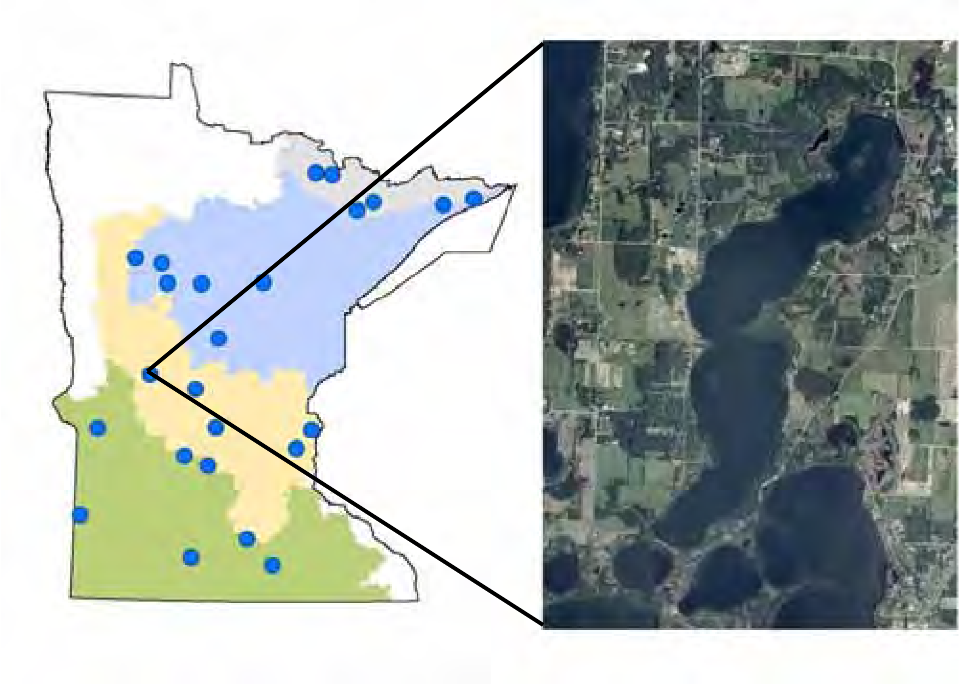
Sentinel Lake Assessment Report
Lake Carlos (21-0057)
Douglas County, Minnesota



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&
Minnesota Department of Natural Resources
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Executive Summary

The Minnesota Pollution Control Agency (MPCA) is working in partnership with the Minnesota Department of Natural Resources (MDNR) on the Sustaining Lakes in a Changing Environment (SLICE) Sentinel Lakes Program. The focus of this interdisciplinary effort is to improve understanding of how major drivers of change such as development, agriculture, climate change, and invasive species can affect lake habitats and fish populations, and to develop a long-term strategy to collect necessary information to detect undesirable changes in Minnesota Lakes (Valley 2008). To increase our ability to predict consequences of land cover and climate change on lake habitats, SLICE utilizes intensive lake monitoring strategies on a wide range of representative Minnesota lakes. This includes analyzing relevant land cover and land use, identifying climate stressors, and monitoring effects on the lake's habitat and biological communities.

The Sentinel Lakes Program has selected 24 lakes for long-term intensive lake monitoring (Figure 1). The "Deep" lakes typically stratify during summer months only. "Shallow" lakes are defined as mixing continuously throughout summer. "Cold water" lakes are defined as lakes that either harbor cisco, lake whitefish, or lake trout and are the focus of research funded by the Environmental Trust Fund (ETF). "Super sentinel" lakes also harbor cold-water fish populations and research on these lakes is also funded by the ETF. Lake Carlos is a cold water, super sentinel, lake that has a resident cisco population.

Lake Carlos is a popular recreation lake that has a surface area of 1055 hectare (ha; 2,607 acres) and has a maximum depth of 50 meters (163 feet). Nearly all (98%) of the shoreline of Lake Carlos is developed. The State of Minnesota (Carlos State Park), owns 2.3 kilometers (1.4 miles) of shoreline on the north end of the lake. The lake supports a large range of water recreational activities.

Lake Carlos was formed from glacial activity, which produced its great depths and complex basin morphology. The lake is located in Douglas County, just north of the city of Alexandria in the Long Prairie River Watershed. Lake Carlos has a large watershed and is last in a chain of lakes that form headwaters of the Long Prairie River. There is extensive water quality data on Lake Carlos as a result of monitoring by citizen volunteers, Alexandria Area Lakes Sanitary District, and the MPCA. This data was used to analyze and identify water quality trends and current condition of Lake Carlos.

Historic trophic status data for Lake Carlos indicates the lake is moderately fertile (mesotrophic) and has been since the beginning of data collection in 1948. As part of the Sentinel lakes research project funded by the ETF, reconstructions of Lake Carlos's water quality prior to European settlement using sediment cores will be completed by 2012. Based on data from 1985-2009, summer-mean total phosphorus (TP) is typically between 15-20 micrograms per liter (ug/L) and chlorophyll-a is generally 5 ug/L or less. Summer-mean Secchi has been variable, but is generally between 3-4 meters in most summers. These values are below typical ecoregion reference lake values for the North Central Hardwood Forest ecoregion and could be considered exceptional. Because of its great depth and volume the lake is able to efficiently assimilate P loading from its extensive watershed, which results in relatively low algal concentrations. Even though most water quality parameters meet expectations, some trends may merit attention. For example, chloride (Cl) levels have been steadily increasing since 1948 until present. Although there are no biological implications at current Cl concentrations, this measure is a direct reflection of human activities in the watershed, such as road salting and the upstream discharge of wastewater.

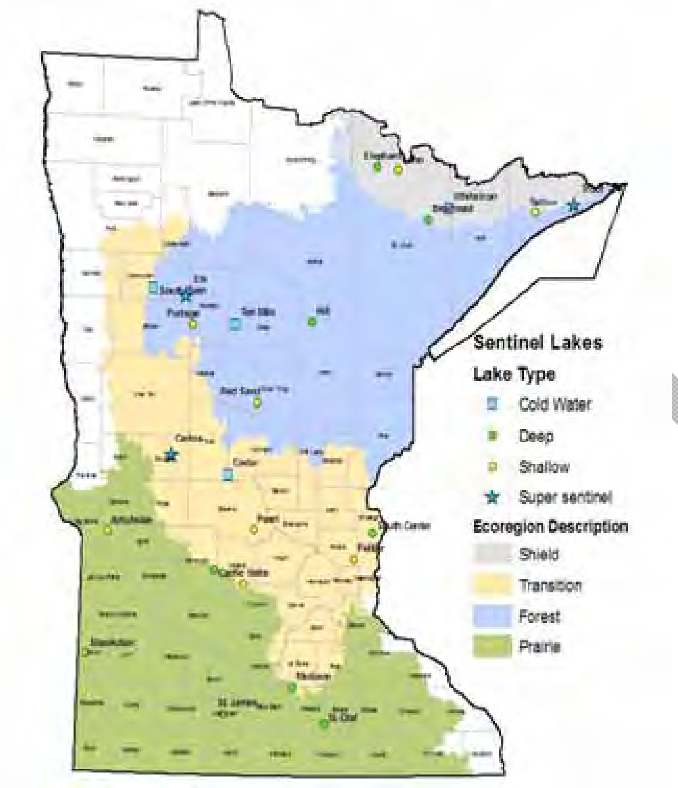
Lake Carlos supports a relatively diverse fish community with several warm, cool, and cold water fish species. Six fish species intolerant to nutrient pollution are currently present in the lake. Lake Carlos currently provides many opportunities for anglers. Each year, Lake Carlos hosts multiple bass tournaments and it continues to be a popular destination for walleye anglers. Largemouth bass and northern pike populations are abundant but growth is relatively slow. In contrast, walleye are less abundant, but grow relatively fast compared with other similar lakes. Lake Carlos is not as fertile and is much deeper than most basins within the Glenwood Management Area and consequently has a lower biological carrying capacity for large game fish. A natural lack of complex shallow water habitats (e.g., aquatic plants, coarse woody habitat, a variety of substrates) limits the numbers and size of game fish that depend on those habitats. Consequently, protecting or restoring current shallow water habitats will be important for continued viability of Carlos's fish community. Furthermore, tullibee or cisco are an important cold-water forage fish present in the lake that roam deep offshore waters; however, their status in Carlos and other Minnesota lakes is threatened due to climate change and landuse changes that can lead to warmer water and more increased hypolimnetic oxygen depletion from increased primary productivity. New technological tools (hydroacoustics) and netting techniques will be deployed on Carlos Lake during summer 2010 by MDNR Fisheries and University of Minnesota Duluth (Lead: Dr. Tom Hrabik) to determine the current population status of cisco.

Invasive species such as zebra mussels and curly-leaf pond weed are present in Lake Carlos. In summer 2009, zebra mussels were discovered throughout the lake. Given the potential for zebra mussels to alter lake foodwebs and water quality, it will be important to monitor zebra mussel populations and their effect on water quality, habitats, and foodwebs. Curly-leaf pondweed has been present for some time in Lake Carlos; however, growth has remained sparse presumably due to the good water quality in Carlos and modestly diverse assemblage of native aquatic plants.

The cumulative effect of conventional development and agricultural practices, non-native species invasion and impacts from a warmer more variable climate on lakes is a slow, insidious erosion of resilience. Actions should be taken at multiple levels (global to local to individual) to reduce the human footprint on the climate and landscape.

Other current and future work by MDNR, MPCA, and the US Geological Survey in Carlos will focus on intensive monitoring and modeling that will lend insight into the potential consequences of climate, watershed, and in-lake stressors on lake habitats and fish populations and promote proactive protection and restoration measures.

Figure 1. MDNR map of Sentinel lakes and major land types.



Introduction

This report provides a relatively comprehensive analysis of physical, water quality and ecological characteristics of Lake Carlos in Douglas County, Minnesota (MN). This assessment was compiled based on Minnesota Department of Natural Resources (MDNR) surveys of the lake's fish and aquatic plant communities, Minnesota Pollution Control Agency (MPCA) and volunteer water quality monitoring, and analysis of various other sources of data for the lake. The water quality assessment focuses on data collected during the 2008 and 2009 season; however, historical data are used to provide perspective on variability and trends in water quality. Water quality data analyzed will include all available data in STORET, the national repository for water quality data. Further detail on water quality and limnological concepts and terms in this report can be found in the Guide to Lake Protection and Management: (http://www.pca.state.mn.us/water/lakeprotection.html).

History

MDNR fishery survey records provide the basis for much of the Lake Carlos history assembled for this report. Fisheries lake surveys were conducted in 1948, 1954, 1973, 1980, and 1992. Fisheries population assessments were conducted in 1985, 1988, 1996 and 2000. Lake Carlos has been included in Glenwood Area's annual ice house counts from 1988 thru 2009.

1910 First fish stocking records for Lake Carlos

1910-1945 Within this time period, steelhead (Oncorhynchus mykis) and lake trout (*Salvelinus namaycush)* were stocked.

1937 Lowest lake level is recorded at 412.01 meters (1351.75 feet).

1937 Land on north side of Lake Carlos is acquired for a state park. Over the years, Lake Carlos State Park is developed to include 122 campsites, 4 camper cabins, 2 group camps, and one group center.

1948 First fisheries lake survey noted there were 11 resorts, 137 cottages and 144 boats on Lake Carlos.

1973 Lake survey found 9 resorts (73 cabins), 310 cottages and 467 watercraft, consisting of 395 boats, 48 pontoons and 24 sailboats.

1973 Summer kill of cisco (*Coregonis artedi*) noted during MDNR Fisheries surveys.

1980 Lake survey found 9 resorts (70 cabins), 342 homes or cottages and 638 boats.

1992 Lake survey found 5 resorts and 420 homes and cottages.

2003 Highest lake level is recorded at 1358.02 feet.

2009 Zebra mussel (*Dreissena polymorpha*) infestation confirmed in Lake Carlos.

Background

Lake Morphometric and Watershed Characteristics

Lake Carlos is located in central Douglas County within the Long Prairie River watershed. Lake Carlos is approximately five miles north of Alexandria, MN and is the last in a chain of lakes that extends from Alexandria to where it outlets to the Long Prairie River. Public accesses are located on the west and east central shorelines and on the north shore within Carlos State Park. Lake Carlos is classified as a deep, dimictic lake that mixes during spring and fall and forms a distinct thermocline during the summer.

A summary of Lake Carlos's morphometric characteristics is presented in Table 1. Lake Carlos is a deep lake with a maximum depth of about 50 meters (m; 163 ft; Table 1). About 35 percent of the lake is considered littoral. Percent littoral area refers to that portion of the lake that is 4.6 m (15 ft) or less in depth, which often represents depth to which rooted plants may grow in the lake. Lakes that have exceptionally clear water, such as Lake Carlos, may have rooted plant growth at depths greater than 4.6 m (15 ft). Lakes with a high percentage of littoral area often have extensive rooted plant (macrophyte) beds. These plant beds are a natural part of the ecology of these lakes and are important to maintain and protect.

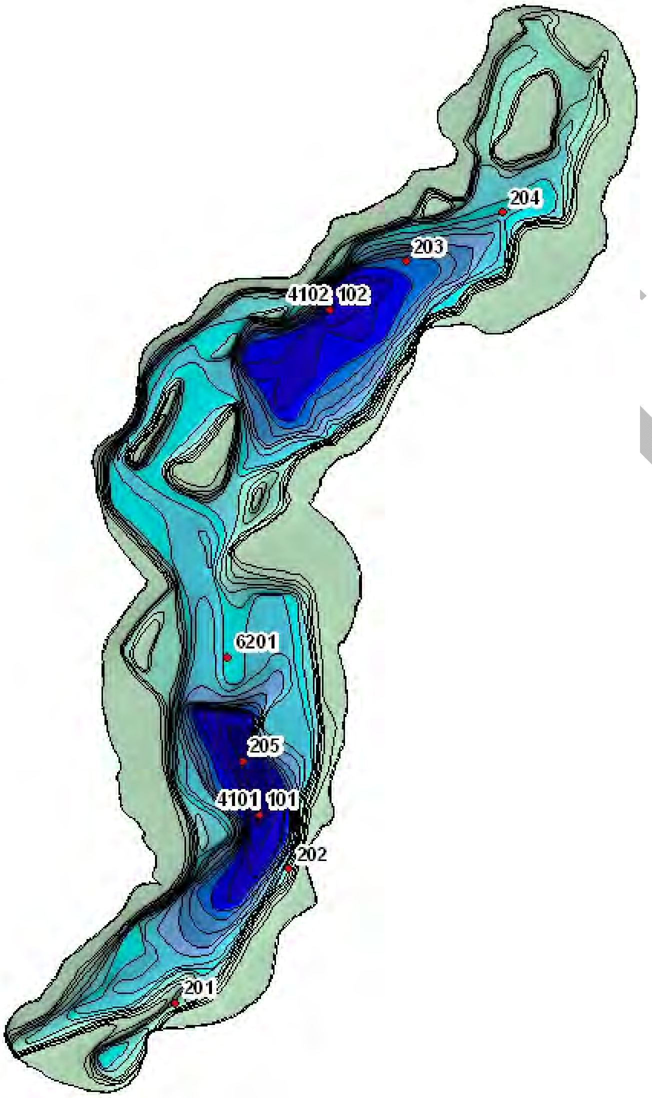
The Alexandria area, including Lake Carlos has unique topography as a result of the last glaciation. Surficial geology of the Lake Carlos region is characterized by glacial drift over very ancient Precambrian granites, slates, and related formations. Since only a few drill holes have penetrated the drift, very little is known of these older formations (Theil, 1958). Glacial outwash left behind deep deposits of sand and gravel. As a result, Lake Carlos has many sharp points and humps throughout the basin (Figure 2). Lake Carlos was likely formed as an ice block basin in outwash localized by preglacial valleys (Zumberge, 1952). Lake Carlos soils are defined as well drained dark colored soils formed from calcareous glacial till from the Waukon-Barnes series within an undulated to rolling area.

Water levels in the chain of lakes in the region of Lake Carlos are controlled by numerous dams maintained by the MDNR.

Table 1. Lake Carlos morphometric characteristics.

Lake Name	Lake ID	Lake Basin	Littoral Area	Total Watershed Area	Watershed: Lake	Max. Depth	Mean Depth	Lake Volume
		Acres	%	Acres	Ratio	Meters	Meters	Acre-Ft.
Carlos	21-0057	2,607	35	156,569	62:1	50	14	119,922

Figure 2. Lake Carlos bathymetric contour and site map as of 2009.



Lake Mixing and Stratification

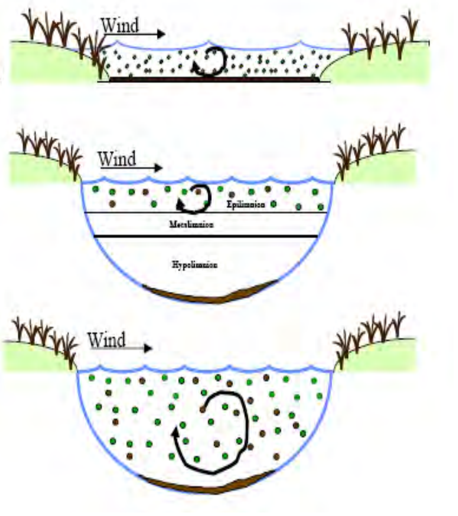
Lake depth and mixing have significant influences on lake processes and water quality. *Thermal stratification* (formation of distinct temperature layers), in which deep lakes (maximum depths of 9 meters or more) often stratify (form layers) during summer months and are referred to as *dimictic* (Figure 3). These lakes fully mix or turn over twice per year; typically in spring and fall. Shallow lakes (maximum depths of 6 meters or less) typically do not stratify and are often referred to as *polymictic*. Lakes with moderate depths may stratify intermittently during calm periods, but mix during heavy winds and during spring and fall. Measurement of temperature throughout the water column (surface to bottom) at selected intervals (e.g. every meter) can be used to determine whether the lake is well mixed or stratified. Depth of the thermocline (zone of maximum change in temperature over the depth interval) can also be determined. In general, dimictic lakes have an upper, well-mixed layer (epilimnion) that is warm and has high oxygen concentrations. In contrast, the lower layer (hypolimnion) is much cooler and often has little or no oxygen. This low oxygen environment in the hypolimnion is conducive to total phosphorus (TP) being released from lake sediments. During stratification, dense colder hypolimnion waters are separated from nutrient hungry algae in the epilimnion. Intermittently (weakly) stratified polymictic lakes are mixed by high winds. Mixing events allow for nutrient rich sediments to be re-suspended and available to algae.

