We calibrated specific conductance using a standard solution of 0.099 mS/cm. We again washed the Hydrolab® three times with the standard solution before submersing the probes and calibrating the Hydrolab®.

Depth was calibrated on site by placing the Hydrolab® probes just at the surface of the water and calibrating the hydrolab® to a depth of 0 m.

Sample Site Measurements:

Measurements at each site were taken by different team members, appendix 1 table 3 details measurements performed by each team member. Depth measurements were taken from the four corners of the boat using a HawkEye® H22PX Handheld Sonar System. Four Secchi disk measurements were taken in the shadow of the boat at each site.

At each site, temperature, conductivity, DO, and pH profiles were measured using the Hydrolab® Quanta. At each site, half-meter measurements were taken in the metalimnion to clarify the changes occurring in this region. Hydrolab® readings were taken to different depths at different sites depending on the depth of the thermoline and the overall depth of the site. In general, 2 to 5 measurements were taken in the hypolimnion of each site.

Photosyntheitically active radiation (PAR) was measured to a depth of 7 m at each site using a Li-COR® quantum/radiometer/photometer LI-189. The measuring device was held away from the shadow of the boat by threading the wire through a PVC pipe which was then extended out over the water. Additional half-meter measurements were taken at 0.5 and 1.5 m.

Water samples for chemical analysis were taken at 3 m depth at each site, then a sample from within the thermocline and a sample from within the hypolimnion. The only exception to this was Munro Lake, which was too shallow to stratify so samples were taken from 1, 2, and 3 m depths. Samples were taken by lowering a horizontal Van Dorn to the desired depth. We then pulled the Van Dorn horizontally to ensure it contained water from the desired depth. We then deployed the messenger and pulled the Van-Dorn to the surface. An acid-washed bottle was rinsed three times with water from the Van-Dorn, then filled, capped and labeled with the site information as our water sample. The sample was then chilled on ice for transportation to the lab.

Chlorophyll a samples were taken from the same depths as the water chemistry samples. We rinsed an acid washed bottle three times with water from the Van-Dorn, then filled the bottle from the Van Dorn. A 60 mL syringe was then rinsed three times with this water, then filled to the 60 mL mark. 0.45 membrane filter paper was placed in a clean filtration device and placed on the end of the syringe. At most sites 120 mL of water was passed through the filter, but at three sites, Fairy Island, South Fishtail Bay, and Black Lake North Site, 60 mL of water were filtered. After filtration, the filter paper was then removed with tweezers and folded into tin foil to protect it from the sun. The tin foil was then labeled and transported on ice to the lab for analysis.

Analysis

Water chemistry samples were analyzed in the lab for total Nitrogen (TN) and total Phosphorus (TP) content. For each site, epilimnetic P and N, and light extinction coefficients were calculated and a one-way ANOVA test was performed on each data set to determine if there were differences among the four lakes. Pairwise comparisons were then performed using ttests to determine specifically which lake varied from which other lakes for each parameter. Regression analysis was performed to determine the effect of light attenuation and epilimnetic concentrations of TN and TP on epilimnetic chlorophyll a concentrations at each site. Trophic State Index (TSI) values were calculated for each lake using the equations outlined by Carlson (1977).

Results

The lakes ranged in volume from 757,082,357 m^3 to 3,114,853 m^3 (table 1), a difference of 753967504 m^3. Mullett Lake was the largest lake both in terms of volume and surface area. Mullett Lake's volume was 242% greater than Munro Lake's volume, the smallest lake in the study. Munro Lake also has the shallowest average depth (Table 1), 3.96 m shallower than Douglas Lake, which has the second shallowest average depth, and 10.6 m shallower than Burt Lake, the lake with the deepest average depth.

Table 1 Surface area, average depth, volume, and hydraulic residence time by lake. (Gannon and Paddock 1974, *Burt Lake Watershed Project, 2001, **Mullett Lake Watershed Protection Plan, ***Fairchild and Sell, 1978)

	Surface Area (ha)	Average Depth (m)	Volume (m^3)	Residence time (years)
Black Lake	4052	7.7	313,882,624	No Data
Burt Lake*	6848	12	632,173,568	1.04
Douglas Lake	1509.3	5.4	82,996,677	3
Long Lake	160	7	11,311,422	No Data
Mullett Lake**	7025	11.3	757,082,357	0.92
Munro Lake***	277.6	1.44	3,114,853	1.3

Differences in average light extinction coefficients were significant among the six lakes (ANOVA p<<0.001) (Figure 7). Munro Lake had a higher average light extinction coefficient than Black Lake (Tukey HSD p=0.003), Burt Lake (Tukey HSD p=0.001), Douglas Lake (Tukey HSD p=0.04), Long Lake (Tukey HSD p<0.001), and Mullett Lake (Tukey HSD p<0.001)(Figure 7). Douglas Lake had a higher average light extinction coefficient than Long Lake (Tukey HSD p=0.009) and Mullett Lake (Tukey HSD p=0.019)(Figure 7).

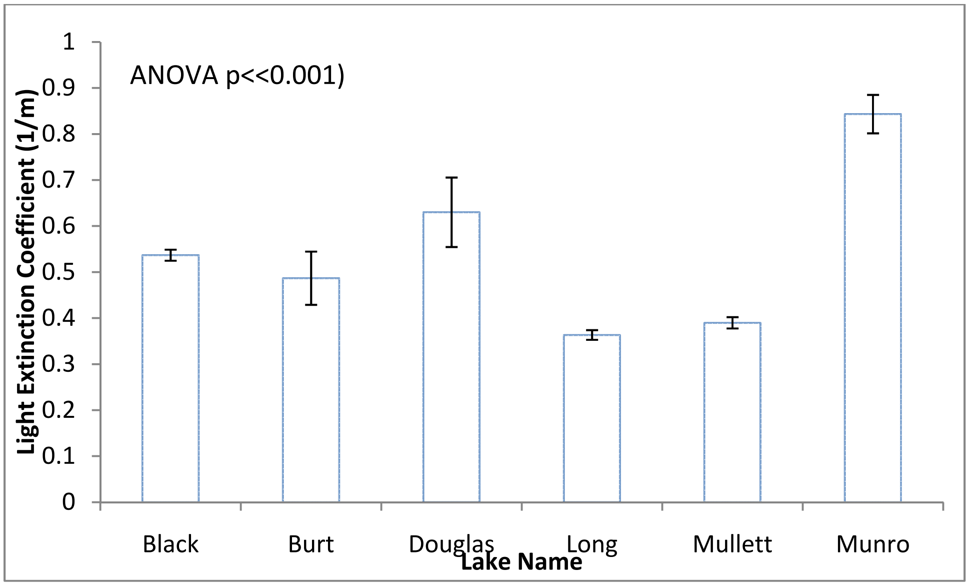

Figure 7 Average light extinction coefficient by lake. Error bars represent standard error.