Figure 3. Lake stratification.

Polymictic Lake
Shallow, no layers,
Mixes continuously
Spring, Summer & Fall

Dimictic Lake
Deep, form layers,
Mixes Spring/Fall

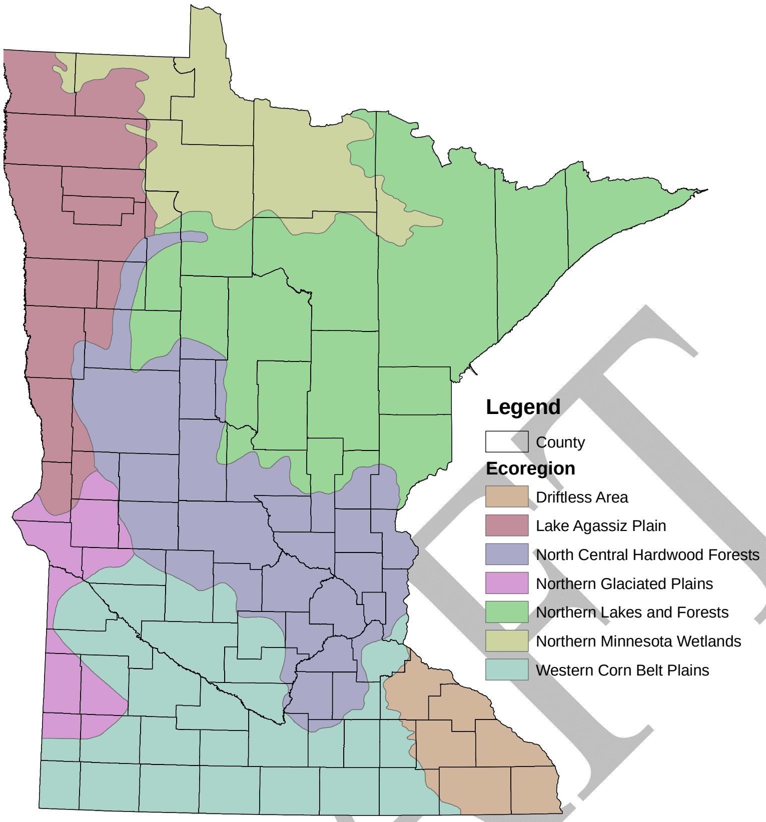
Intermittently Stratified
Moderately deep
Mixes during high winds
Spring, Summer, & Fall



Ecoregion and Land Use Characteristics

Minnesota is divided into seven regions, referred to as ecoregions. Ecoregions are segregated by soils, land surface form, natural vegetation and current land use. Data gathered from representative, minimally impacted (reference) lakes within each ecoregion serve as a basis for comparing water quality and biological attributes of other lakes. Lake Carlos lies within the North Central Hardwood Forest (NCHF) ecoregion (Figure 4). NCHF ecoregion values will be used for land use (Table 2) and summer-mean water quality comparisons (Table 9) and model applications.

Figure 4. Minnesota ecoregions as mapped by United States Environmental Protection Agency.



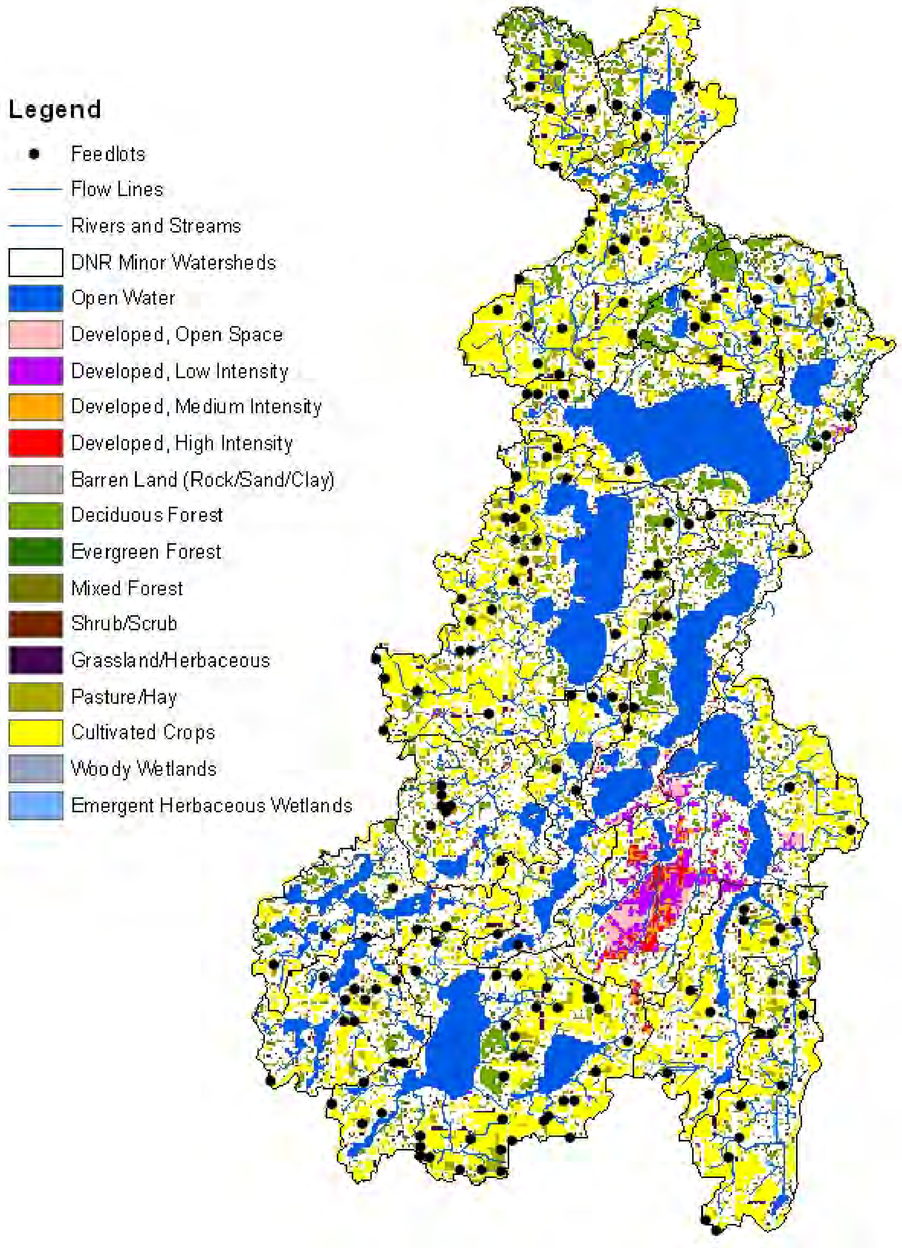
Since land use affects water quality, it has proven helpful to divide Minnesota into regions where land use and water resources are similar. Land use within the Lake Carlos or Long Prairie River watershed is primarily cultivated agriculture, pasture/open space, and water/wetland (Figure 5). In 2009, row crops covered 16.5% of Carlos's watershed area with soybeans and corn accounting for the largest area (7.5% and 4.4% of the watershed respectively; source: USDA National Agricultural Statistical Service; http://www.nass.usda.gov/). Land use percentages have been compared for 1969, 1991, and 2001(Table 2). Trends show a slight reduction in cultivated landuse along with an increase in development and pasture/open space. Although development is increasing, it still remains a relatively small area of the overall watershed. Further expansion of high density development in the Alexandria area may be of future concern due to its close proximity to Lake Carlos and surrounding lakes. As for feedlots, no comparable data were available for the 1969 and 1991 timeframes so no conclusions can be drawn on trends among these three periods. Together runoff from crop fields, feedlots, and impervious urban and residential developments maybe contributing significant external nutrient loads into lakes upstream from Carlos and directly into the lake.

Table 2. Watershed and land use characteristics as compared to ecoregion reference lakes.

Land Use	Carlos 1969	Carlos 1991	Carlos 2001	NCHF Typical Land Use %
Developed	7	8	9	2-9
Cultivated (Ag)	38	33	30	22-50
Pasture & Open	21	27	22	11-25
Forest	12	9	16	6-25
Water & Wetland	23	23	23	14-30
Feedlots (#)	-	-	174	

[1] National Land Cover Database www.mrlc.gov/index.php
[2] Minnesota Land Cover 1991-1992:MAP www.lmic.state.mn.us/chouse/land_use_DNRmap.html
[3] Minnesota Land Management Information Center www.lmic.state.mn.us/chouse/metadata/luse69.html

Figure 5. Lake Carlos watershed land use.



Lake Level

Water levels have been measured on Lake Carlos since 1925. During the period of record (1925 – 2009), water level has varied by 6.27 feet, based on 1550 readings. Analyzing lake level and precipitation data can be difficult since timing of lake level measurements may not always capture maximum and minimum water levels each year. This can make it difficult to discern how much the lake level fluctuates and precise reason for the fluctuation. Precipitation data were taken from the Carlos weather station. Based on a pairing of lake level and precipitation data on an annual basis, some patterns are evident. In general, minimum and maximum water levels show good correspondence to the amount of precipitation; however, short term fluctuations may occur due to magnitude and intensity of precipitation events along with evaporation rates during a given year.

All lake level readings and annual mean precipitation values are plotted in Figure 6. Two time periods with robust records of water level data: 1937-1947 and 1988-2008 were further investigated. Water level fluctuations for these time periods are a direct reflection of annual precipitation (Figure 7 and Figure 8). In 1936, the Alexandria area was experiencing drought conditions with an annual precipitation value of 10.36 inches, as a result lake levels dropped significantly. Shortly, following the drought precipitation values returned to normal and lake levels recovered. In 1941, 32.7 inches of precipitation caused lake levels to rise drastically (Figure 7). In the recent record (1988-2008), lake levels continued to respond to fluctuations in precipitation (Figure 8).

The complete water level record may be obtained from the MDNR web site at: http://www.dnr.state.mn.us/lakefind/showlevel.html?id=29025000.

Figure 6. Historic mean water level and precipitation.

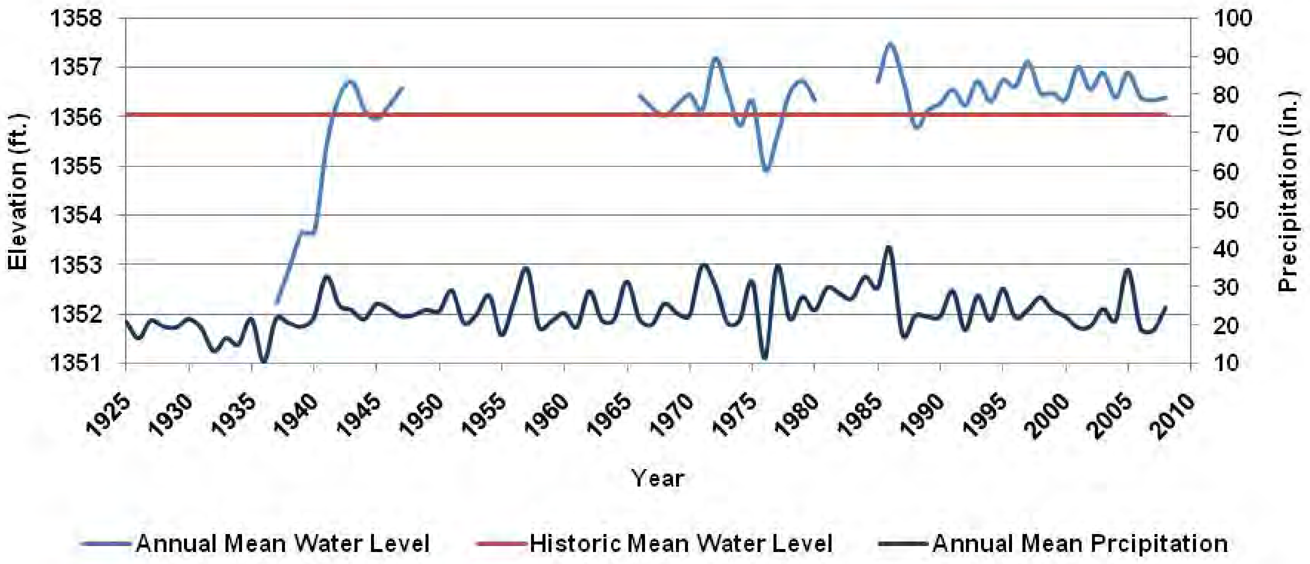


Figure 7. 1937-1947 lake level fluctuations and precipitation.

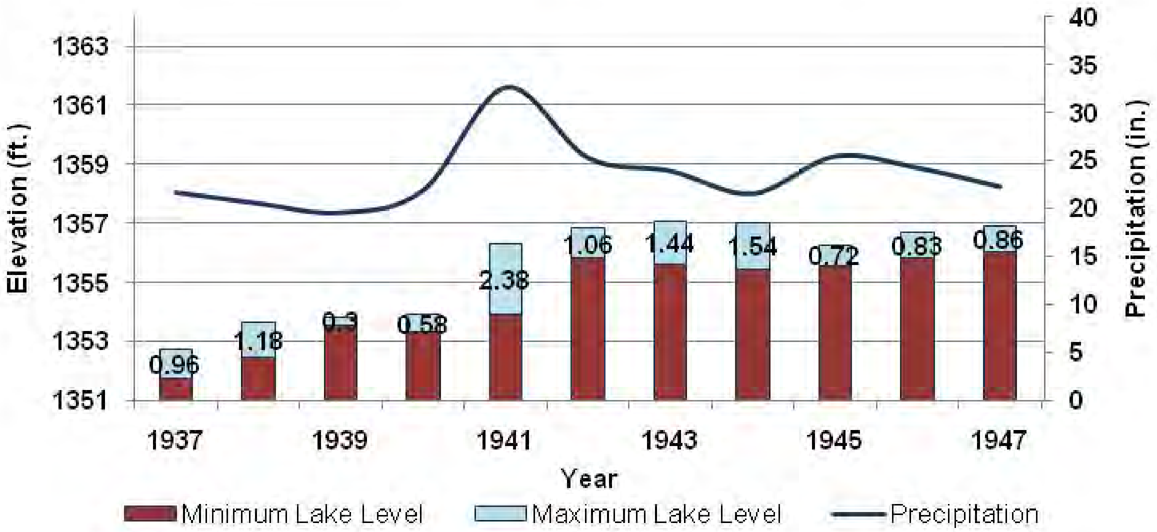
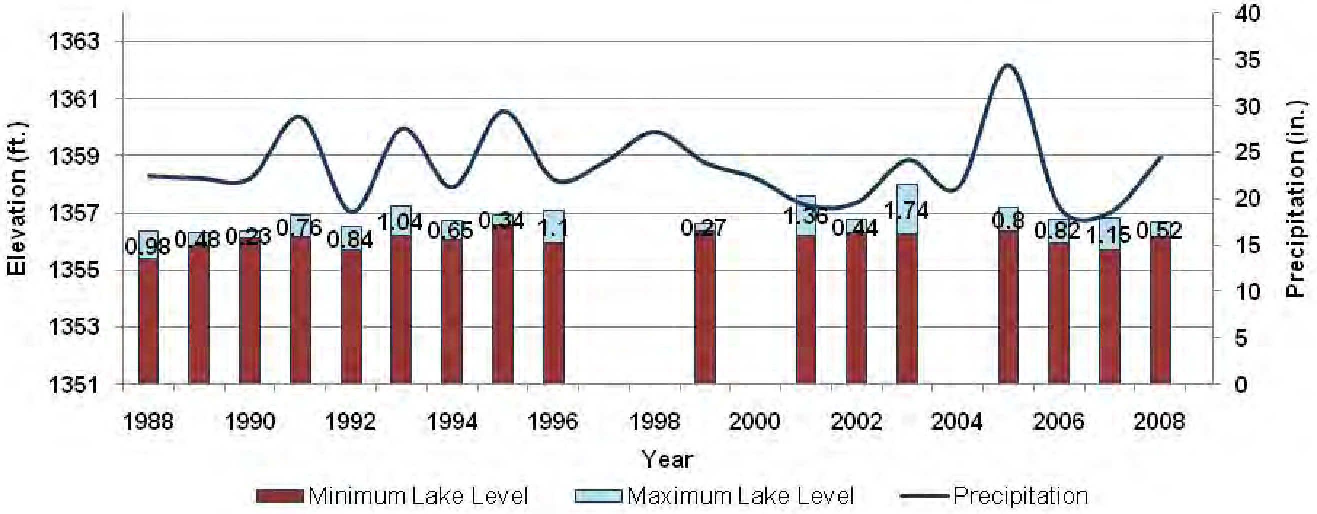


Figure 8. 1988-2008 lake level fluctuations and precipitation.



Precipitation and Climate Summary

Large rain events increase runoff into the lake and may influence in-lake water quality and lake levels. This will be considered in the discussion of lake water quality for 2008. Precipitation varies from year to year (Figure 9). Based on state climatology records, precipitation averages between 0.61 – 0.71 m (24 and 28 inches) annually in west central Minnesota (Figure 10). Precipitation in recent years has been slightly lower than this range. Typical evaporation and runoff values for lakes in this area are 0.94 meters per year (m/yr) of evaporation and 0.1 m/yr of runoff. This implies that evaporation typically exceeds precipitation. Thus, unless watershed runoff or groundwater inputs are sufficient to maintain lake level, lake levels will decline over the summer open water period in most years. The 2008 water year precipitation was about 0.05-.1 m (2-4 inches) below normal for this part of the state (Figure 10).

Figure 9. Precipitation annual mean values 1925-2008.