There were significant differences in average eilimnetic TN concentrations among the six lakes (ANOVA p<<0.001)(Figure 8) Munro Lake had a higher average TN concentration than Black Lake (Tukey HSD p=0.001), Burt Lake (Tukey HSD p<0.001), Douglas Lake (Tukey HSD p=0.016), Long Lake (Tukey HSD p=0.001)), and Mullett Lake (Tukey HSD p=0.001) (Figure 8) Significant differences did not exist between any of the other lakes (ANOVA p=0.16)(Figure 8).

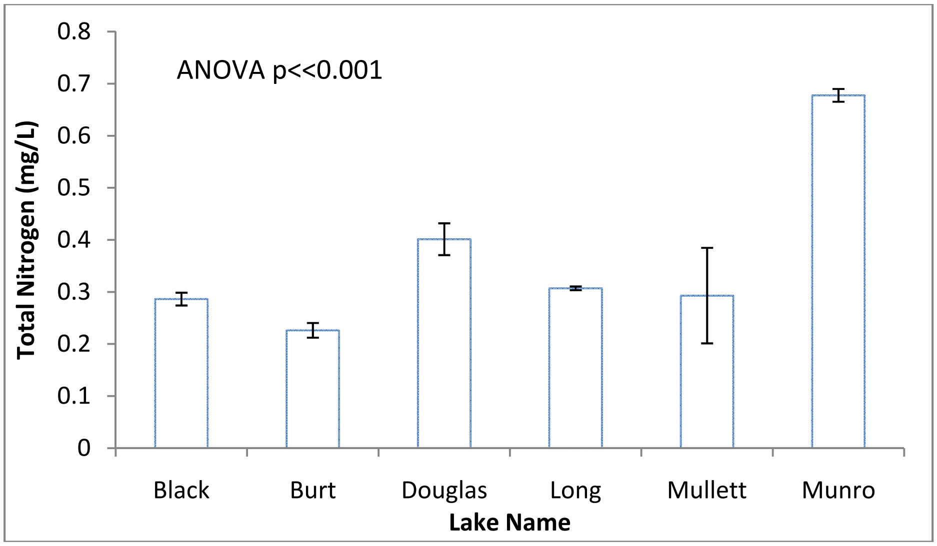

Figure 8 Average epilimnetic TN concentrations by lake. Error bars represent standard error

Differences among the lakes of average epilimnetic TP concentrations were significant (ANOVA p<<0.001) (Figure 9) Munro Lake had a significantly greater average epilimnetic TP concentration than Black Lake (Tukey HSD p=0.023), Burt Lake (Tukey HSD p<0.001), Long Lake (Tukey HSD p<0.001) and Mullett Lake (Tukey HSD p<0.001). Douglas Lake’s average TP concentration was greater than that of Black Lake (Tukey HSD p=0.023), Burt Lake (Tukey HSD p<0.001), Long Lake (Tukey HSD p<0.001), and Mullett Lake(Tukey HSD p<0.001)(Figure 9). Black Lake had a significantly higher average epilimnetic TP concentration than did Burt Lake (Tukey HSD p=0.036) and Mullett Lake (Tukey HSD p=0.005) Figure 9).

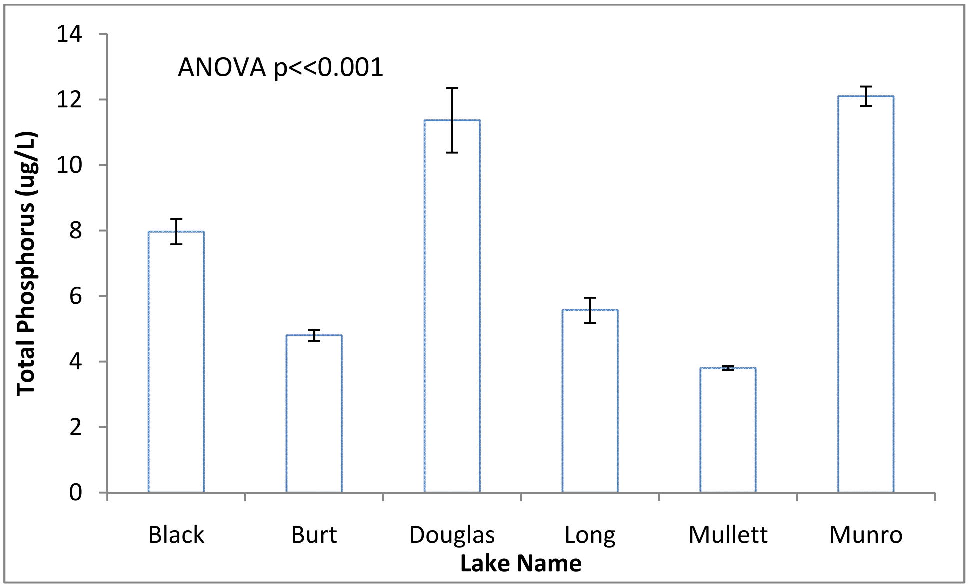

Figure 9 Average epilimnetic TP by lake. Error bars represent standard error.

There were significant differences in the average concentration of chlorophyll a in the epilimnion regions of all six lakes (ANOVA p<0.001) (Figure 10) Munro Lake had a greater average Chl a concentration in its epilimnion than did Black Lake (Tukey HSD p<0.001), Burt Lake(Tukey HSD p<0.001), Douglas Lake(Tukey HSD p=0.002), Long Lake (Tukey HSD p<0.001), and Mullett Lake (Tukey HSD p<0.001)(Figure 10). Burt Lake had a lower average chl a concentration than Black Lake (Tukey HSD p=0.013), Douglas Lake (Tukey HSD p<0.001), and Long Lake (Tukey HSD p=0.008)(Figure 10). Mullett lake had a significantly lower average epilimnetic chl a concentration than Black Lake (Tukey HSD p=0.043), Douglas Lake (Tukey HSD p=0.001), and Long Lake (Tukey HSD p=0.028)(Figure 10).

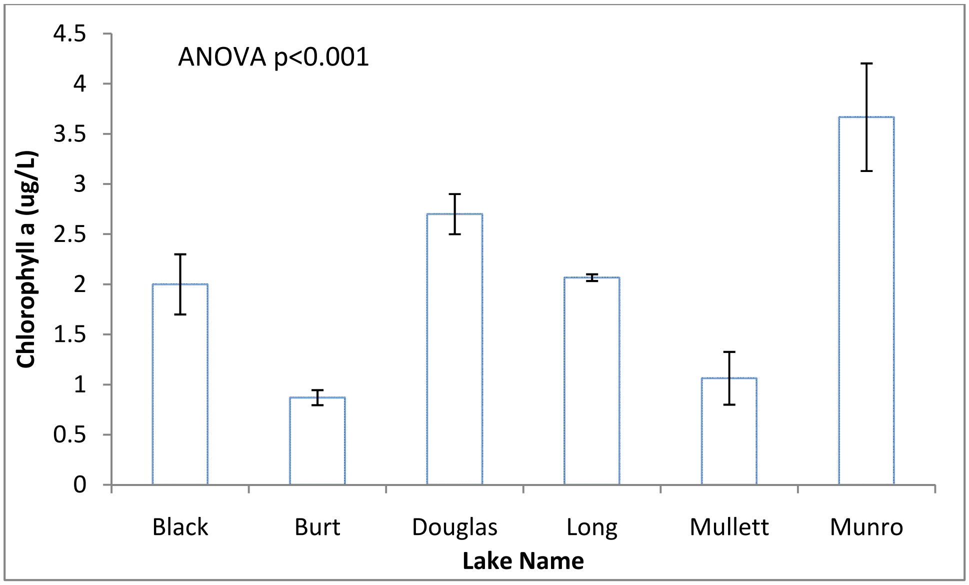

Figure 10 Average epilimnetic chlorophyll a oncentration by lake. Error bars represent standard error.

Regression analysis of each site's light extinction coefficient and epilimnetic chlorophyll a concentration revealed a significant linear relationship between the two factors (least-squares regression, $p<0.001$) (Figure 11). Greater extinction coefficients correlated with greater concentrations of epilimnetic chlorophyll a (Figure 11). The coefficient of determination indicates 50.7% of the variations in chlorophyll a concentrations in the epilimnion can be explained by differences in light attenuation (Figure 11).

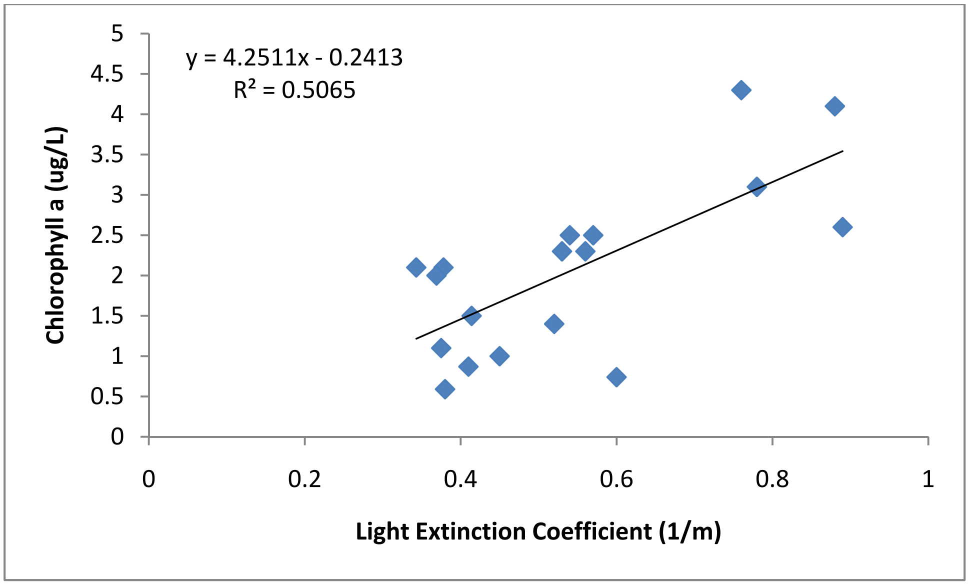

Figure 11 Regression analysis of light extinction coefficient verses epilimnetic chlorophyll a concentrations by sample site for all six lakes.(least-squares, $p<0.001$)

Regression analysis of each site's epilimnetic TN concentration and chlorophyll a concentration revealed a significant linear relationship between TN and chlorophyll a concentrations (least-squares regression, $p<.001$) (Figure 12). Increases in epilimnetic TN correlated to increased concentrations of chlorophyll a (Figure 12) The coefficient of determination indicates 53.7% of the differences in chlorophyll a concentrations can be explained by changes in TN concentration in the epilimnion (Figure 12).

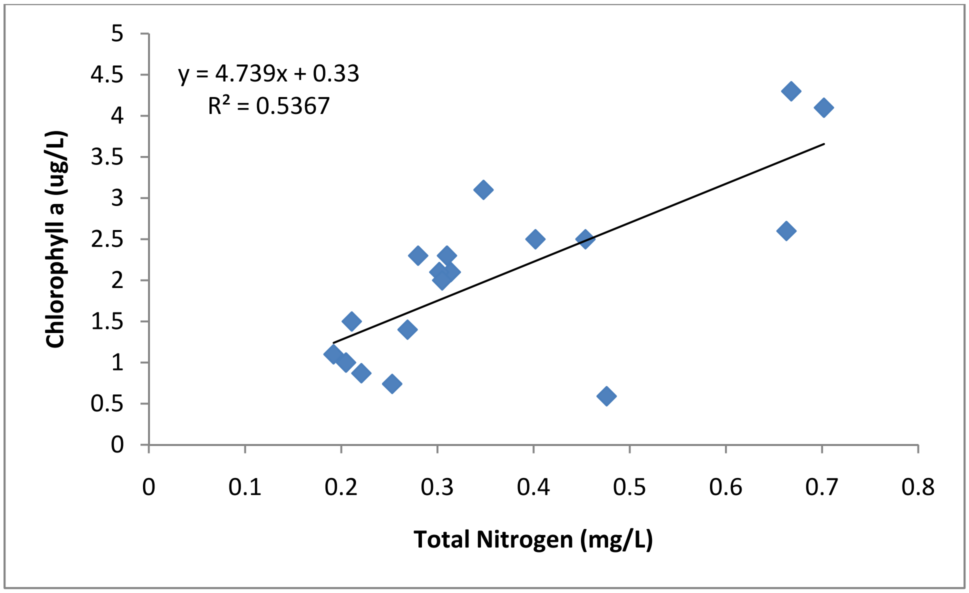

Figure 12 Regression analysis of epilimnetic TN versus epilimnetic chlorophyll a concentrations by sample site for all six lakes. (least-squares, $p<0.001$)

Regression analysis indicates a linear relationship between each site's epilimnetic TP concentration and chlorophyll a concentrations in the epilimnion (least-squares regression, $p<<0.001$) (Figure 13). Increases in epilimnetic TP concentrations correlated to greater concentrations of chlorophyll a (Figure 13). The coefficient of determination indicates 62.4% of the differences in epilimnetic chlorophyll a concentrations can be explained by changes in TP concentrations (Figure 13).

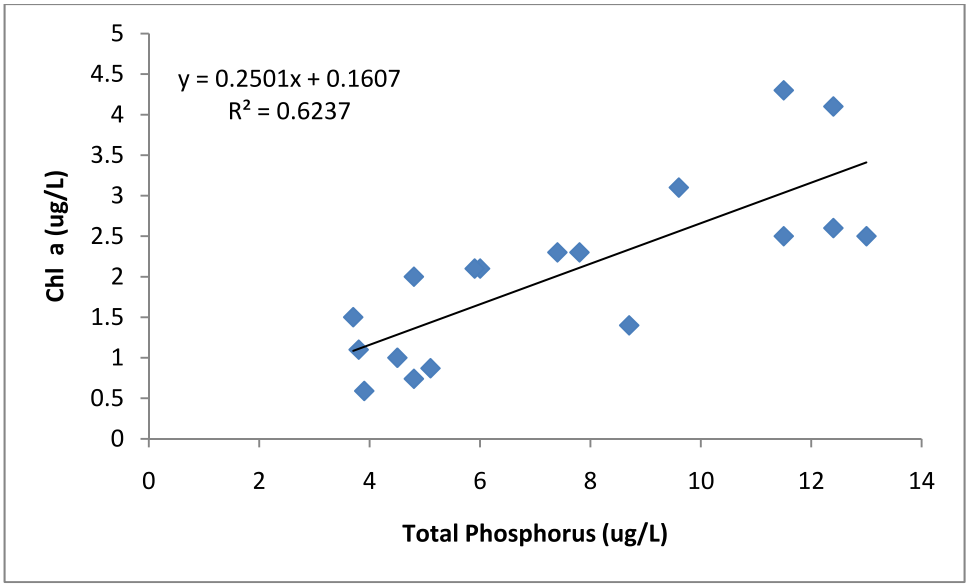

Figure 13 Regression analysis of epilimnetic TP versus epilimnetic chlorophyll a concentrations by sample site for all six lakes. (least=squares p<<0.001)