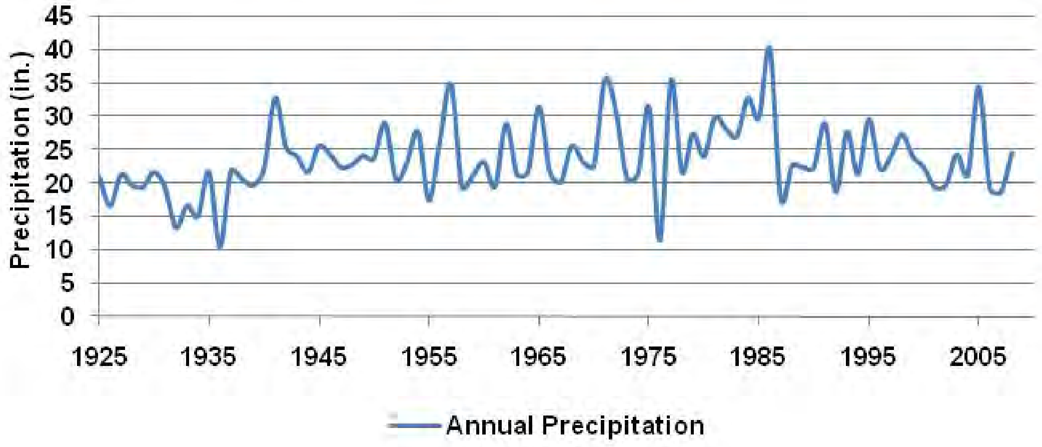
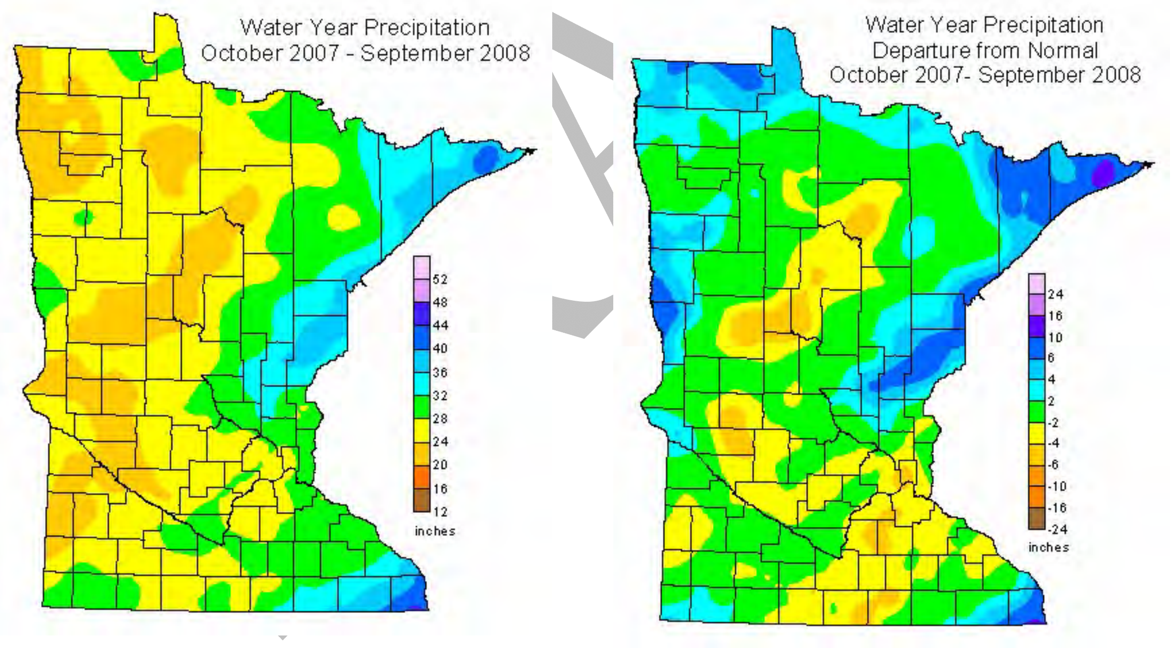


Figure 10. 2008 Minnesota water year precipitation and departure from normal prepared by State Climatology Office, MDNR.



Methods

Fisheries and Aquatic Plants

Frequency of occurrence of aquatic plant species were assessed using the point-intercept method (Madsen 1999). This method entailed visiting sampling points on a grid within the vegetated zone of the lake, throwing a two-sided rake over one side of the boat at each point, raking the bottom at approximately 1 m, retrieving the rake and identifying all species present, and recording the depth. Survey points were spaced approximately 80-m (0.7 points per littoral acre). Hydroacoustics were used to survey vegetation biovolume (percent of water column occupied by vegetation) along 40-m transects using methods and equipment described by Valley et al. (2005). Local kriging with VESPER 1.6 was used to create 15-m raster grids of biovolume (Walter et al. 2001; Minasny et al. 2002). Kriging is a geostatistical interpolation procedure for predicting attributes in unsampled locations.

Most recent fisheries surveys follow guidelines outlined by MDNR Special Publication 147 (1993; Manual of Instructions for Lake Survey). Fish community integrity surveys were also completed on each Sentinel lake following methods described by Drake and Pereira (2002).

Water Quality

Water quality data were collected by various organizations including the MPCA, MDNR, Alexandria Lakes Area Sanitary District (ALASD), and Environmental Research Group Inc. Data were collected by MPCA staff from May through October for 2008 and 2009. Lake surface samples were collected by MPCA staff with an integrated sampler, a poly vinyl chloride (PVC) tube 2 meters (6.6 feet) in length, with an inside diameter of 3.2 centimeters (1.24 inches). Zooplankton samples were collected with an 80 micrometermesh Wisconsin zooplankton net. Phytoplankton (algae) samples were taken with an integrated sampler. TP samples, at depth, were collected with a Kemmerer sampler. Temperature, dissolved oxygen (DO) profiles, and Secchi disk transparency measurements were also taken. Samples were collected at primary site, 101, and a secondary site, 201 (Figure 2). Sampling procedures were employed as described in the MPCA Standard Operating Procedure for Lake Water Quality, which can be found at: http://www.pca.state.mn.us/publications/wq-s1-16.pdf.

Laboratory analysis was performed by the Minnesota Department of Health laboratory using United States Environmental Protection Agency-approved methods (Table 3). Samples were analyzed for nutrients, color, solids, pH, alkalinity, conductivity, chloride, metals, and chlorophyll-a (chl-*a*). Phytoplankton samples were analyzed at the MPCA using a rapid assessment technique.

Table 3. Laboratory methods and precision.

Parameter and unit	Reporting limit	Method number	Precision:[1] mean difference	Difference as percent of observed
Total Phosphorus µg/L	3.0	EPA365.1	4.8	2.7 %
Total Kjeldahl N mg/L	0.1	EPA351.2	0.05	2.8 %
$NO_2 + NO_3$ mg/L	0.05	EPA353.2		
Total Suspended Solids mg/L	1.0	SM2540D	2.8	9.6 %
Total Suspended Volatile Solids mg/L	1.0	SM2540E	--	--
Alkalinity mg/L CaCO3	10	SM 2320 B	--	--
Chloride mg/L	1.0	EPA 325.2		
Color CU	5	EPA 110.2		
Chlorophyll-a µg/L		SM10200H	1.7	7.4 %
Pheophytin		SM10200H	--	--

Zooplankton

Zooplankton samples were collected monthly from ice-out (April/May) through October 2008 and 2009. Two replicate vertical tows were completed at each sampling event. The net was lowered to within 0.5 meter of the bottom and withdrawn at a rate of approximately 0.5 meters per second. Contents were rinsed into sample bottles and preserved with 100% reagent alcohol. Analysis was conducted by MDNR personnel.

Each zooplankton sample was adjusted to a known volume by filtering through 80 microgram per liter (µg/L) mesh netting and rinsing specimens into a graduated beaker. Water was added to the beaker to a volume that provided at least 150 organisms per 5-milliliter aliquot. A 5-milliliter aliquot was withdrawn from each sample using a bulb pipette and transferred to a counting wheel. Specimens from each aliquot were counted, identified to the lowest taxonomic level possible (most to species level), and measured to the nearest .01 millimeter using a dissecting microscope and an image analysis system. Densities (#/liter), biomass (µg/L), percent composition by number and weight, mean length (millimeter), mean weight (µg) and total counts for each taxonomic group identified were calculated with the zooplankton counting program ZCOUNT (Charpentier and Jamnick 1994 in Hirsch 2009).

Results and Discussion

Fisheries Assessment

Lake Carlos has a diverse fish community (Table 4). There has been little change in diversity between the first survey in 1948 and the last assessment in 2008. Smallmouth bass (*Micropterus dolomieu*) was the only species not represented in the 2008 survey catch. Smallmouth bass were last netted in 2004. Common carp (*Cyprinus caprio*) and shorthead redhorse (*Moxostoma macrolepidotum*) are the only species that were captured in 2008 that were not captured in 1948. Although absent from the 1948 and 2008 surveys, tullibee were netted in 1973 and 1996.

In 2008 and 2009, survey crews assessed "biotic integrity" of the fish community in Lake Carlos (Drake and Pereira 2002). Indices of biotic integrity have been used for decades across North America to assess status of aquatic communities and to classify biotic impairments (Angermeier and Karr 1994). Although formal criteria have yet to be developed for classifying biotic impairments in Minnesota Lakes, indices of biotic integrity (IBI) surveys from over 325 lakes across the state provide a good assessment of the range of conditions expected for lakes of differing productivity.

IBI surveys conducted in Lake Carlos in 2008 and 2009 were close to the median when compared with other lakes of similar productivity (Carlos score = 92 and 94 respectively). Specifically in Carlos, between 2008 and 2009, crews sampled six species intolerant to nutrient pollution including blacknose shiners (*Notropis heterolepis*), horneyhead chubs (*Nocomis biguttatus*), banded killifish (*Fundulus diaphanus*), Iowa darter (*Etheostoma exile*), and cisco (*Coregonus artedi*). Muskgrass (*Chara* sp.) appears to provide important habitat for several intolerant littoral fish species (Valley et al. 2010). In addition to nutrient reductions, protection of muskgrass (*Chara sp.)* beds will be importantfor protecting these species and fish community integrity in general.

Table 4. Fish species sampled during previous fisheries surveys, trophic guild, thermal guild, environmental tolerance and the first survey where each species was documented in Lake Carlos.

Common name	Species name	Trophic guild	Thermal guild	Environmental tolerance[a]	First sampled
Black crappie	*Pomoxis nigromaculatus*	Predator	Cool-warm	Neutral	1948
Bowfin	*Amia calva*	Predator	Warm	Neutral	1948
Largemouth bass	*Micropterus salmoides*	Predator	Warm	Neutral	1948
Northern pike	*Esox lucius*	Predator	Cool	Neutral	1948
Walleye	*Sander vitreus*	Predator	Cool-warm	Neutral	1948
Brown trout	*Salmo trutta*	Predator	Cold	NA	2004[a]
Cisco	*Coregonus artedi*	Planktivore	Cold	Intolerant	1973
Black bullhead	*Ameiurus melas*	Omnivore	Warm	Tolerant	1948
Bluntnose minnow	*Pimephales notatus*[b]	Omnivore	Warm	Neutral	1948
Brown bullhead	*Ameiurus nebulosus*	Omnivore	Cool-warm	Neutral	2008
Common carp	*Cyprinus carpio*	Omnivore	Warm	Tolerant	1973
White sucker	*Catostomus commersonii*	Omnivore	Cool-warm	Tolerant	1948
Yellow bullhead	*Ameiurus natalis*	Omnivore	Warm	Neutral	1948
Banded killifish	*Fundulus diaphanus*	Insectivore	Cool-warm	Intolerant	1948
Blacknose shiner	*Notropis heterolepis*	Insectivore	Cool-warm	Intolerant	1948
Bluegill sunfish	*Lepomis macrochirus*	Insectivore	Warm	Neutral	1948
Common shiner	*Notropis cornutus*	Insectivore	Warm	Neutral	1948
Golden shiner	*Notemigonus crysoleucas*	Insectivore	Warm	Neutral	1948
Green sunfish	*Lepomis cyanellus*	Insectivore	Warm	Neutral	1948
Hornyhead chub	*Nocomis biguttatus*	Insectivore	Warm	Intolerant	2008
Iowa darter	*Etheostoma exile*	Insectivore	Cool	Intolerant	1948
Johnny darter	*Etheostoma nigrum*	Insectivore	Cool-warm	Neutral	1948
Log perch	*Percina caprodes*	Insectivore	Undetermined	Neutral	1948
Mimic shiner	*Notropis volucellus*	Insectivore	Warm	Intolerant	1948
Pumpkinseed sunfish	*Lepomis gibbosus*	Insectivore	Warm	Neutral	1948

Shorthead redhorse	*Moxostoma macrolepidotum*	Insectivore	Warm	Neutral	2008
Smallmouth bass	*Micropterus dolomieu*	Predator	Warm	Neutral	1948
Rock bass	*Ambloplites rupestris*	Predator	Cool-warm	Neutral	1948
Central mudminnow	*Umbra limi*	Insectivore	Cool-warm	Neutral	2009
Brook stickleback	*Culaea inconstans*	Insectivore	Cool	Neutral	2009
Brook silverside	*Labidesthes sicculus*	Insectivore	Warm	Neutral	2008
Tadpole madtom	*Noturus gyrinus*	Insectivore	Warm	Neutral	2008
Spottail shiner	*Notropis hudsonius*	Insectivore	Warm	Neutral	1948
Yellow perch	*Perca flavescens*	Insectivore	Cool-warm	Neutral	1948

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[a] Unexpected catch of a single individual in the 2004 survey. The origin of this fish is uncertain. Brown trout were periodically stocking in Spruce Creek, a tributary of the Long Prairie River within Douglas County. The last maintenance stocking into Spruce Creek occurred in 1978. It is more probable that this capture escaped from an aquaculture facility located within the northwest watershed area.

While Lake Carlos supports a diverse fish community, community structure is out of balance. Lake Carlos is not as fertile or productive as most basins within the Glenwood Management Area., The littoral area is limited (small relative to the overall size of the lake). Thus, Lake Carlos does not have a comparable biological carrying capacity even though it is a large lake.

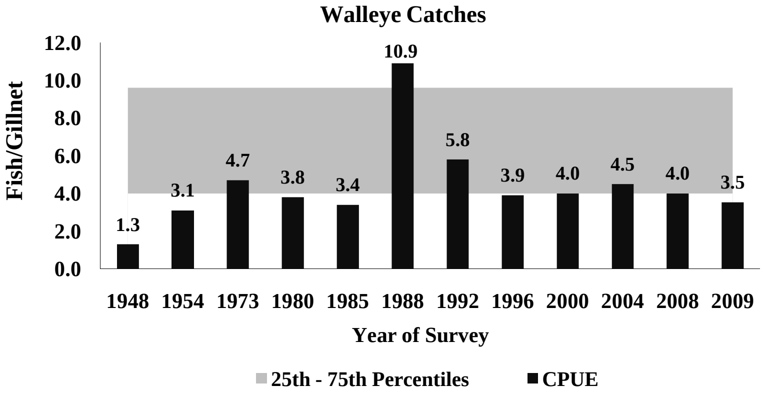
At present, the fish community of Lake Carlos is top heavy with small predators, particularly, northern pike (*Esox lucius*) and largemouth bass (*Micropterus salmoides*) (Figure 11). With exception of walleye (*Sander vitreus*), predator-prey imbalance has been manifested in slow growth of game fishes. Northern pike captured in the 2004 survey did not attain quality-size 533.4 millimeters (mm; 21.0 in) until well into their fifth growing season. Largemouth bass did not grow to preferred-size 381.0 mm (15.0 in) until age-7. Four-year-old bluegill (*Lepomis macrochirus*) averaged only 88.9 mm (3.5 in) in total length. Natural mortality likely claims much of gamefish production before they reach harvestable-size. Due to slow growth, even modest harvest of larger game fishes could degrade fishing quality in terms of average size of fish caught.

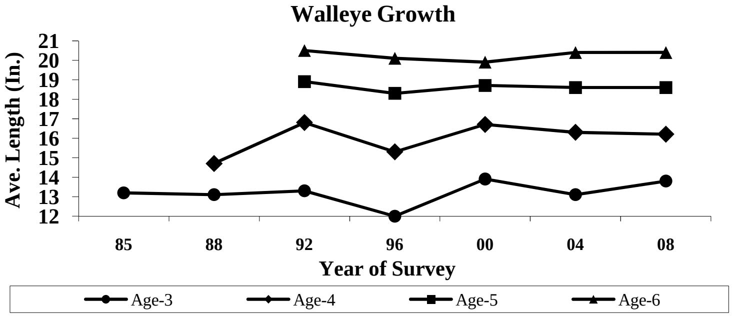
Relative contributions of annual walleye fingerling stockings and natural reproduction to adult abundance have been difficult to determine due to basin connectivity and stockings of mixed-age walleye. Walleye gillnet catches averaged 4.0 fish/net. The inter-quartile range of mean catch rates for lake class 22 is 4.0 - 9.6 fish/net. Walleye Catch Per Effort (CPE) has been below or near the lower end of the inter-quartile range in most surveys. Mean weight of netted walleye was 1134.0 grams (g; 2.5pounds/ lbs) and growth is relatively high. All consecutive age groups but the 1998 year class were documented in the 2008 population sample. Correlation between year class strength and stocking efforts is clouded by stockings of unknown or mixed age fish on a near-annual frequency. Evaluations of stocking efficacy are also confounded by past documentation of inter-basin movements. Walleye growth proved good. Age-5 fish captured in 2008 averaged 472.4 mm (18.6 in) in total length.

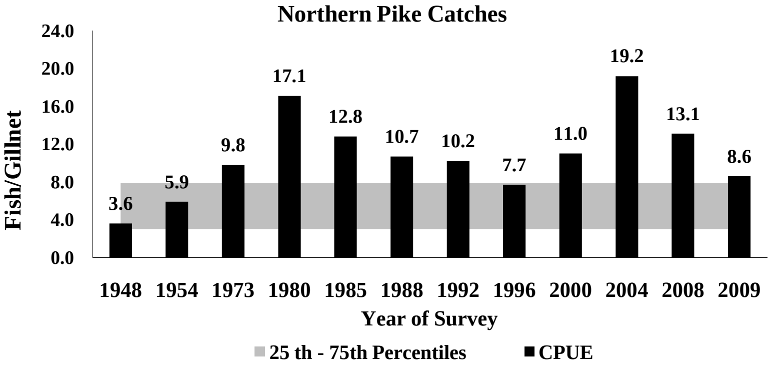
Excessive predation on yellow perch (*Perca flavescens*) by overly abundant predators, likely explains very low survey catches of perch (Figure 11). Yellow perch are preferred prey of largemouth bass, northern pike, and walleye (Anderson and Schupp 1986, Reed and Parsons 1996, Pereira et al. 2002). Although bluegill are often an alternative prey source for predator fish, the bluegill population in Carlos is skewed towards individuals too small to be harvested, but too big to be consumed by predators. Cisco, otherwise known as tullibee, are also a key cold-water forage fish present and presumably abundant in Carlos; however, the extent that these fish are available to predators and whether they are utilizing them as prey is currently unknown. Studies by MDNR and University of Minnesota-Duluth in 2010 and 2011 will evaluate the population status and habitat use of cisco and any co-mingling predators. Below, habitat conditions in Carlos for cisco are described in more detail.