Trophic state index values are given in figure 14. TSI(TP) gave the lowest index value for each lake, and for all lakes except Long, TSI(SD) gave the highest index value (Figure 14). Index values for Douglas Lake were the most consistent, ranging from 39.1 for TSI(TP) to 41.6 for TSI(SD) (Figure 14). Mullett Lake had the greatest range of index values, from 23.4 for TSI(TP) to 42.4 for TSI(SD) (Figure 14).

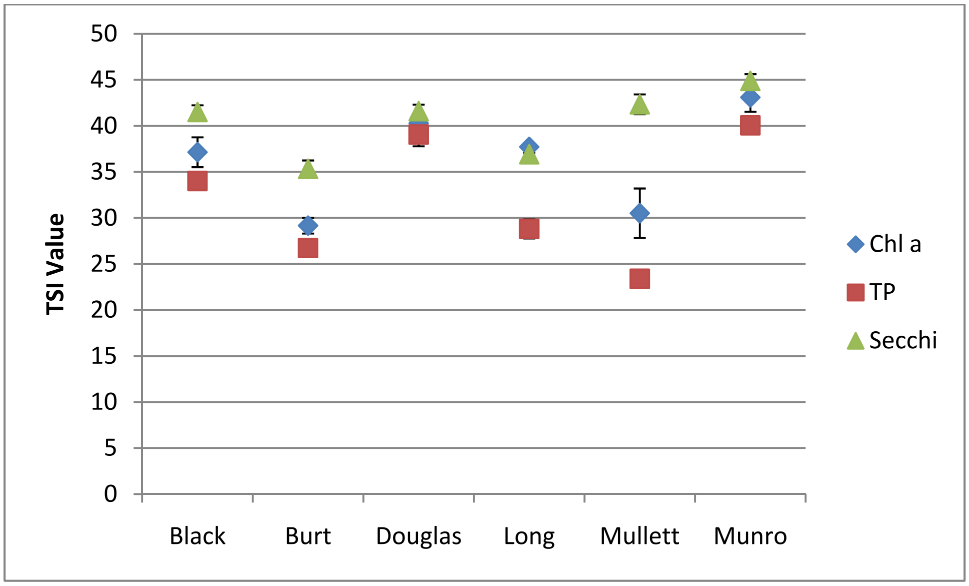

Figure 14 Average TSI values for each lake based on average chl a concentrations, average TP concentrations, and average secchi depth (SD) of each site.

Discussion

Greater concentrations of chlorophyll a corresponded with higher light extinction coefficients. This implies that light is not the limiting factor in these four lakes, as greater productivity is witnessed in areas where light does not penetrate as far into the water column. The higher light extinction coefficients at these sites are probably cause by their greater productivity, as increased numbers of photosynthetic plankton in the water column lead to an increased amount of light absorption (Smith, 1999).

Although significant linear relationships were found between both epilimnetic TP and chlorophyll a concentrations and epilimnetic TN and chlorophyll a concentrations, a greater percentage of the observed differences in epilimnetic chlorophyll a concentrations were attributed to differences in TP concentrations. This suggests that P is the limiting nutrient in these six lakes, an idea which is further support by the TN/TP ratio for each lake. Sakamoto (1966) suggests that for TN/TP ratios greater than 17, P would be the limiting nutrient in the lake. Smith (1952) expanded on this idea, noting that greater numbers of species in an area broadened the TN/TP range over which P became limiting, and recommended only ratios greater than 37.7 be considered P limited. The lowest TN/TP ratio of the six lakes was 77.9 for Douglas Lake. This is well above the 37.7 cutoff point for P limitation, suggesting that P is the limiting nutrient in all six lakes.

Munro Lake had a significantly higher average TN concentration than all other lakes and a higher average TP concentration than all other lakes except Douglas Lake, Munro lake also had the greatest average concentration of chl a. Burt Lake and Mullett Lake had the lowest average TP concentrations of all other lakes except long, and the two lakes had the lowest average chl a concentrations in their epilimnetic waters. This supports out hypothesis that the largest lakes would exhibit the lowest nutrient concentrations and the lowest productivity.

Following the standards set by Michigan Clean Water Corps (Debnarz, 2007), in this paper I classify oligotrophic lakes as having a TSI value less than 38, and mesotrophic lakes as having a TSI value in the range of 38 to 48. Under this definition, all three TSI values for Douglas and Munro Lakes (Chl a, TP, and Secchi Depth) indicate these two lakes to be mesotrophic. This classification is in agreement with former studies conducted on Douglas Lake (Geddes et. al., 1997). However, Fairchild and Sell (1978) indicate that TSI values for Munro Lake are typically much higher, classifying Munro as a eutrophic lake. All three TSI values classify Burt and Long Lakes to be oligotrophic. This is consistent with other TSI values obtained from yearly monitoring of Burt Lake, which typically find the lake to be on the borderline between meso- and oligotrophic.

Although TSI values for Chl a and TP place Black and Mullet Lakes as oligotrophic lakes, TSI(SD) values for these two lakes indicate them to be mesotrophic. The Tip of the Mitt Watershed Council records Black Lake as an oligotrophic Lake and Mullett Lake as a mesotrophic Lake. Although Mullet and Black were the only two lakes to be classified into two different trophic states by our data, they were not the only two lakes to experience differences in TSI values based on the three different parameters. These differences in the TSI values based on Secchi depth, Chl a, and TP can lend greater insight into factors affecting the trophic state of the lake through an investigation of the possible causes of these differences (Carlson, 1977, Stoermer and Keller, 2008).

For all of the lakes we sampled except Long lake, TSI(SD) gave the highest TSI value, and for all six of the lakes we sampled TSI(TP) gave the lowest index value. Because P is limiting in these lakes, we would expect a close correspondence between TSI(TP) and TSI(chl a) values in these lakes, which is witnessed in Munro, Black, Burt, and Douglas Lakes. There was a greater difference in TSI(TP) and TSI(Chl a) values in Long and Mullett Lake, although both parameters led to an index value within the same trophic class for each lake.