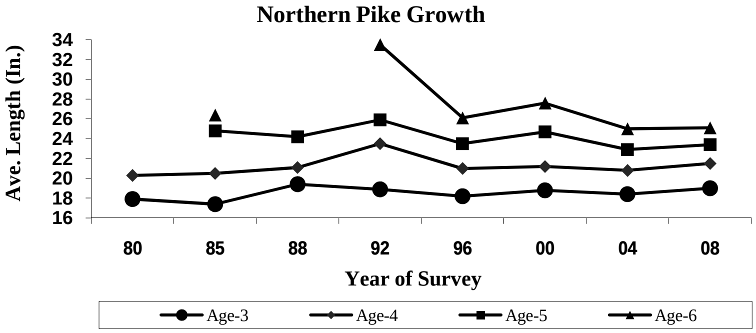
Similar to other lakes in the Alexandria chain of lakes, common carp abundance has increased. Trap net catches averaged 3.0 fish/net. Previous catches had ranged from 0.1 to 0.5 fish/net. Based on recent findings by Bajer and Sorensen (2009), winterkill episodes in connected shallow lakes may facilitate carp recruitment. Increased monitoring of winter dissolved oxygen in connected lakes may facilitate better understanding of carp spawning habitat and inform management options.

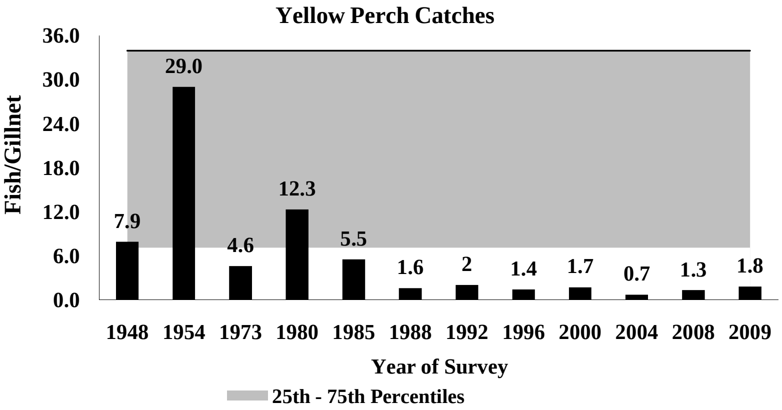
Figure 11. Historic catches (numbers per net) and growth of key fish species in Lake Carlos. Nets during most surveys covered a range of habitats and areas within the 4.6m (15 ft) zone of the lake. Electrofishing catches per hour for largemouth reflect catch rates only for a 20.2 hectare (ha; 50 acre) area less than 3.0 m (10 ft) along the northern shoreline.

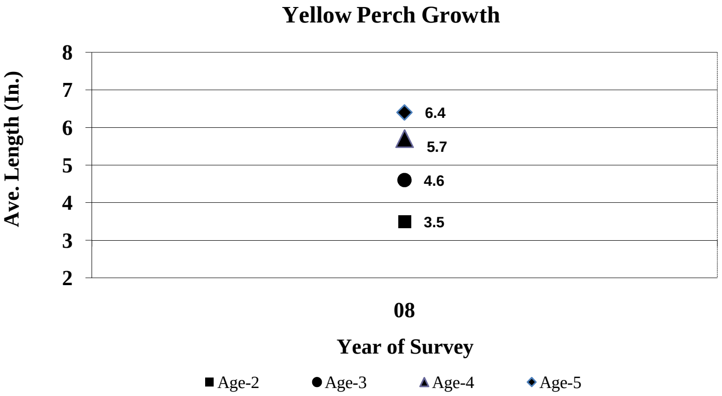


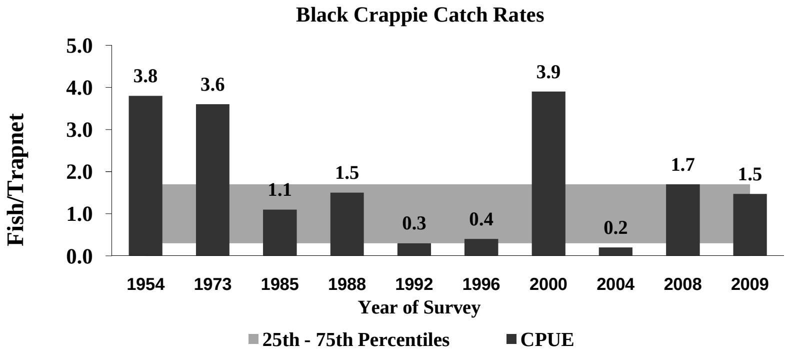


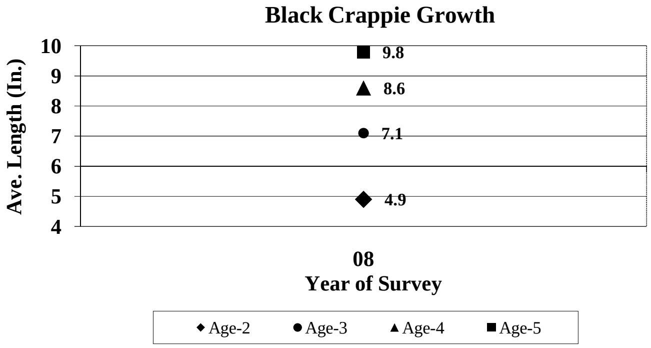

Northern Pike Catches
24.0
20.0
16.0
12.0
8.0
4.0
0.0
Fish/Gillnet
3.6
5.9
9.8
17.1
12.8
10.7
10.2
7.7
11.0
19.2
13.1
8.6
1948
1954
1973
1980
1985
1988
1992
1996
2000
2004
2008
2009
Year of Survey
25 th - 75th Percentiles
CPUE

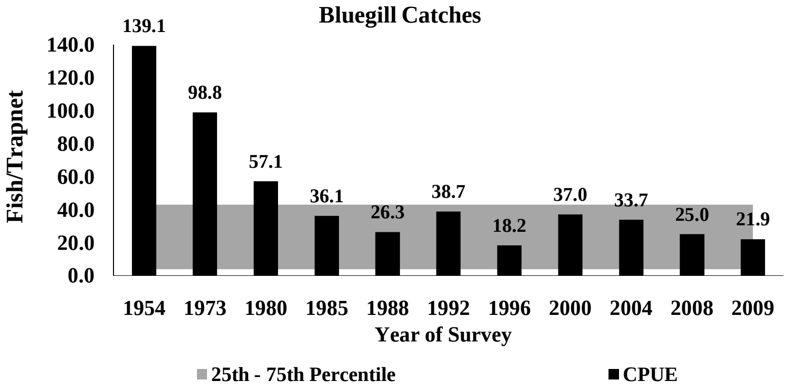

Northern Pike Growth
34
32
30
28
26
24
22
20
18
16
Ave. Length (In.)
80
85
88
92
96
00
04
08
Year of Survey
Age-3
Age-4
Age-5
Age-6

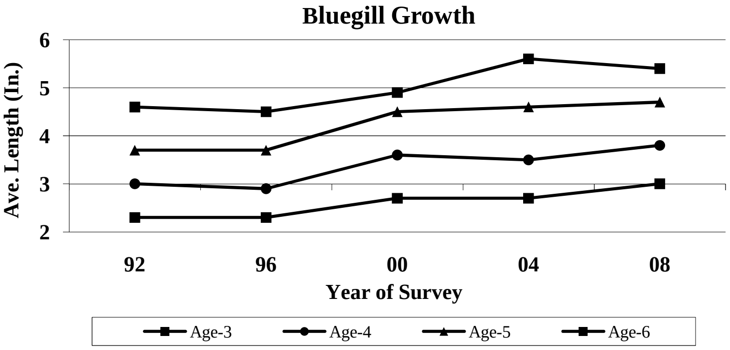

Yellow Perch Catches
Fish/Gillnet
36.0
30.0
24.0
18.0
12.0
6.0
0.0
7.9
29.0
4.6
12.3
5.5
1.6
2
1.4
1.7
0.7
1.3
1.8
1948
1954
1973
1980
1985
1988
1992
1996
2000
2004
2008
2009
Year of Survey
25th - 75th Percentiles

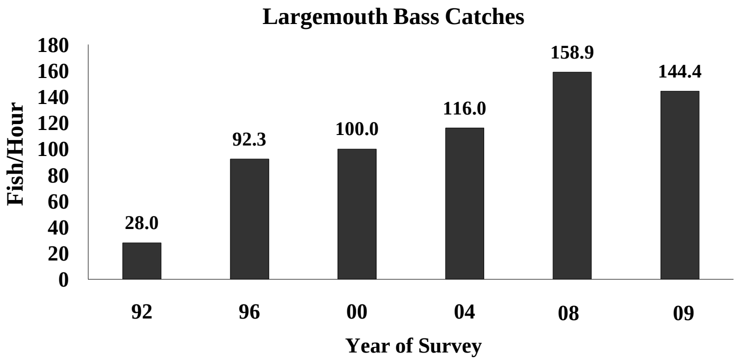

Yellow Perch Growth
Ave. Length (In.)
8
7
6
5
4
3
2
6.4
5.7
4.6
3.5
08
Year of Survey
■ Age-2
● Age-3
▲ Age-4
◆ Age-5

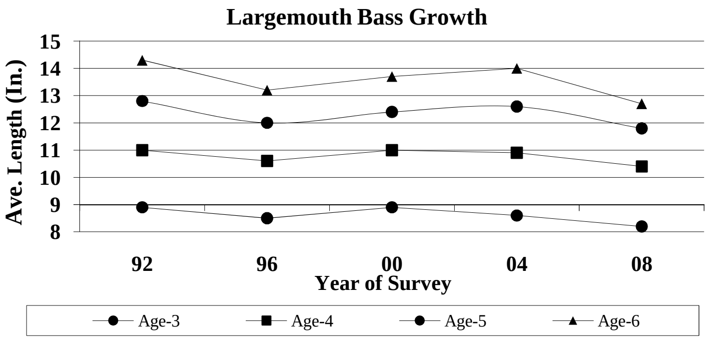

Black Crappie Catch Rates
Fish/Trapnet
5.0
4.0
3.0
2.0
1.0
0.0
3.8
3.6
1.1
1.5
0.3
0.4
3.9
0.2
1.7
1.5
1954
1973
1985
1988
1992
1996
2000
2004
2008
2009
Year of Survey
25th - 75th Percentiles
CPUE

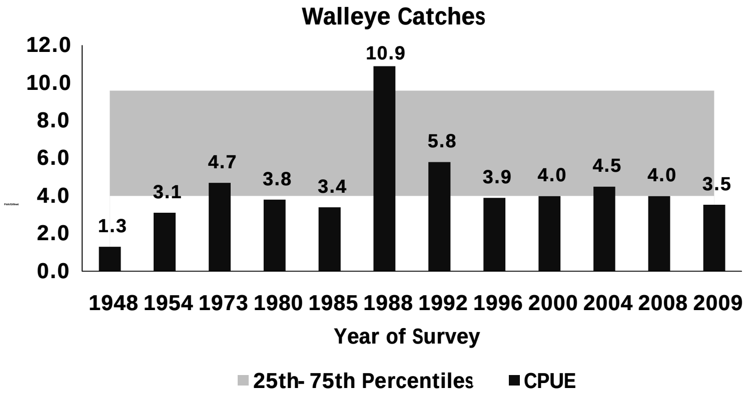

Black Crappie Growth
Ave. Length (In.)
10
9
8
7
6
5
4
9.8
8.6
7.1
4.9
08
Year of Survey
◆ Age-2
● Age-3
▲ Age-4
■ Age-5

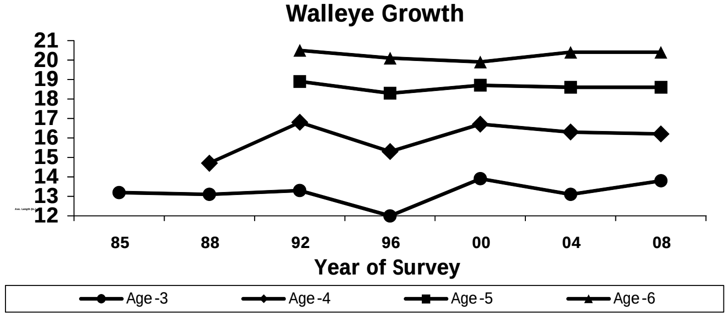

Bluegill Catches
Fish/Trapnet
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
139.1
98.8
57.1
36.1
26.3
38.7
18.2
37.0
33.7
25.0
21.9
1954
1973
1980
1985
1988
1992
1996
2000
2004
2008
2009
Year of Survey
25th - 75th Percentile
CPUE

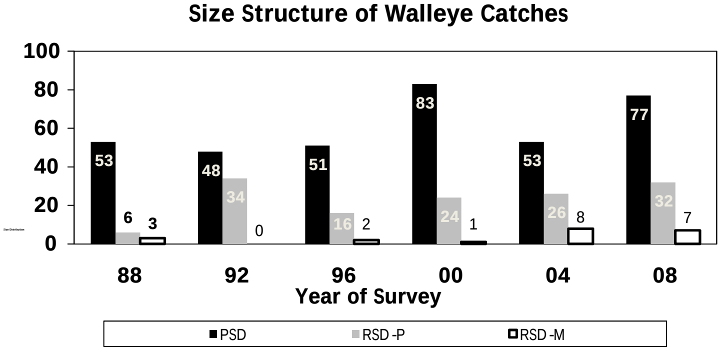

Bluegill Growth
Ave. Length (In.)
6
5
4
3
2
92
96
00
04
08
Year of Survey
Age-3
Age-4
Age-5
Age-6

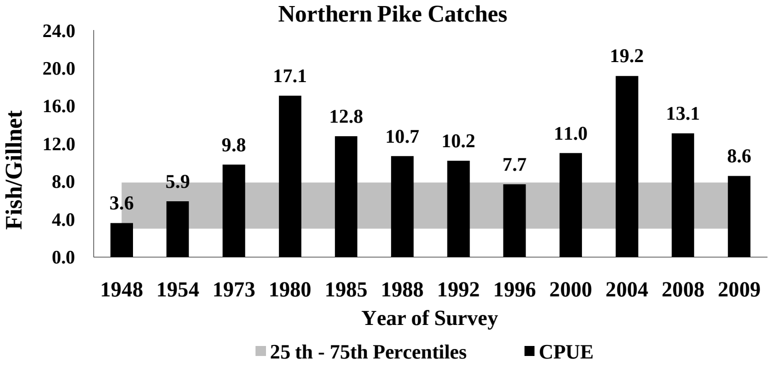

Largemouth Bass Catches
Fish/Hour
180
160
140
120
100
80
60
40
20
0
28.0
92.3
100.0
116.0
158.9
144.4
92
96
00
04
08
09
Year of Survey

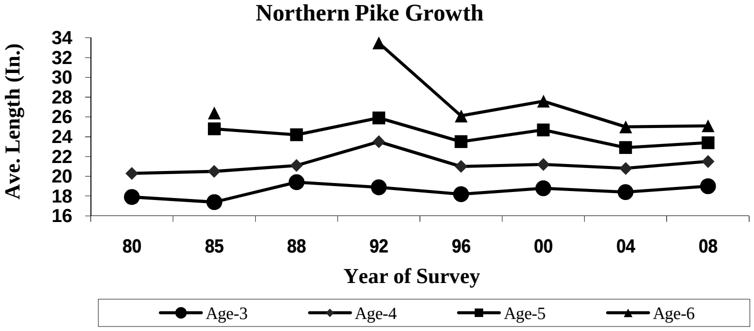

Largemouth Bass Growth
Ave. Length (In.)
15
14
13
12
11
10
9
8
92
96
00
04
08
Year of Survey
Age-3
Age-4
Age-5
Age-6

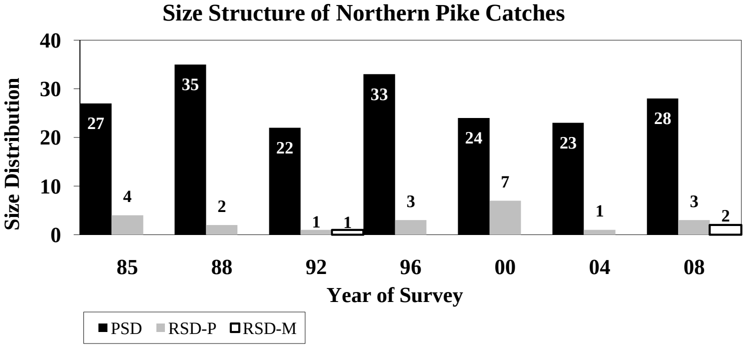

Walleye Catches
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1.3
3.1
4.7
3.8
3.4
10.9
5.8
3.9
4.0
4.5
4.0
3.5
1948 1954 1973 1980 1985 1988 1992 1996 2000 2004 2008 2009
Year of Survey
25th- 75th Percentiles
CPUE

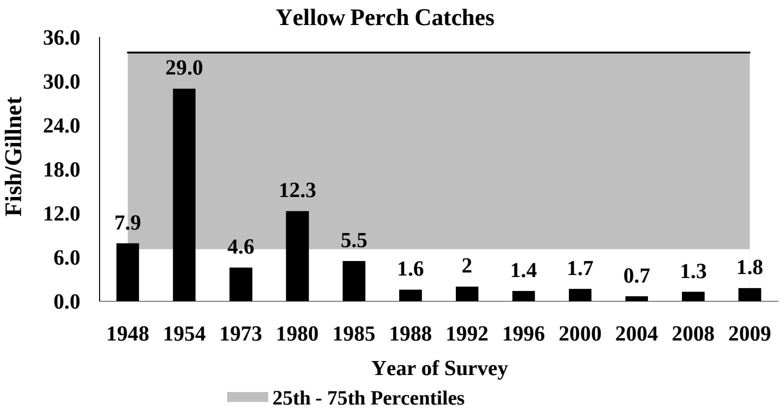

Walleye Growth
21
20
19
18
17
16
15
14
13
12
85
88
92
96
00
04
08
Year of Survey
Age-3
Age-4
Age-5
Age-6