In four of the five lakes with zebra mussels, TSI(TP) and TSI(Chl a) values are closer in value to each other and have a lower value than does TSI(SD). Where zebra mussels are present in lakes, they tend to reduce the amount of both particulate and soluble P in the water column (Higgins and Zanden, 2010). Zebra mussels filter large quantities of phytoplankton and out of the water column, leading to a reduction of photosynthetic biomass that both improves water clarity and reduces the level of primary production occurring in the water column (Higgins and Zanden, 2010). Thus we would expect zebra mussel invasion to result in lower TSI values for all three parameters. However, it is possible TSI(SD) in these lakes was not as greatly affected as TSI(TP) and TSI(Chl a) because there are abiotic factors present that are affecting water clarity. Two of the lakes studied, Douglas and Black Lakes, are noted for the presence of the tannins in their waters (Tip of the Mitt Watershed Council). Tannins color waters and can reduce water clarity (Stoermer and Keller, 2008). Additionally, the substrates of the lakes sampled in this study tend to consist of fewer boulders and cobbles and more sand than lakes typically colonized by zebra mussels (Higgins and Vander Zanden, 2010, Stoermer and Keller, 2008). Suspended sand could play a role in reducing water clarity, especially in the shallower lakes. Stoermer and Keller (2008) also propose calcium precipitation occurring in the lakes as a possible factor leading to reduced water clarity. All of these factors could contribute to the higher TSI value calculated for SD. The presence of tannins and calcium particles in the lakes could also contribute to the P limitation of the lakes, as P can precipitate out of solution with both substances (Stoermer and Keller, 2008). However, this could prove to be beneficial to the future health of the lakes, as it could provide them a mechanism to deal with a greater capacity of P loading without harmful affects by precipitating the P out of the water column.

If abiotic factors are affecting water clarity in these lakes, TSI(SD) would not be expected to give a very accurate estimate of the trophic state of the lake. In lakes where P is a limiting nutrient, TSI(TP) tends to be a more accurate representation of the lake's trophic state than is TSI(SD) (Carlson, 1977). However, TSI(Chl a) is expected to be the most accurate indication of trophic state in these lakes because it has the most direct relationship to the actual levels of primary productivity in the lakes (Carlson, 1977). Therefore, although TSI(SD) is often the cheapest and easiest method of estimating trophic state, for the most accurate measure of trophic status in these lakes managers should use chlorophyll a concentrations whenever possible.

Managers should also be on the alert for the possible introduction of the quagga mussel, Dreissena rostriformis bugensis. Zebra mussels are densest in areas with plentiful large hard substrata, such as boulders or cobbles (Higgins and Vander Zanden, 2010). Although the shallows of the lakes studied do contain some rocks and gravel, the substrate in these lakes is mainly sand and organic material (Stoermer and Keller, 2008). Because zebra mussels cannot attach to sand, this limits the amount of habitat available to them and therefore limits their affect on the entire lake. Quagga mussels, in contrast, are capable of attaching to hard or soft substrates and have been found in depths up to 100 m (Higgins and Vander Zanden, 2010). When quagga mussles colonize these lakes, they will not be as inhibited by habitat as zebra mussels and are therefore expected to have a greater affect on the lake ecosystem.

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Appendix 1

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Table 2 Latitude and longitude, average depth, depth to the thermocline, and average specific conductance for each sample site

	Latitude, Longitude	Average Depth (m)	Depth to Thermocline	Average Specific Conductance (mS/cm)
Black-North Site	N45° 27.25’ W084° 15.429’	14.3 (SE=0.16)	4.5	0.268 (SE=0.001)
Black-West Site	N45° 27.018’ W084° 16.235’	14.2 (SE=0.33)	5	0.267 (SE=0.001)
Black-South Site	N45° 26.678’ W084° 15.268’	11.8 (SE=0.54)	5.5	0.271 (SE=0.001)
Burt-South Site	N45˚25.751 W084˚39.387	15.3 (SE=0.18)	8.5	0.27 (SE<0.001)
Burt-West Site	N 45˚27.157 W084˚40.15	13.7 (SE=0.07)	8	0.268 (SE<.001)
Burt-North Site	N 45˚28.981 W084˚39.471	11.3 (SE=0.01)	6.5	0.27 (SE<.001)
Grapevine Point	N45° 34.399’ W084° 41.147’	22.3 (SE=0.14)	10	0.254 (SE=0.001)
Fairy Island	N45° 35.209’ W084° 42.674’	21.8 (SE=0.15)	9.5	0.255 (SE=0.001)
South Fishtail Bay	N45° 33.816’ W084° 40.356’	22.9 (SE=0.49)	10	0.251 (SE=0.001)
Long-South	N45.53226° W084.39510°	16.29 (SE=0.04)	5	0.191 (SE<0.001)
Long-Mid Lake	N45.53662° W084.40282°	9.85 (SE=0.09)	5	0.189 (SE<0.001)
Long-North	N45.54025° W084.41383°	9.83 (SE=0.02)	5	0.191 (SE=0.001)
Mullett-North Site	N45.543819 W084.517588	16.63 (SE=0.05)	9	0.3 (SE=0.002)
Mullett-West Site	N45.485148 W084.56418	35.7 (SE=0.15)	7	0.35 (SE=0.001)
Mullett-South Site	N45.462911 W084.553822	24.2 (SE=0.38)	6	0.35 (SE=0.001)
Munro-South Site	N 45° 61.537' W 84° 68.300'	3.4 (SE=0.038)	None	0.155 (SE=0.0)
Munro-East Site	N 45° 61.584' W 84° 68.315'	3.36 (SE=0.018)	None	0.155 (SE=0.001)
Munro-North Site	N 45° 61.544' W 84° 68.283'	3.4 (SE=0.015)	None	0.154 (SE=0.0)

Table 3 Team member measurement performance by sample site in all six lakes.

Sample Site	Hydrolab	Secchi Disk	PAR
Grapevine Point	Molly/Balin	Will/Sid	Emily/Megan
Fairy Island	Will/Sid	Molly/Balin	Erik/Pat
South Fishtail Bay	Emily/Megan	Emily/Megan	Will/Sid
Black-North Site	Balin/Sid	Will/Molly	Will/Molly
Black-West Site	Will/Molly	Megan/Pat	Megan/Pat
Black-South Site	Megan/Pat	Emily/Erik	Emily/Erik
Burt-South Site	Emily/Erik	Megan/Pat	Megan/Pat
Burt-West Site	Balin/Sid	Emily/Erik	Emily/Erik
Burt-North Site	Will/Molly	Balin/Sid	Balin/Sid
Long-South	Will/Troy	Megan/Sid/Balin	Emily/Pat
Long-Mid	Will/Troy	Megan/Sid/Balin	Emily/Pat
Long-North	Will/Troy	Megan/Sid/Balin	Emily/Pat
Mullett-North	Will/Molly	Megan	Emily/Pat
Mullett-West	Will/Molly	Megan	Emily/Pat
Mullett-South	Will/Molly	Megan	Emily/Pat
Munro-South Site	Will/Molly	Megan/Sid	Emily/Pat
Munro-East Site	Will/Molly	Megan/Sid	Emily/Pat
Munro-North Site	Will/Molly	Megan/Sid	Emily/Pat