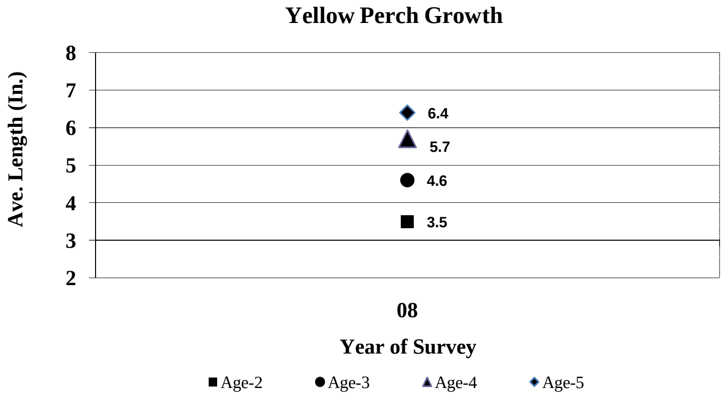

Size Structure of Walleye Catches
100
80
60
40
20
0
53
6
3
48
34
0
51
16
2
83
24
1
53
26
8
77
32
7
88
92
96
00
04
08
Year of Survey
PSD
RSD-P
RSD-M

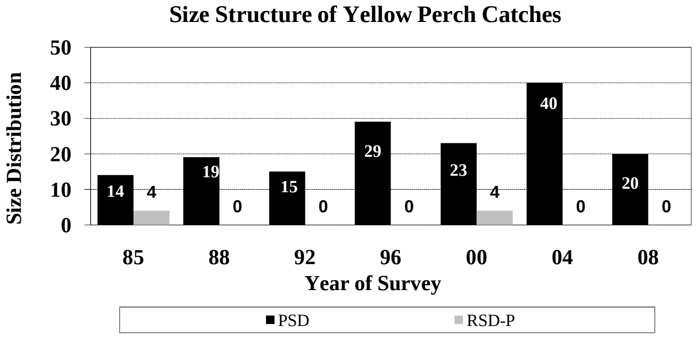

Northern Pike Catches
Fish/Gillnet
24.0
20.0
16.0
12.0
8.0
4.0
0.0
3.6
5.9
9.8
17.1
12.8
10.7
10.2
7.7
11.0
19.2
13.1
8.6
1948 1954 1973 1980 1985 1988 1992 1996 2000 2004 2008 2009
Year of Survey
25 th - 75th Percentiles
CPUE

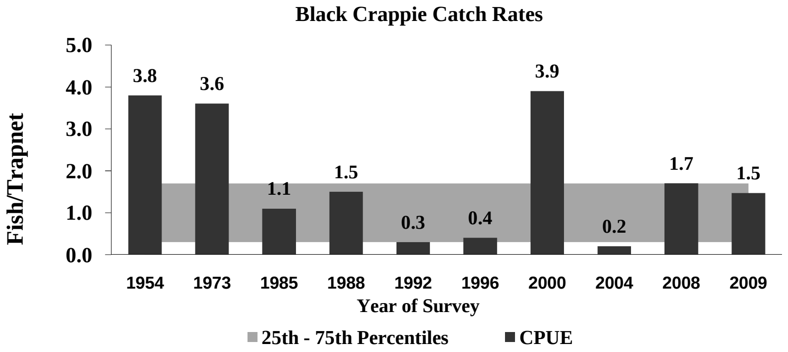

Northern Pike Growth
Ave. Length (In.)
34
32
30
28
26
24
22
20
18
16
80
85
88
92
96
00
04
08
Year of Survey
Age-3
Age-4
Age-5
Age-6

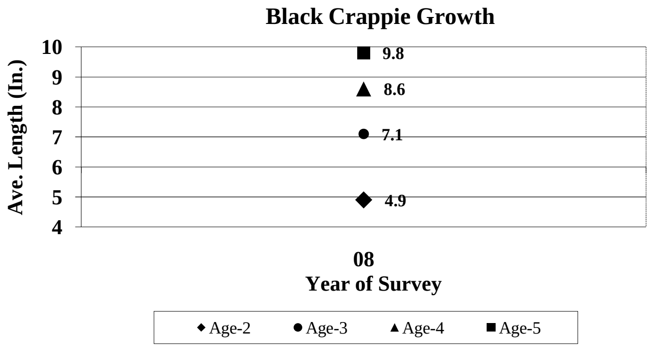

Size Structure of Northern Pike Catches
Size Distribution
40
30
20
10
0
27
4
35
2
22
1
1
33
3
24
7
23
1
28
3
2
85
88
92
96
00
04
08
Year of Survey
PSD
RSD-P
RSD-M

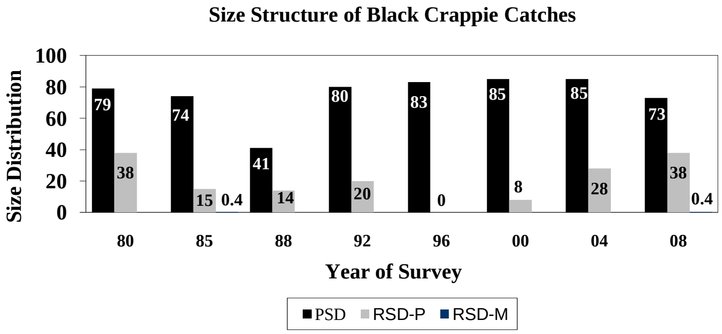

Yellow Perch Catches
Fish/Gillnet
36.0
30.0
24.0
18.0
12.0
6.0
0.0
7.9
29.0
4.6
12.3
5.5
1.6
2
1.4
1.7
0.7
1.3
1.8
1948
1954
1973
1980
1985
1988
1992
1996
2000
2004
2008
2009
Year of Survey
25th - 75th Percentiles

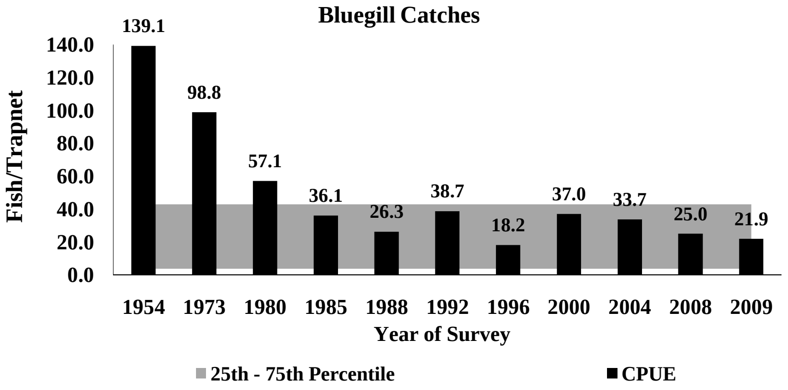

Yellow Perch Growth
Ave. Length (In.)
8
7
6
5
4
3
2
6.4
5.7
4.6
3.5
08
Year of Survey
■ Age-2
● Age-3
▲ Age-4
◆ Age-5

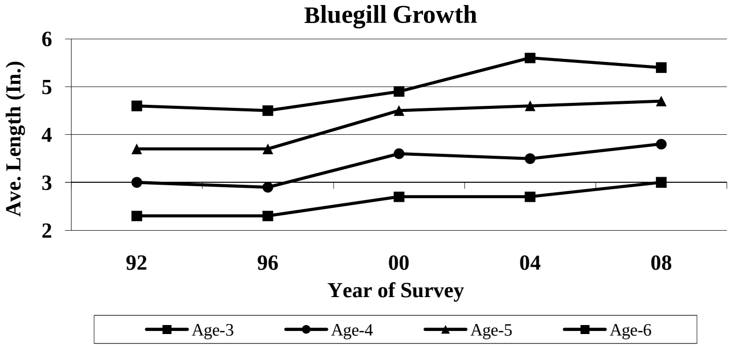

Size Structure of Yellow Perch Catches
Size Distribution
50
40
30
20
10
0
14
4
19
0
15
0
29
0
23
4
40
0
20
0
85
88
92
96
00
04
08
Year of Survey
■ PSD
■ RSD-P

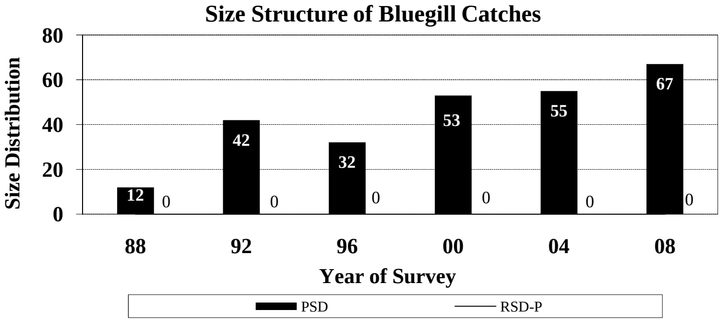

Black Crappie Catch Rates
Fish/Trapnet
5.0
4.0
3.0
2.0
1.0
0.0
3.8
3.6
1.1
1.5
0.3
0.4
3.9
0.2
1.7
1.5
1954
1973
1985
1988
1992
1996
2000
2004
2008
2009
Year of Survey
25th - 75th Percentiles
CPUE

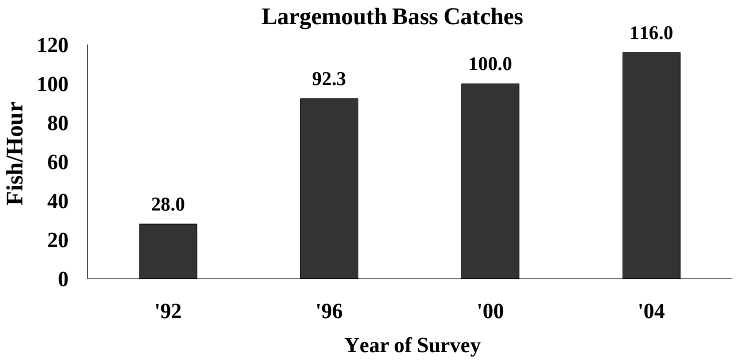

Black Crappie Growth
Ave. Length (In.)
10
9
8
7
6
5
4
9.8
8.6
7.1
4.9
08
Year of Survey
Age-2
Age-3
Age-4
Age-5

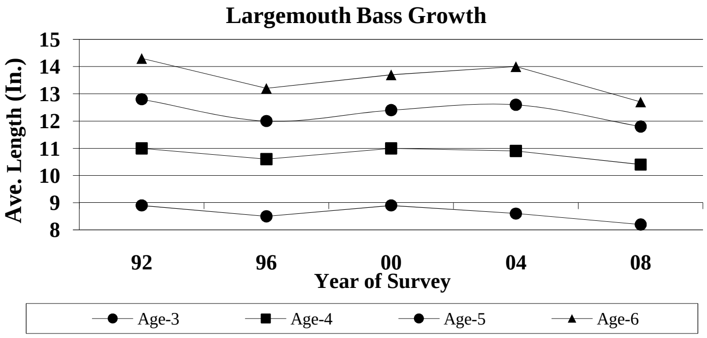

Size Structure of Black Crappie Catches
Size Distribution
100
80
60
40
20
0
79
38
74
15
0.4
41
14
80
20
83
0
85
8
85
28
73
38
0.4
80
85
88
92
96
00
04
08
Year of Survey
PSD
RSD-P
RSD-M

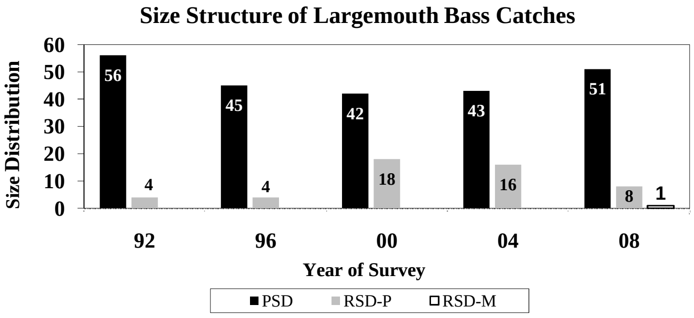

Bluegill Catches
Fish/Trapnet
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
139.1
98.8
57.1
36.1
26.3
38.7
18.2
37.0
33.7
25.0
21.9
1954
1973
1980
1985
1988
1992
1996
2000
2004
2008
2009
Year of Survey
25th - 75th Percentile
CPUE

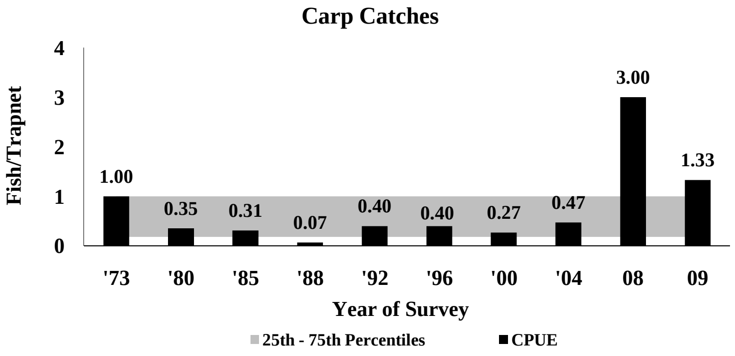

Bluegill Growth
Ave. Length (In.)
6
5
4
3
2
92
96
00
04
08
Year of Survey
Age-3
Age-4
Age-5
Age-6


Size Structure of Bluegill Catches
Size Distribution
80
60
40
20
0
12
0
42
0
32
0
53
0
55
0
67
0
88
92
96
00
04
08
Year of Survey
PSD
RSD-P


Largemouth Bass Catches
Fish/Hour
120
100
80
60
40
20
0
28.0
92.3
100.0
116.0
'92
'96
'00
'04
Year of Survey


Largemouth Bass Growth
Ave. Length (In.)
15
14
13
12
11
10
9
8
92
96
00
04
08
Year of Survey
Age-3
Age-4
Age-5
Age-6


Size Structure of Largemouth Bass Catches
Size Distribution
60
50
40
30
20
10
0
56
4
45
4
42
18
43
16
51
8
1
92
96
00
04
08
Year of Survey
PSD
RSD-P
RSD-M


Carp Catches
Fish/Trapnet
4
3
2
1
0
1.00
0.35
0.31
0.07
0.40
0.40
0.27
0.47
3.00
1.33
'73
'80
'85
'88
'92
'96
'00
'04
08
09
Year of Survey
25th - 75th Percentiles
CPUE

Cisco Population and Habitat Status

Cisco are the most common coldwater lake fish in Minnesota and are present in 648 lakes throughout the state. Extended periods of stratification (a potential outcome of climate warming) and eutrophication can reduce hypolimnetic oxygen in deep lakes and thus impact cisco populations (De Stasio et al. 1996, Stefan et al. 1996). Indeed, historical records by the MDNR show that cisco numbers have been declining statewide since 1975. These declines appear to be due primarily to climate-driven stressors, since cisco have been declining in lakes that have not experienced significant cultural eutrophication.

Lake Carlos is a deep lake that strongly stratifies. The thermocline usually sets up at approximately 10 meters early in the summer, but can be driven as deep as nearly 20 meters by fall (Figure 12a). Hypolimnetic temperatures are generally cold (~6 °C) near the bottom of the lake. A distinct metalimnetic oxygen minimum develops during the summer in Lake Carlos. The seasonal progression of this minimum is illustrated (Figure 12b). After isothermal conditions persisted into late May of 2007 and 2008, the oxygen minimum developed in July between 10 and 20 meters. Oxygen concentrations gradually declined in the minima throughout the remaining summer and early fall. Thermocline deepening events (probably wind-driven) eroded the metalimnetic oxygen minimum through summer and fall (especially evident in the 9/23/2008 and 10/6/2008 profiles). Hypolimnetic oxygen concentrations also declined throughout the summer, but at a lesser rate than in the metalimnion. By November, the lake is once again isothermal.

Metalimnetic oxygen minima are rather rare in lakes and are known to worsen in culturally enriched lakes (Lake Washington is a famous example). Metalimnetic oxygen minima can have profound impacts on coldwater fish such as cisco. Coldwater fish can get trapped in the partially oxygenated hypolimnion. If hypolimnetic oxygen concentrations become too low and push them up into a metalimnion that is also hypoxic, coldwater fish can get "squeezed" and large summer die-offs are possible, as was the case in late summer 2006 (Figure 12c). Hypolimnetic oxygen concentrations were less than 0.6 milligram per liter (mg/L) by September 1 and the metalimnion was anoxic below 11 meters. A cisco mortality event was ongoing that day (Peter Jacobson, personal observation).

Profiles taken during the period of greatest oxythermal stress (July 28 through August 27 for stratified lakes; Jacobson et al. - submitted manuscript) illustrate that the metalimnetic oxygen minimum was present in all years sampled. Minimum oxygen concentrations in the metalimnetic oxygen minimum ranged from 3.3 mg/L in 1986 to 0.1 mg/L in 2006 (1973 might have had a higher concentration, but oxygen was measured at very few depths). Hypolimnetic oxygen concentrations varied considerably between years. Concentrations as high as 5.5 mg/L at a temperature 0f 8.4 °C were recorded in 1986. In 2006, the hypolimnion was anoxic.

Profiles taken during the period of greatest oxythermal stress also provide a benchmark measurement of coldwater habitat (temperature at 3 mg O_2 (TDO_3) interpolated from profiles; Jacobson et al. - submitted manuscript). The temperatures at 3 mg O_2 calculated from Lake Carlos profiles are presented in Table 5. Because of unusual profiles that arise from presences of a metalimnetic oxygen minimum, two values of TDO_3 are possible (one from the hypoxic portion of the metalimnion and one from the hypolimnion). Note that oxygen concentrations of 3 mg/L do not always develop in both zones every summer. When they do, the mean hypolimnetic TDO3 was 7.1 °C and the mean metalimnetic TDO_3 was 17.1 °C. This suggests that in years when sufficient oxygen is available in the hypolimnion, oxythermal habitat is excellent in Lake Carlos. On a scale of 0 to 100 (with 0 being worst and 100 best) calculated from Jacobson et al. (submitted manuscript), Lake Carlos has a cisco Habitat Suitability Index of 100 based on the hypolimnetic TDO_3 values; however, the Habitat Suitability Index for cisco is 60 based on metalimnetic TDO_3 values. The most appropriate value to use is the metalimnetic Habitat Suitability Index because that is probably limiting the cisco population in the lake. While a Habitat Suitability Index of 60 still represents moderately good oxythermal habitat for cisco, it is certainly not as good if the metalimnetic oxygen minimum was not present.

Table 5. Temperatures at 3 mg O2 interpolated from the profiles taken by PCA and DNR during the period of greatest oxythermal stress (July 28 through August 27) from Lake Carlos.

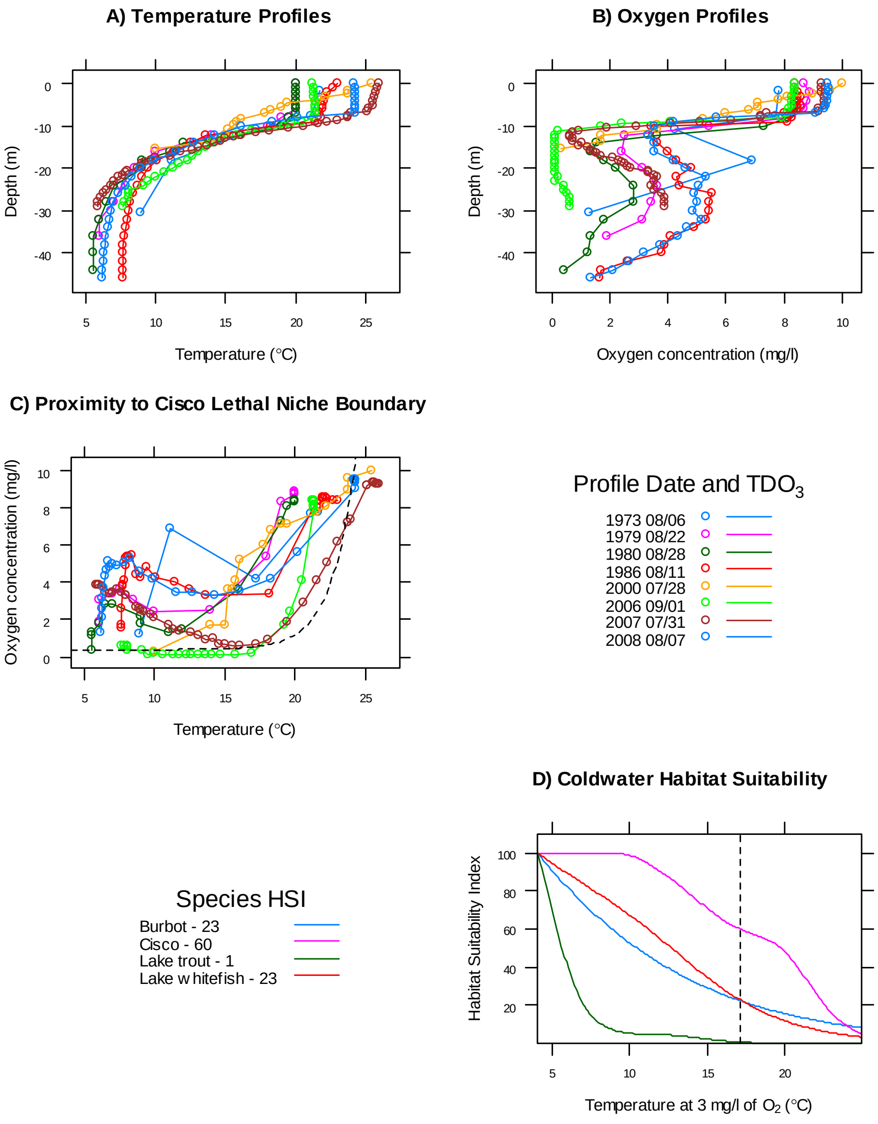
Date	Hypolimnetic TDO_3	Metalimnetic TDO_3
8/6/1973	9.6	-
8/22/1979	6.0	14.9
8/28/1980	-	14.9
8/11/1986	7.6	-
7/28/2000	-	14.8
9/1/2006	-	20.0
7/31/2007	5.8	20.7
8/7/2008	6.3	-
Mean	7.1	17.1

Profile data replotted as temperature vs. oxygen illustrate how close oxythermal habitat approached lethal conditions (Jacobson et al. 2008). Most profiles contained conditions where cisco could survive. Only the 9/1/2006 profile represented a lethal condition. Interestingly, Lake Carlos was an unusual outlier in the statewide analysis of the 2006 cisco summer kills (Jacobson et al. 2008). Lake Carlos mortality occurred at water temperatures cooler than all of the other 16 lakes that experienced cisco mortality. Although Jacobson (et al. 2008) speculated on a number of reasons for the uniqueness of the Carlos mortality event, metalimnetic oxygen minimum may have played a role. It is possible that Carlos cisco were under longer, more chronic oxythermal stress in the slowly declining oxygen concentrations within the hypolimnion, than the rapidly (and more acute) lethal conditions that occurred in the metalimnia of the other lakes.

Since, cisco are affected by the metalimnetic oxygen minimum in Lake Carlos, they may be more susceptible to climate warming than if the lake had a more typically oxygenated metalimnion. Projections from the model presented in Jacobson et al. (submitted manuscript) suggest that the metalimnetic temperature at 3 mg O_2 during the period of greatest oxythermal stress would increase from 17.1 to 21.3 °C after climate warming (assuming a 4 °C increase in mean July air temperature). That would drop the Habitat Suitability Index for cisco from 60 to 35, suggesting that conditions for cisco in Lake Carlos would be significantly poorer (Figure 12d). Summer mortality events could become common (e.g. a several of the profiles in Figure 12 could shift into lethal conditions), but cisco would probably persist in the lake; however, because Lake Carlos is stratified and cisco rely on oxygen below the thermocline in the summer, oxythermal habitat is vulnerable to eutrophication. Projections from the model presented in Jacobson et al. (submitted manuscript), suggest metalimnetic temperature at 3 mg O_2 during the period of greatest oxythermal stress would increase even further to 22.9 °C, if mean total epilimnetic phosphorus concentrations increased from the current mean of 19 to 38 µg/L. Those two ecological stressors combined would drop the Habitat Suitability Index for cisco down to 17. Summer mortality events could become frequent enough that extirpation of cisco would be possible in Lake Carlos.

Interestingly, very few cisco have been sampled in Lake Carlos during standard MDNR lake surveys, but the lake is known to contain a substantial population. The extensive summerkill during the summer of 2006 (Jacobson et al. 2008) revealed large numbers of cisco. A sample of 43 dead and dying cisco were collected from the surface of the lake during the mortality event. Of the 43, 6 were immature males with a mean length of 163 millimeters (mm; range 136-179 mm), 7 were immature females with a mean length of 167 mm (range 150-182), 18 were mature males with a mean length of 217 mm (range 191-249), and 12 were mature females with a mean length of 219 mm (range 177-253). Size and maturity of these cisco suggest that they are generally smaller than typical Minnesota tullibees. Smaller than average cisco are usually found in deep, clear lakes like Carlos. They are also known to inhabit very deep water during the summer, which probably explains lack of cisco in relatively shallow gill nets set during the standard lake surveys. Specialized deep gill net sets and hydroacoustic sampling should more adequately sample cisco in Lake Carlos. These specialized surveys, along with annual DO/temp profiles during the entire open water season will be critically important for monitoring effects of climate change and eutrophication on the cisco population. Paleolimnological reconstructions of water quality (and especially a chironomid-based reconstruction of hypolimnetic oxygen) should also shed light on the question of whether the metalimnetic oxygen minimum in Lake Carlos has gotten worse since European settlement.

Figure 12. Cisco oxythermal habitat in Lake Carlos. A) and B) are MDNR and MPCA profiles taken during the period of greatest oxythermal stress (July 28 through August 27, also included is a profile from 9/1/2006). C) is the profile data replotted for comparison with lethal oxythermal conditions for cisco (dashed line). The dashed line in D) represents current coldwater habitat suitabilities for White Iron Lake in relation to the entire gradient of Habitat Stability Index's (HSI) in Minnesota.



Aquatic Plant Assessment

Bulrush beds (*Scirpus spp.*) are extensive across the northern shore of the lake (Figure 13) and according to 2005 estimates, cover approximately 80 acres of the littoral zone. Cane (*Phragmites australis*) and cattail (*Typha* spp.) are present but less common (.65 and .57 ha /1.6 and 1.4 acres respectively; Figure 13). At low to modest levels of abundance or biovolume, submersed vegetation covered approximately 13.5% of the lake's surface area or 142.4 ha (352 acres) in 2009 (Figure 14). Vegetation was most abundant in depths between 3.1and 6.1m (10 and 20 ft; Figure 15) but only occupied approximately 16% of the water column. Vegetation grew along most bottom areas up to 6.7m (22 ft). The submersed community is moderately diverse (Tables 6 and 7) but dominated by low-growing, muskgrass or *Chara* sp., and to a lesser extent, greater bladderwort (*Utricularia vulgaris*) and northern watermilfoil (*Myriophyllum sibiricum*). These three species, among several others were also noted in the original lake survey in 1948 (Table 8). Species frequencies changed little from 2008 and 2009. Additional surveys in Carlos in 2010 and 2011 compared across repeated surveys in all Sentinel lakes will help researchers determine how much aquatic plants naturally vary from year to year and to separate natural 'noise' from a disturbance signal.

Table 6. Percent frequency of occurrence of aquatic plant species at depths ≤ 4.6m (15 ft) sampled during point-intercept surveys on Carlos Lake, Douglas County, MN, August 20, 2008 and August 10, 2009.

		Growth Form	Frequency (%)	
Common Name	**Species Name**		**2008**	**2009**
All rooted plants			84.5	84.3
Hardstem bulrush	*Scirpus acutus*	Emergent	11.7	0
Canada waterweed	*Elodea canadensis*	Emergent	0.7	1.5
Cattail group	*Typha sp.*	Emergent	0.2	0.4
Bulrush group	*Scirpus sp.*	Emergent	0	5.5
Cane	*Phragmites australis*	Emergent	0	0.2
Yellow waterlily	*Nuphar sp.*	Floating-leaf	0	0.2
Muskgrass	*Chara sp.*	Submersed	62.2	71.7
Bladderwort group	*Utricularia sp.*	Submersed	18.2	21.5
Northern watermilfoil	*Myriophyllum sibiricum*	Submersed	15.9	17.4
Stonewort	*Nitella sp.*	Submersed	9.1	6.6
Flatstem pondweed	*Potamogeton zosteriformis*	Submersed	7.8	5.3
Leafy pondweed	*Potamogeton foliosus*	Submersed	7.8	0
Clasping-leaf pondweed	*Potamogeton richardsonii*	Submersed	5.1	6.2
Bushy pondweed	*Najas flexilis*	Submersed	4.7	1.1
Coontail	*Ceratophyllum demersum*	Submersed	2.9	1.1
Sago pondweed	*Stuckenia pectinata*	Submersed	2.2	1.7
White-stem pondweed	*Potamogeton praelongus*	Submersed	2.2	1.5
Floating-leaf pondweed	*Potamogeton natans*	Submersed	1.3	0.8
Curly-leaf pondweed[b]	*Potamogeton crispus*	Submersed	1.1	0.8
Variable pondweed	*Potamogeton gramineus*	Submersed	1.1	1.1

Wild celery	*Vallisneria americana*	Submersed	1.1	0.9
Straight-leaf pondweed	*Potamogeton strictifolius*	Submersed	0.5	0
Spiny naiad	*Najas marina.*	Submersed	0.4	0.8
Fries pondweed	*Potamogeton friesii*	Submersed	0.2	0
Naiad group	*Najas sp.*	Submersed	0.2	0
Small pondweed	*Potamogeton pusillus*	Submersed	0	4.5

Table 7. Plant species observed on 19 July 2004 along the northeast shore of Lake Carlos by the MN County Biological Survey.

Common Name	Species Name	Growth Form
Hard-stem bulrush	*Schoenoplectus acutus* var. *acutus*	Emergent
Soft stem bulrush	*Schoenoplectus tabernaemontani*	Emergent
Narrow-leaved cattail	*Typha angustifolia*	Emergent
Broad-leaved cattail	*Typha latifolia*	Emergent
Yellow water lily	*Nuphar variegata*	Floating leaf
Water smartweed	*Persicaria amphibia*	Floating leaf
Floating-leaf pondweed	*Potamogeton natans*	Floating leaf
Ivy-leaved or star duckweed	*Lemna trisulca*	Free floating
Turion-forming duckweed	*Lemna turionifera*	Free floating
Greater duckweed	*Spirodela polyrrhiza*	Free floating
Water-marigold	*Bidens beckii*	Submersed
Coontail	*Ceratophyllum demersum*	Submersed
Canadian waterweed	*Elodea canadensis*	Submersed
Mare's-tail	*Hippus vulgaris*	Submersed
Northern watermilfoil	*Myriophyllum sibiricum*	Submersed
Bushy pondweed, Common naiad	*Najas flexilis*	Submersed
Fries' pondweed	*Potamogeton friesii*	Submersed
Illinois pondweed	*Potamogeton illinoensis*	Submersed
White-stemmed pondweed	*Potamogeton praelongus*	Submersed
Small pondweed	*Potamogeton pusillus*	Submersed
Claspingleaf pondweed	*Potamogeton richardsoni*	Submersed
Flat-stem pondweed	*Potamogeton zosteriformis*	Submersed
Flatstem pondweed	*Potamogeton zosteriformis*	Submersed
White-water crowfoot	*Ranunculus aquatilis* var. *diffusus*	Submersed
Blunt-tipped sago pondweed	*Stuckenia filiformis*	Submersed

Common sago pondweed	*Stuckenia pectinata*	Submersed
Greater bladderwort	*Utricularia vulgaris*	Submersed
Wild celery, Eel-grass	*Vallisneria americana*	Submersed
Water stargrass, Mud plantain	*Zosterella dubia*	Submersed

Table 8. Common species observed during the first lakes survey in July 1948 lake vegetation surveys.

Common Name	Species Name	Growth Form
Crested arrowhead	*Sagittaria cristata*	Emergent
Hardstem bulrush	*Scirpus acutus*	Emergent
Cattail	*Typha sp.*	Emergent
Floating-leaf pondweed	*Potamogeton natans*	Floating leaf
Northern watermilfoil	*Myriophyllum sibiricum*	Submersed
Greater bladderwort	*Utricularia vulgaris*	Submersed
Clasping-leaf pondweed	*Potamogeton richardsonii*	Submersed
Muskgrass	*Chara sp.*	Submersed
White water buttercup	*Ranunculus longirostris*	Submersed
White-stemmed pondweed	*Potamogeton praelongus*	Submersed
Flat-stem pondweed	*Potamogeton zosteriformis*	Submersed
Coontail	*Ceratophyllum demersum*	Submersed

Curly-leaf pondweed

The first documented occurrence of curly-leaf pondweed (*Potamogeton crispus*) in Lake Carlos was 2008; however it's speculated the plant had been present for some time before then. Spring surveys in 2008 and 2009 indicated that curly-leaf pondweed was present but occurred at abundances that were not detected by standard sampling.

Curly-leaf pondweed is a non-native invasive submerged aquatic plant that is widespread throughout the southern part of the state. Exact date of introduction into Minnesota is unknown, but it is believed to have been present in Minnesota lakes since the early 1900s when carp were brought into the state. Curly-leaf pondweed grows most abundantly during early spring and senesces by mid-summer. When curly-leaf pondweed is abundant, mid-summer diebacks often promote algae blooms which limit light penetration for native aquatic plants.

Curly-leaf pondweed thrives in nutrient-rich conditions and at some threshold of nutrient levels (exact quantity unknown), may become a self-sustaining internal driver of poor water quality conditions. These self-perpetuating conditions of curly-leaf booms followed by large summer die-offs and algae blooms are most common in eutrophic to hypereutrophic lakes in the southern half of the state. In northern mesotrophic lakes with abundant native aquatic plants, curly-leaf pondweed is less abundant and typically is integrated with other aquatic plants. Because the plant needs to photosynthesize during winter, curly-leaf pondweed is sensitive to long periods of snow and ice cover on lakes. Reduced snow and ice cover due to climate change may favor increases in this plants abundance in infested lakes and latitudinal range of viability.

Further acting as a resilience mechanism against a shift to a curly-leaf pondweed 'regime' in Lake Carlos is the macroalgae, muskgrass. In 2009, muskgrass was the most common species sampled in Lake Carlos (Table 6). Muskgrass is a benthic plant that is highly desirable from a fish habitat and water quality standpoint. Besides offering quality physical habitat for juvenile and non-game fish (Valley et al. 2010), muskgrass is an important plant for maintaining clear water. In turn, clear water promotes muskgrass (Kufel and Kufel 2002; Ibelings et al. 2007). To best prevent a shift to a curly-leaf pondweed regime and protect fish habitat, muskgrass beds should be protected along with reductions to external phosphorus loading.

Figure 13. Major emergent beds mapped with GPS in summer 2005.