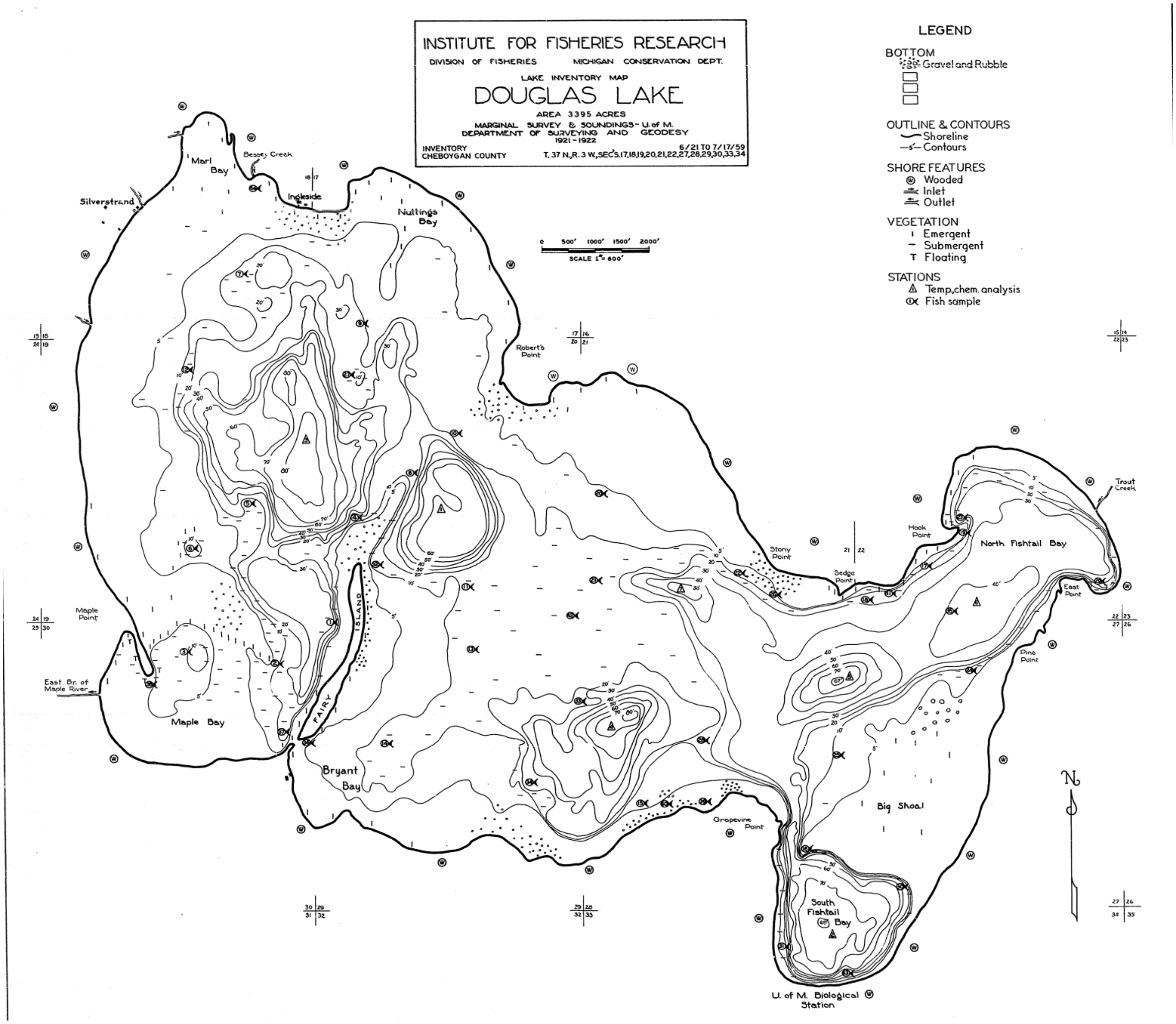

Figure 1 Bathymetric map of Douglas Lake, Cheboygan County, MI (MIDNR)

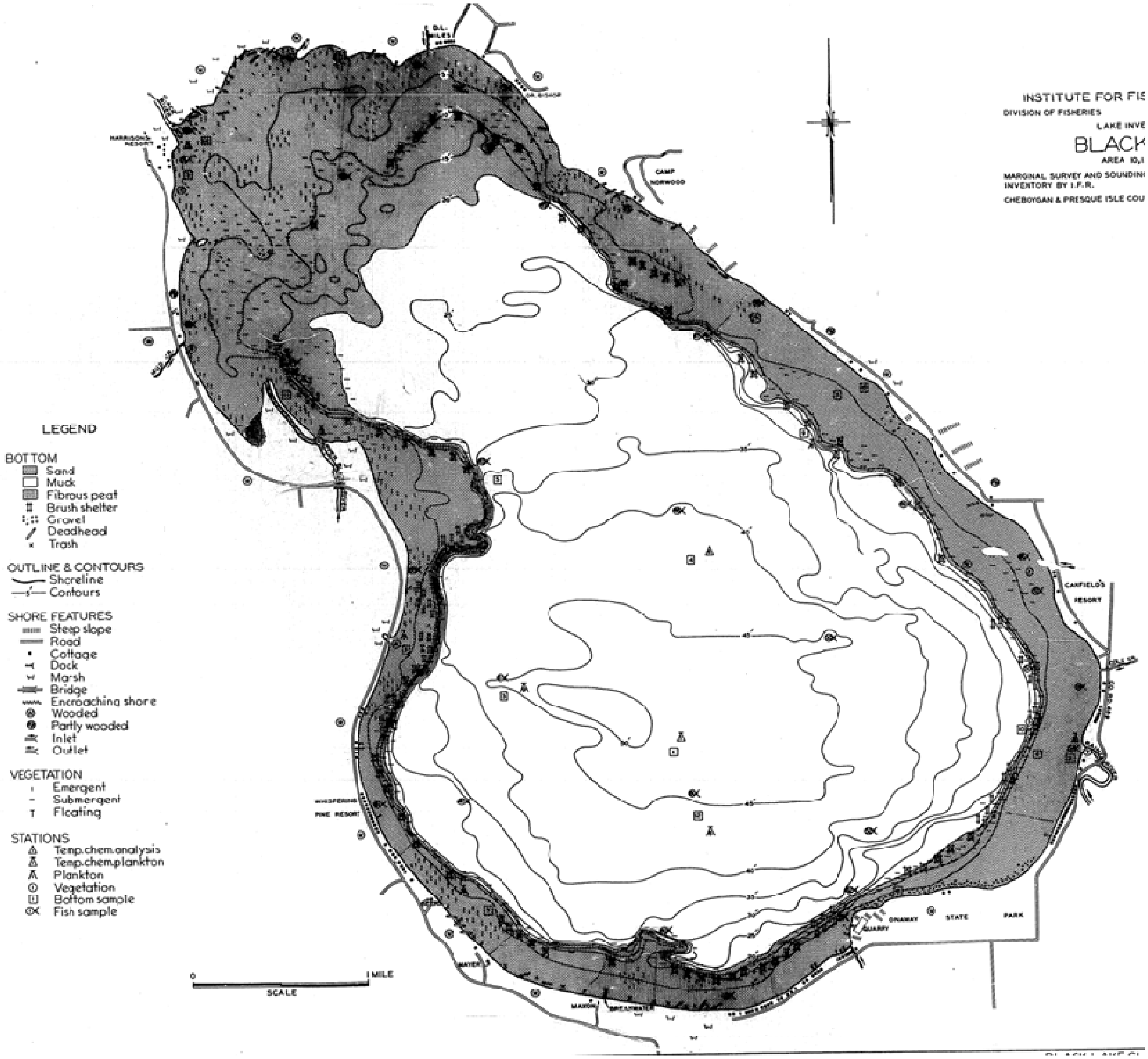

Figure 2 Bathymetric map of Black Lake, Cheboygan and Presque Isle Counties, MI (MIDNR)

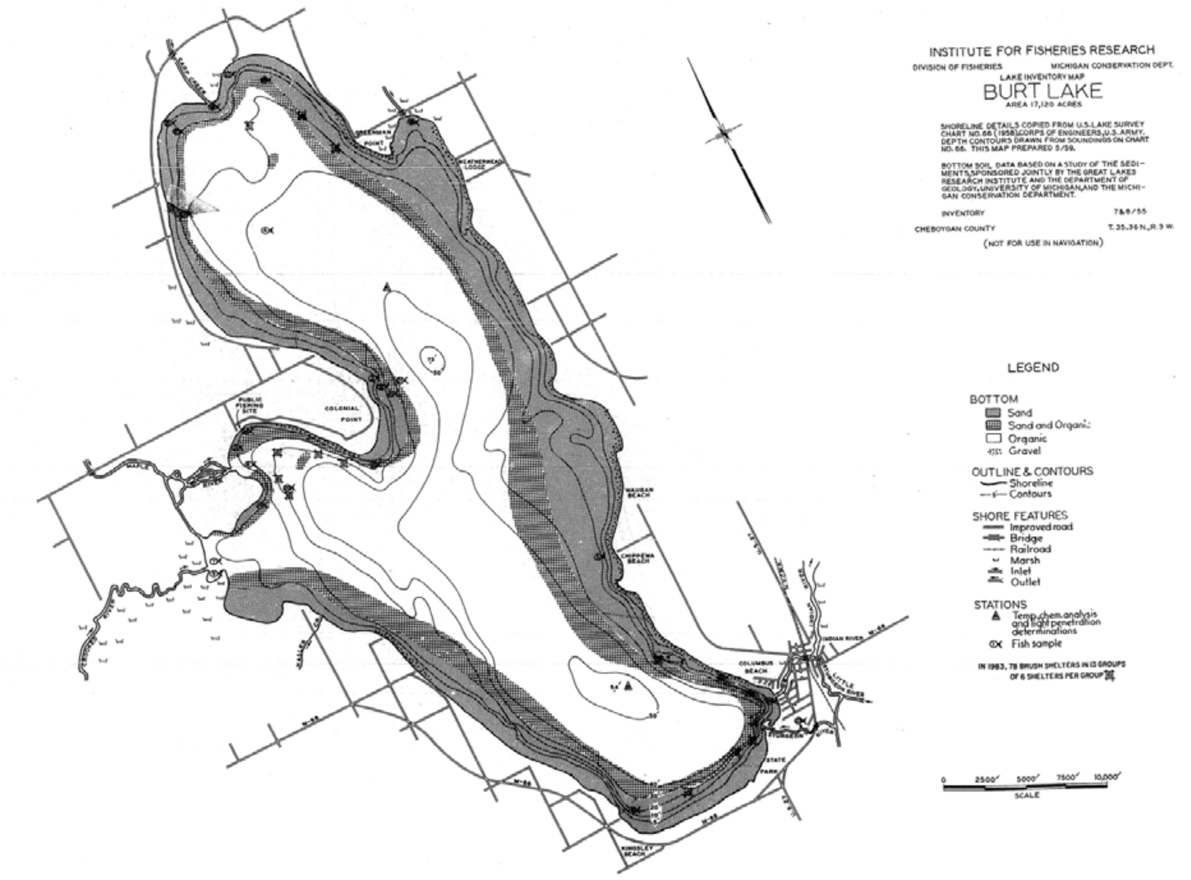

Figure 3 Bathymetric map of Burt Lake, Cheboygan County, MI (MIDNR)

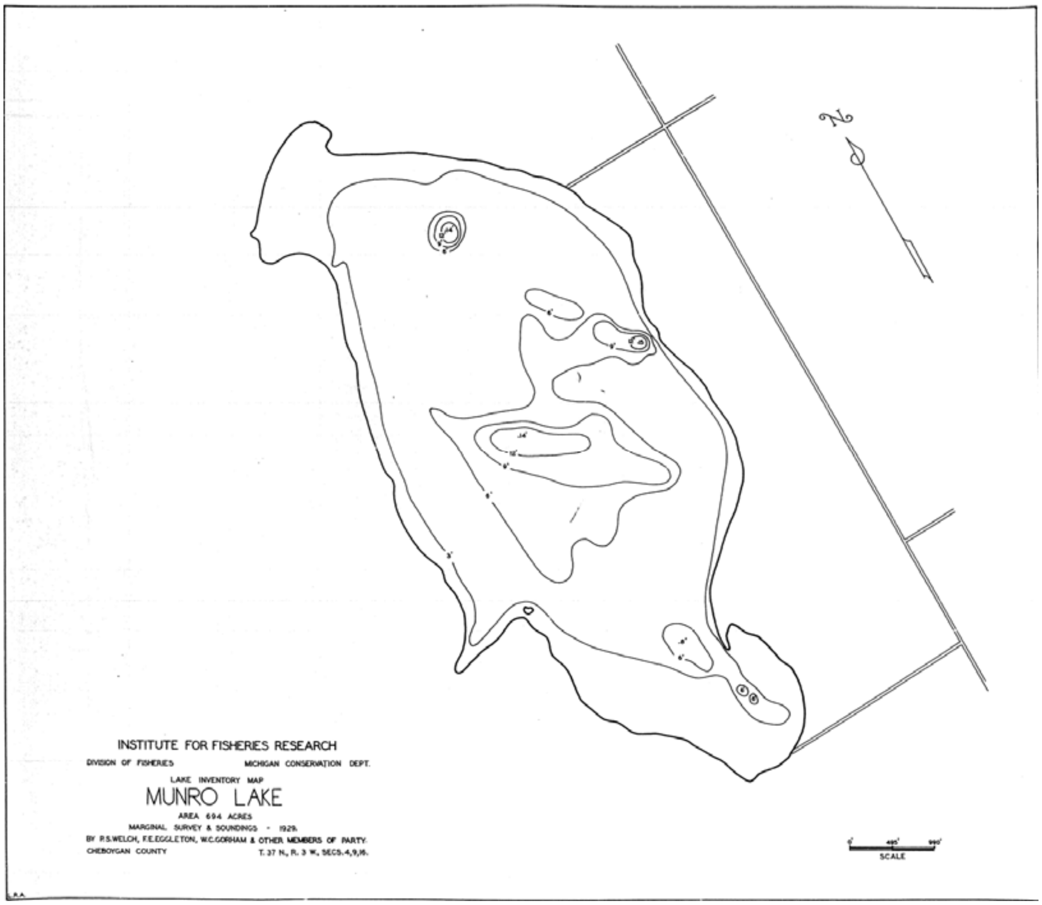

Figure 4 Bathymetric map of Munro Lake Cheboygan County, MI (MIDNR)