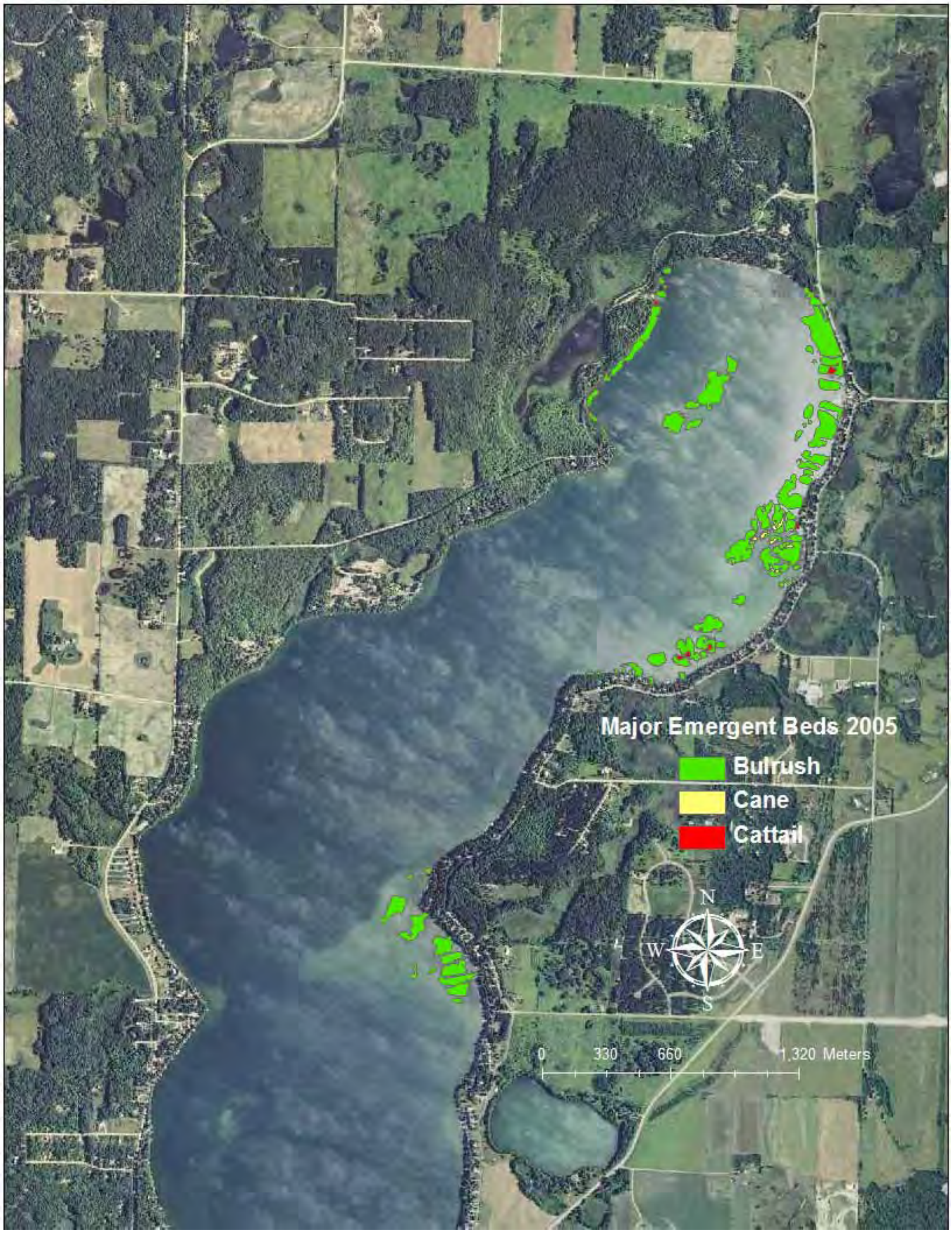


Figure 14. Percent of water column occupied by submersed vegetation (biovolume) in Lake Carlos in August 2009. Assessed using hydroacoustics and interpolation of point estimates of biovolume with local kriging (Valley et al. 2005).

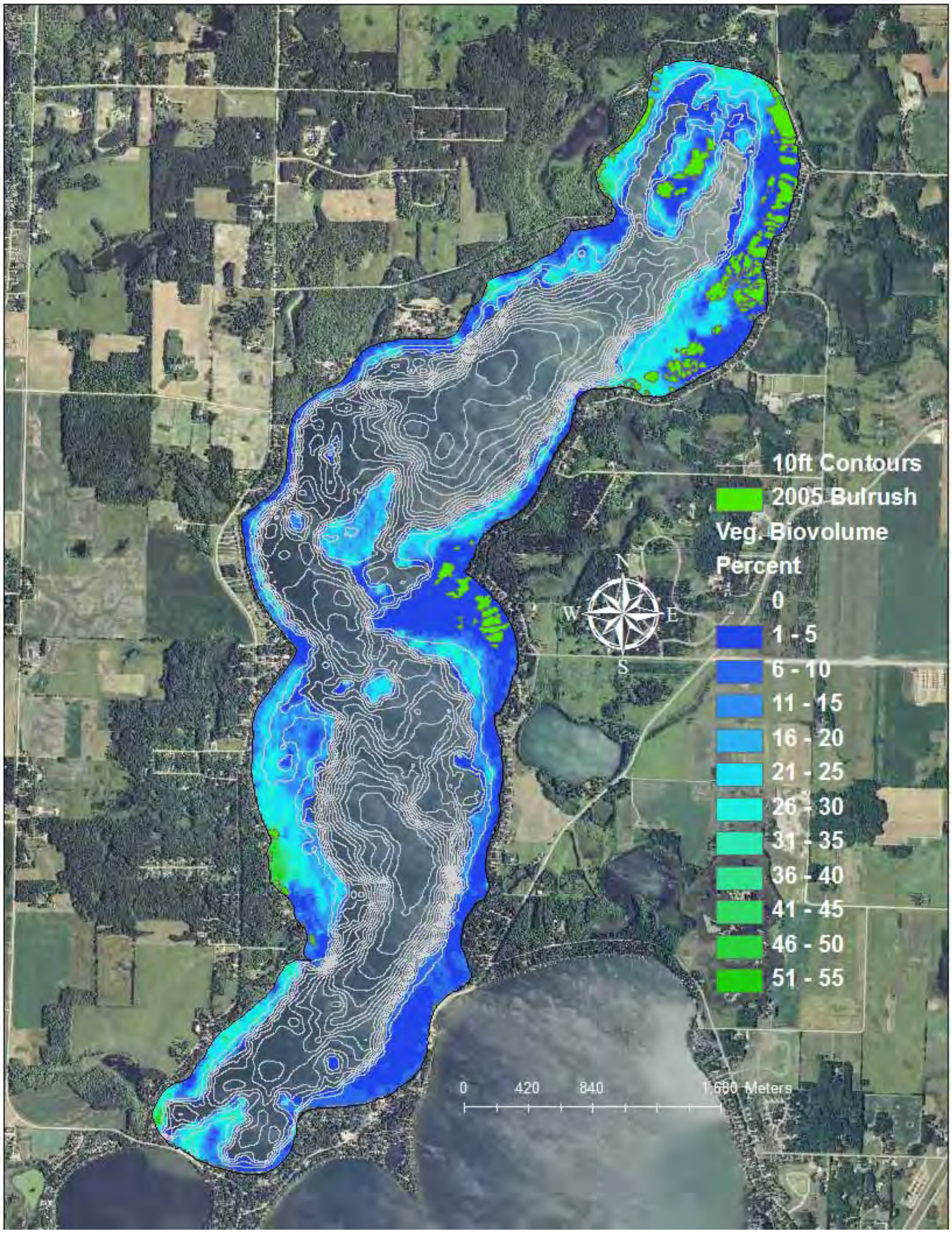
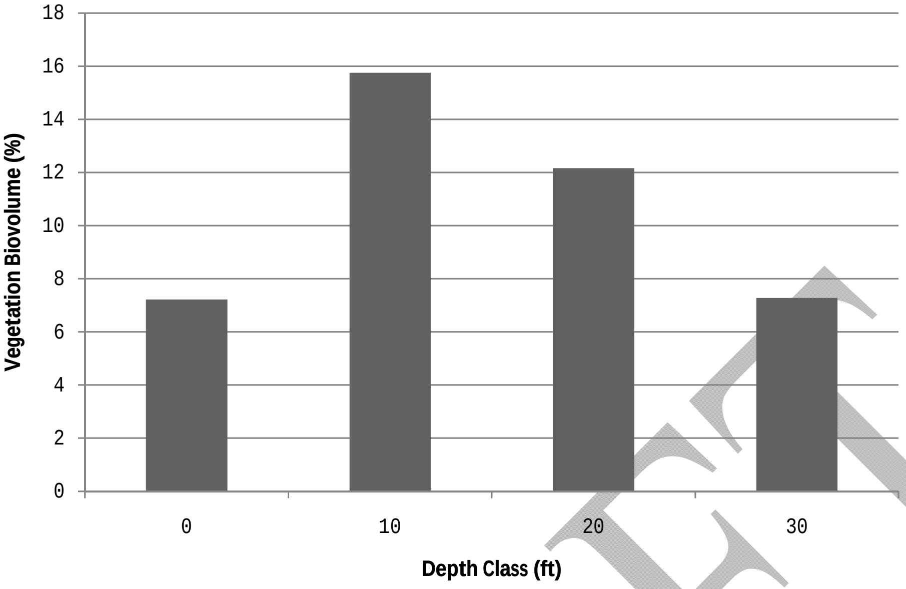


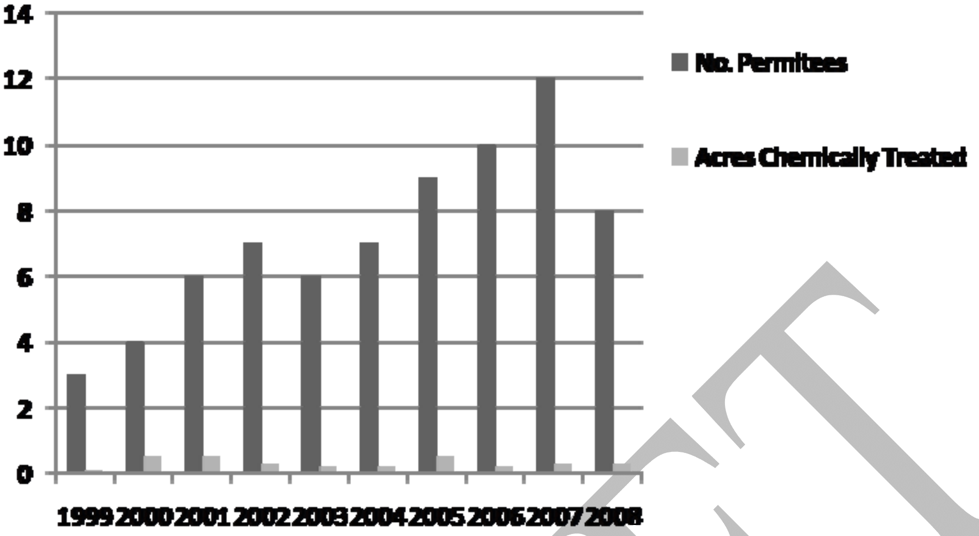
Figure 15. Mean biovolume in 3.1m (10 ft) depth classes predicted from local kriging of vegetation data collected with hydroacoustics in Lake Carlos August 2009.



Aquatic Plant Removal Activities by Lakeshore Owners

Nearly all (98%) of the shoreline of Lake Carlos is developed. The State of Minnesota (Carlos State Park), owns 2.4 km (1.4 mi) of shoreline on the north end of the lake. Approximately 379 dock structures were enumerated from 2008 aerial photos acquired from the U.S. Farm Service Administration (9 docks per mile). Despite heavy development of nearshore areas, nearshore substrates are sandy and most are naturally plant-free. Consequently, not factoring in runoff from properties, direct ecological impact to in-water habitats by human activities is probably modest at worst. Indeed, aquatic plant management permits are typically issued to less than a dozen lakeshore owners a year and only very small areas are treated with herbicides (Figure 16).

Figure 16. Number of aquatic plant management permits issued to lakeshore owners and acres treated with herbicides since 1999 in Lake Carlos.



Zebra Mussel Infestation

The invasive zebra mussel (*Dreissena polymorpha*) was discovered in numerous locations throughout Lake Carlos during the summer of 2009. The best studies of zebra mussel impacts have been done in productive lakes, such as Oneida Lake, New York, and in Lake Erie. In those lakes, there was an initial increase in water clarity, due to the higher algae grazing or filtering rates (Idrisi et al 2001, Munawar et al 2005) by zebra mussels. Although algal biovolume and chl-*a* decreased, primary production was stable due to the compensatory effect of increased water clarity (Idrisi et al 2001). The smallest phytoplankton species were reduced the most by zebra mussels (Idrisi et al 2001, Munawar et al 2005).

Although they can filter large phytoplankton particles, zebra mussels selectively reject toxic varieties such as *Microcystis* (Vanderploeg et al 2001). Initial changes in water clarity become less pronounced over time, often in conjunction with cyanabacteria blooms (Munawar et al 2005). *Microcystis* blooms have been noted in both eutrophic and oligotrophic lakes following zebra mussel establishment. In lakes with zebra mussels, percentage of total phytoplankton made up of cyanobacteria was no longer related to total phosphorus, as it was in non-zebra mussel lakes (Raikow et al 2004). Food webs in zebra mussel lakes have shown a shift toward higher benthic, and lower pelagic production (Mayer et al 2000, Zhu et al 2006). This has been demonstrated from empirical data, stable isotope studies, and models (Knoll et al 2008, Munawar et al 2005, Raikow et al 2004, Vanderploeg et al 2001). The Oneida Lake walleye-perch model predicts a loss of high walleye recruitment years, resulting in a 30% lower adult walleye abundance (Rutherford et al. 1999). There is little published information about effects of zebra mussels in deep oligotrophic lakes, and other than the predicted increase in *Microcystis* dominance, it is difficult to say what we can expect to see in Carlos. Given potential of zebra mussels to alter lake foodwebs and water quality, it will be important to monitor zebra mussel populations and their effect on water quality, habitats, and foodwebs.

Water Quality

Standard summer-mean water quality data for 2008 and 2009 are presented in Table 9, and raw data results are provided in the Appendix. In addition, major cations, anions, and total organic carbon were analyzed. Those values and typical ranges as derived from the National Lakes Assessment (NLA) database for Minnesota are summarized in Table 11. The NLA was a statistically-based survey of the nation's lakes administered by the United States Environmental Protection Agency in 2007. The typical range provided in Table 11 is based on 64 Minnesota lakes that were included in that NLA study and is intended to provide a regional perspective.

Dissolved Oxygen and Temperature Profiles

Profiles were taken at one-meter intervals at site 101 and 102 in Lake Carlos. A comparison of 2008 and 2009, May through October, dissolved oxygen (DO) profiles are found in Figures 17, 18, 19 and 20. Temperature profiles were also taken at sites 101 and 102 in 1977, 2008, and 2009 (Figures 21, 22, 23 and 24). Lake Carlos remained thermally stratified during most of the summer sampling season. This can be attributed to the lake's extreme depth and complex basin morphology. As a result, Lake Carlos is dimictic and resistant to wind mixing events during periods of strong stratification. DO typically dropped below 5 mg/L (necessary to support game fish) at 16 m in 2008 and at 12 m in 2009. Variations could be attributed to temperature and mixing flucutations from year to year. Based on DO profiles for 2008 and 2009, hypoxic conditions (DO<2.0 mg/L) are common starting between June and July and persisting into October. Low DO at these depths reduces habitat for cold water species like cisco. Deep water temperatures vary between sites. Site 102 is continually colder, reaching temperatures near 4 degrees C near bottom as compared to 6 degrees C at site 101. This could be an influence of warmer water entering Lake Carlos form Lake Le Homme Dieu. Strong thermal stratification should minimize internal P recycling by inhibiting deep mixing, while trapping phosphorus within the sediments.

Figure 17. 2008-2009 dissolved oxygen Isopleth profiles site 101 Lake Carlos.

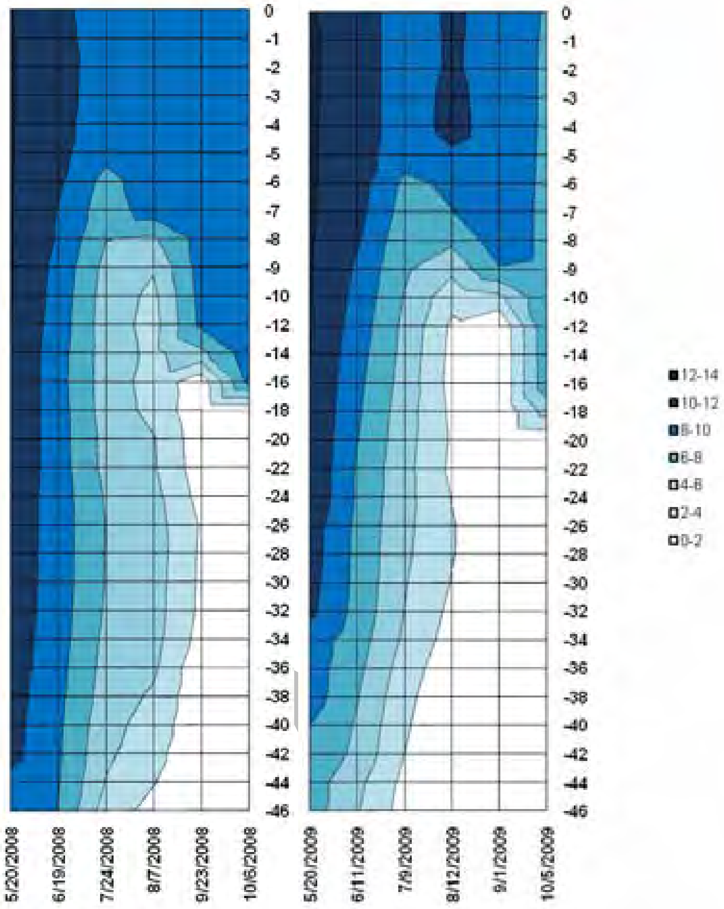


Figure 18. 2008-2009 dissolved oxygen profiles site 101 Lake Carlos.

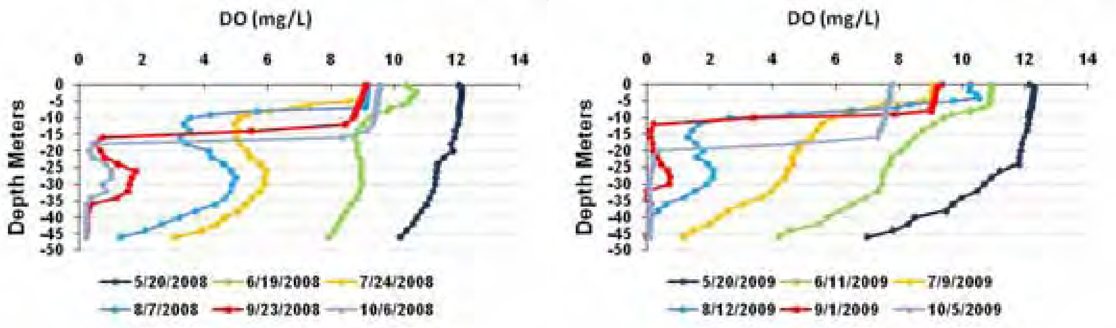


Figure 19. 2008-2009 dissolved oxygen Isopleth profiles site 102 Lake Carlos.