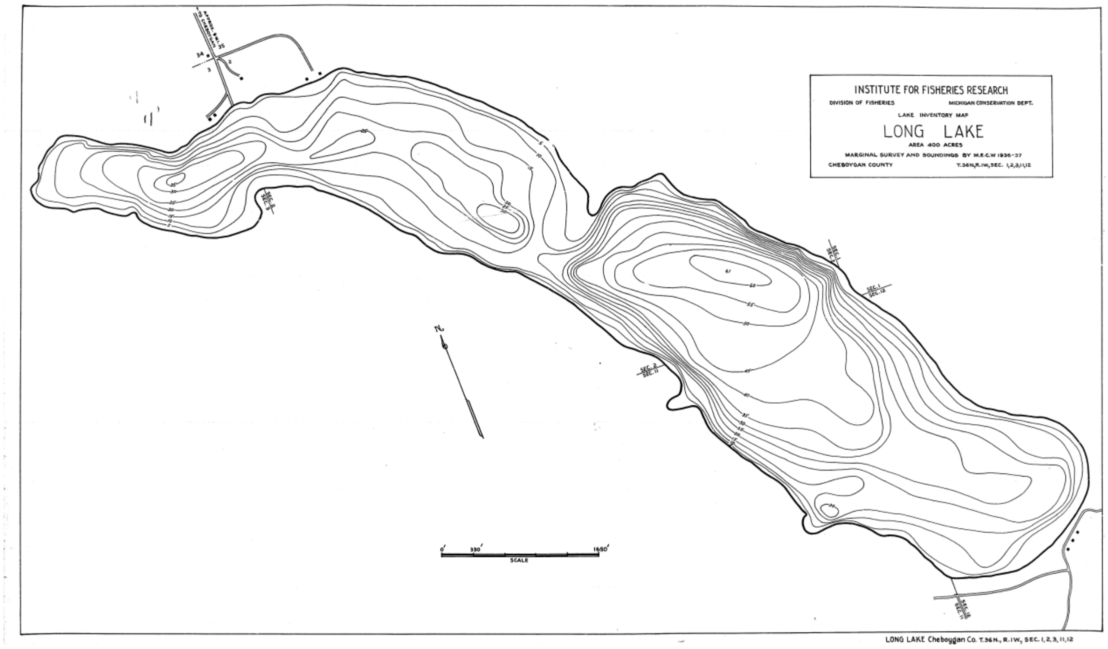

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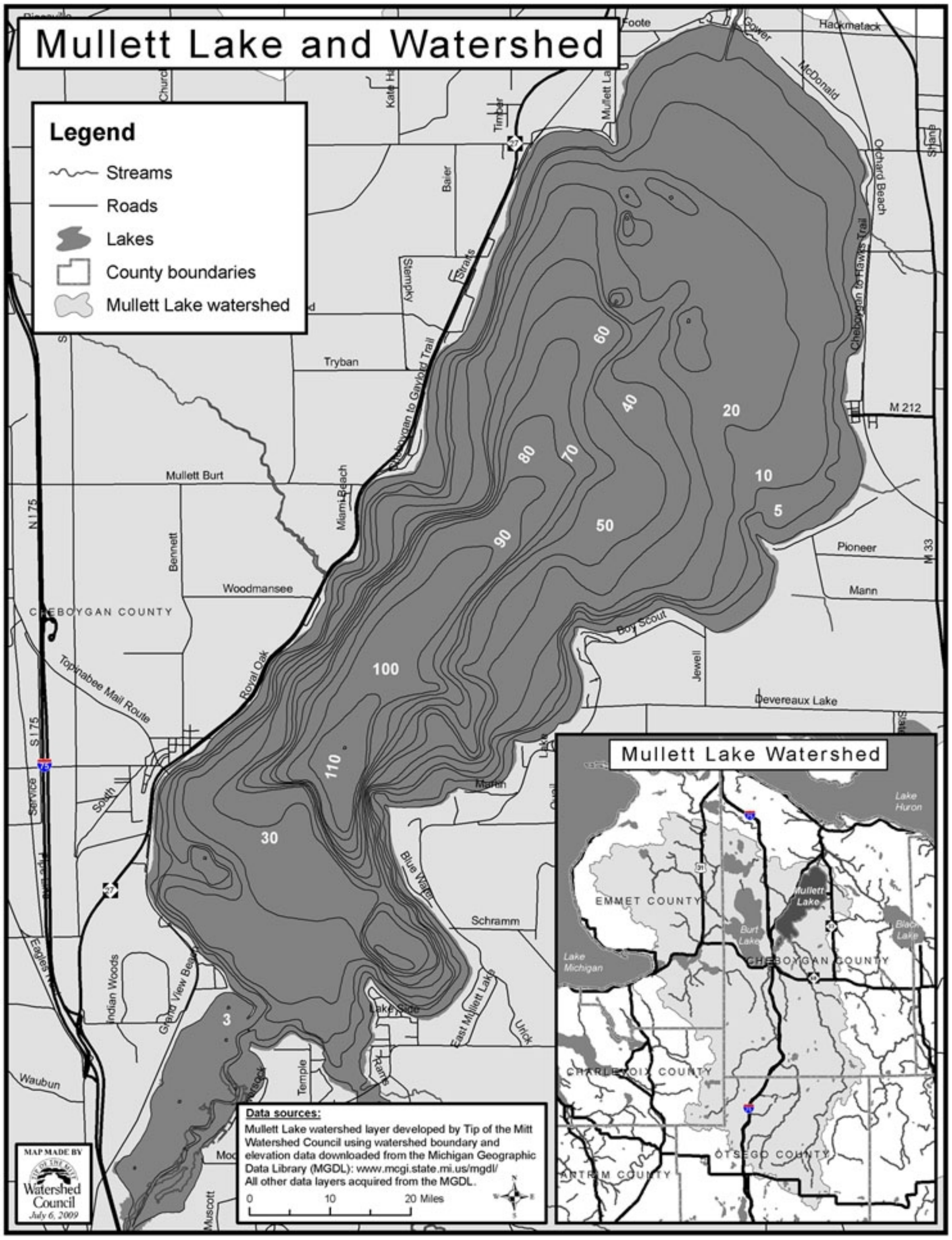
Figure 5 Bathymetric map of Long Lake, Cheboygan County, MI (MIDNR)



Data sources:

Mullett Lake watershed layer developed by Tip of the Mitt Watershed Council using watershed boundary and elevation data downloaded from the Michigan Geographic Data Library (MGDL): www.mcgi.state.mi.us/mgdl/
All other data layers acquired from the MGDL.

Figure 6 Bathymetric map of Mullett Lake, Cheboygan County, MI (Tip of the Mitt)