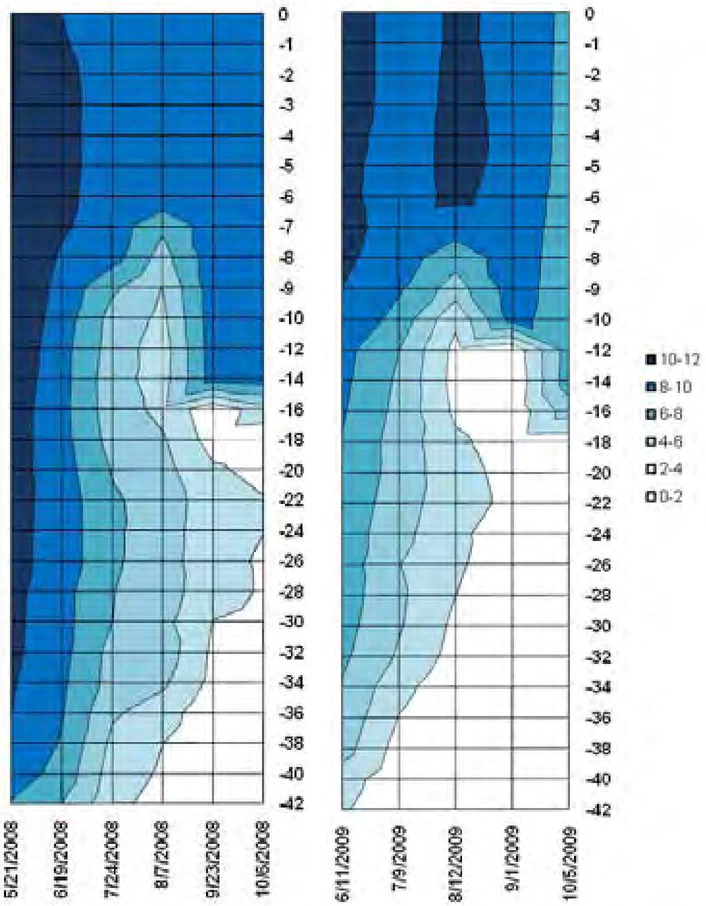


Figure 20. 2008-2009 dissolved oxygen profiles site 102 Lake Carlos.

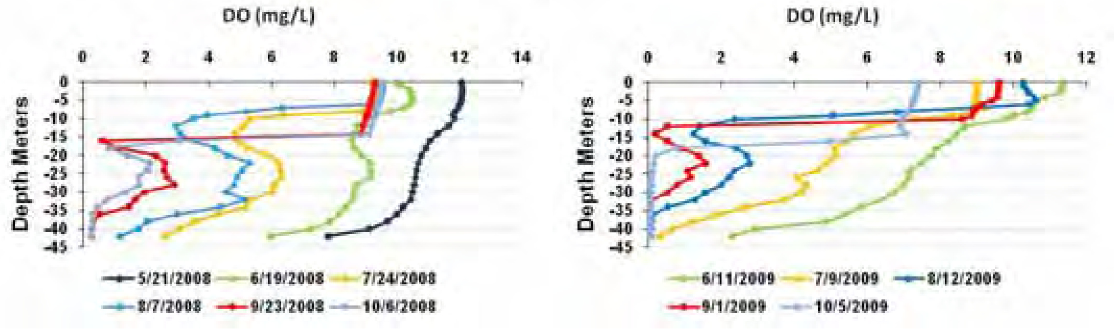


Figure 21. 1977, 2008, and 2009 temperature isopleth profiles site 101 Lake Carlos.

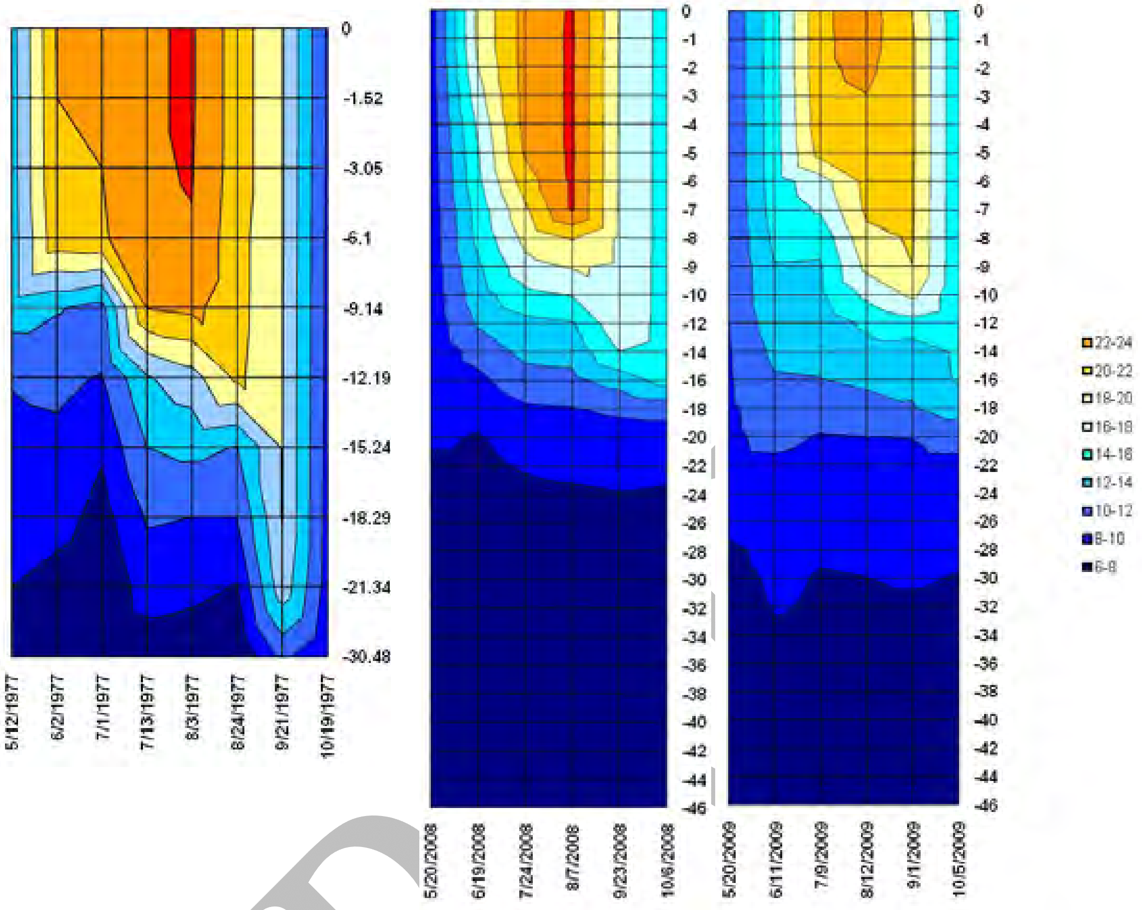


Figure 22. 1977, 2008, and 2009 temperature profiles site 101 Lake Carlos.

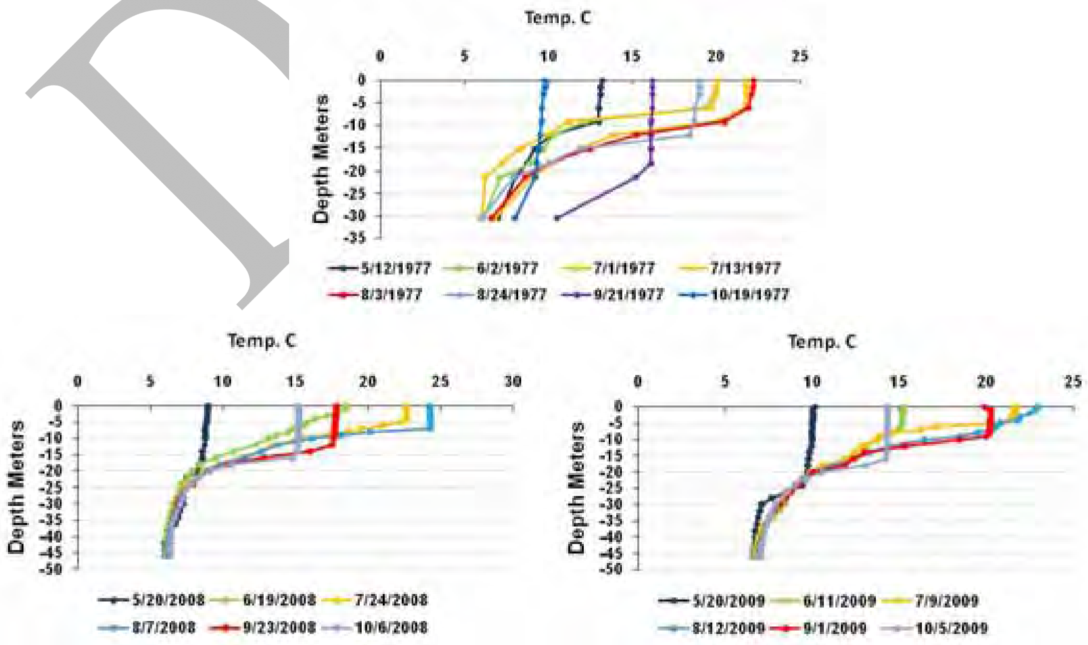


Figure 23. 1977, 2008, and 2009 temperature isopleth profiles site 102 Lake Carlos.

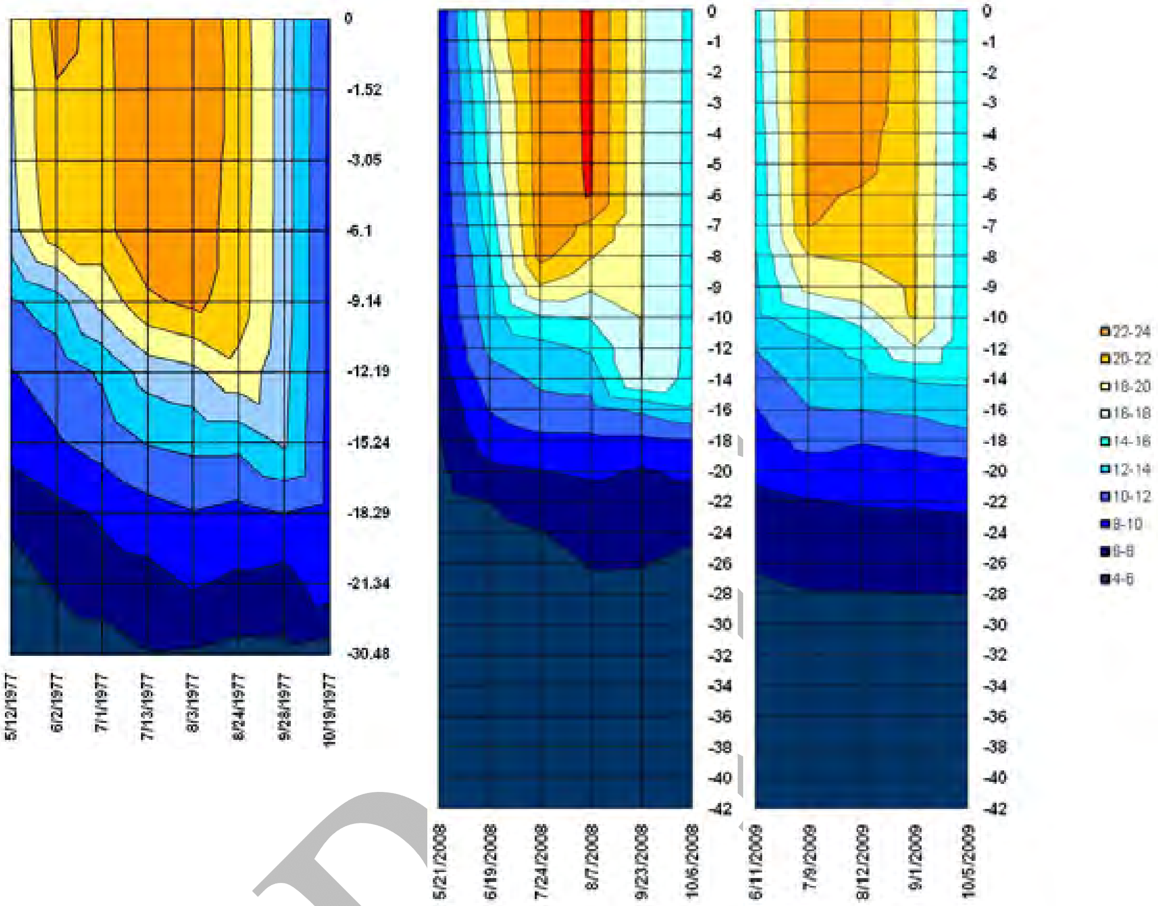
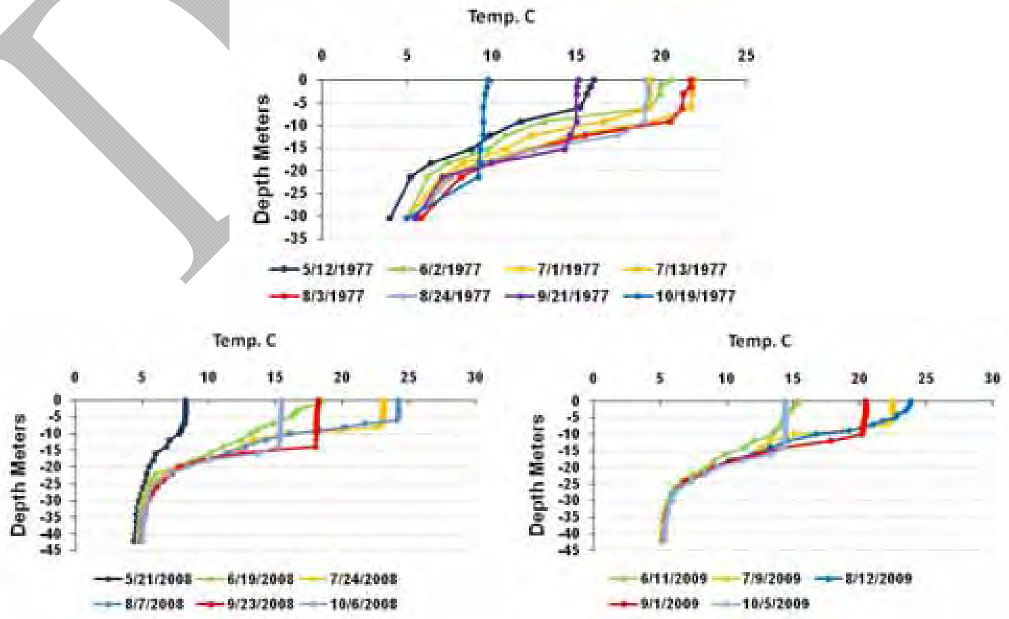


Figure 24. 1977, 2008, and 2009 temperature profiles site 102 Lake Carlos.



Total Phosphorus

TP is the limiting nutrient for plant growth in most freshwater lakes. Lake Carlos surface TP was relatively consistent throughout the 2008 and 2009 open water period, ranging from 13-27 µg/L (Figures 25 and 26). Data were also collected by the ALASD and is combined with MPCA data in Figure 27. Concentrations historically have remained in this range throughout the period of record, 1976-2009. In many deep Minnesota lakes, it is common for TP to remain constant or decline slightly over the summer because watershed inputs are often low during this period and algal growth and death results in sedimentation of TP to the bottom of the lake. There is some internal release of phosphorus from the sediments (Figure 28); however, this source of P remains within the hypolimnion until fall mixing is complete. As such, it is likely that internal recycling of P may not be a major source of P in Lake Carlos. Summer mean TP concentrations were 17.5 ug/L in 2008 and 16.7 ug/L in 2009, which fall below the typical NCHF ecoregion range of 23-50 ug/L.

Figure 25. Lake Carlos trends 2008 and 2009 at site 101.

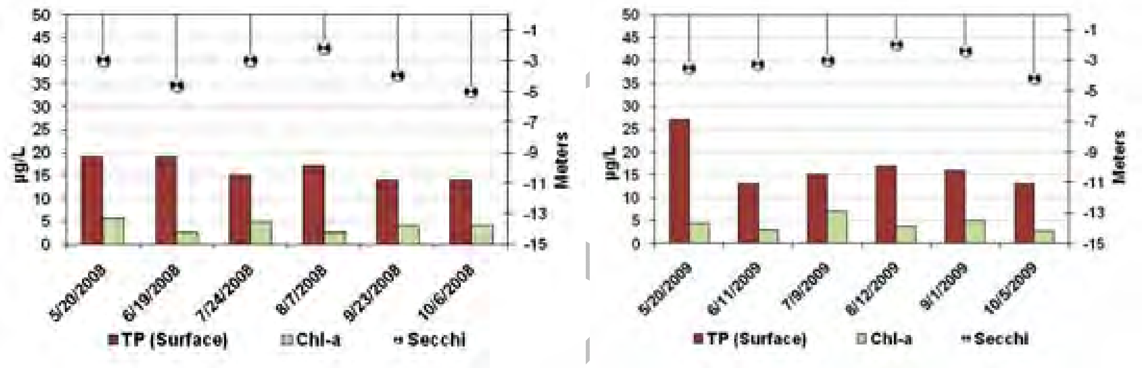


Figure 26. Lake Carlos trends 2008 and 2009 at site 102.

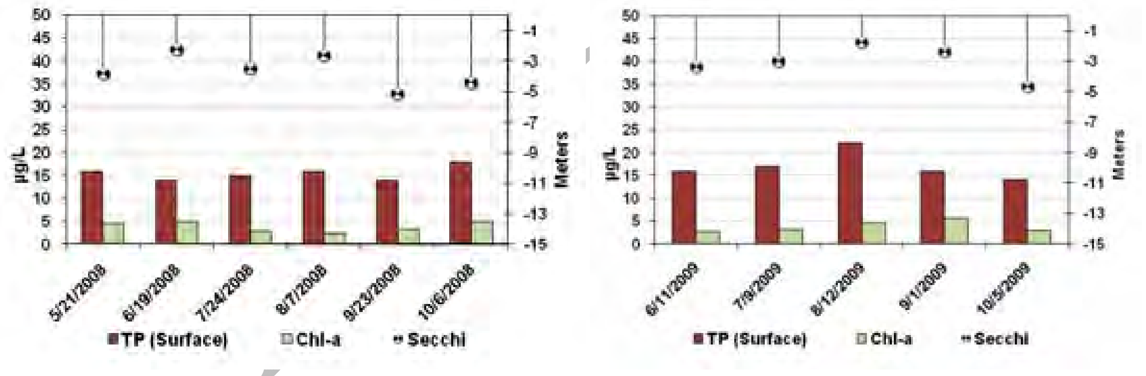


Figure 27. Lake Carlos trends 2008 and 2009 at sites 101 and 205 Sampled by MPCA and Alexandria Lakes Area Sanitary District.

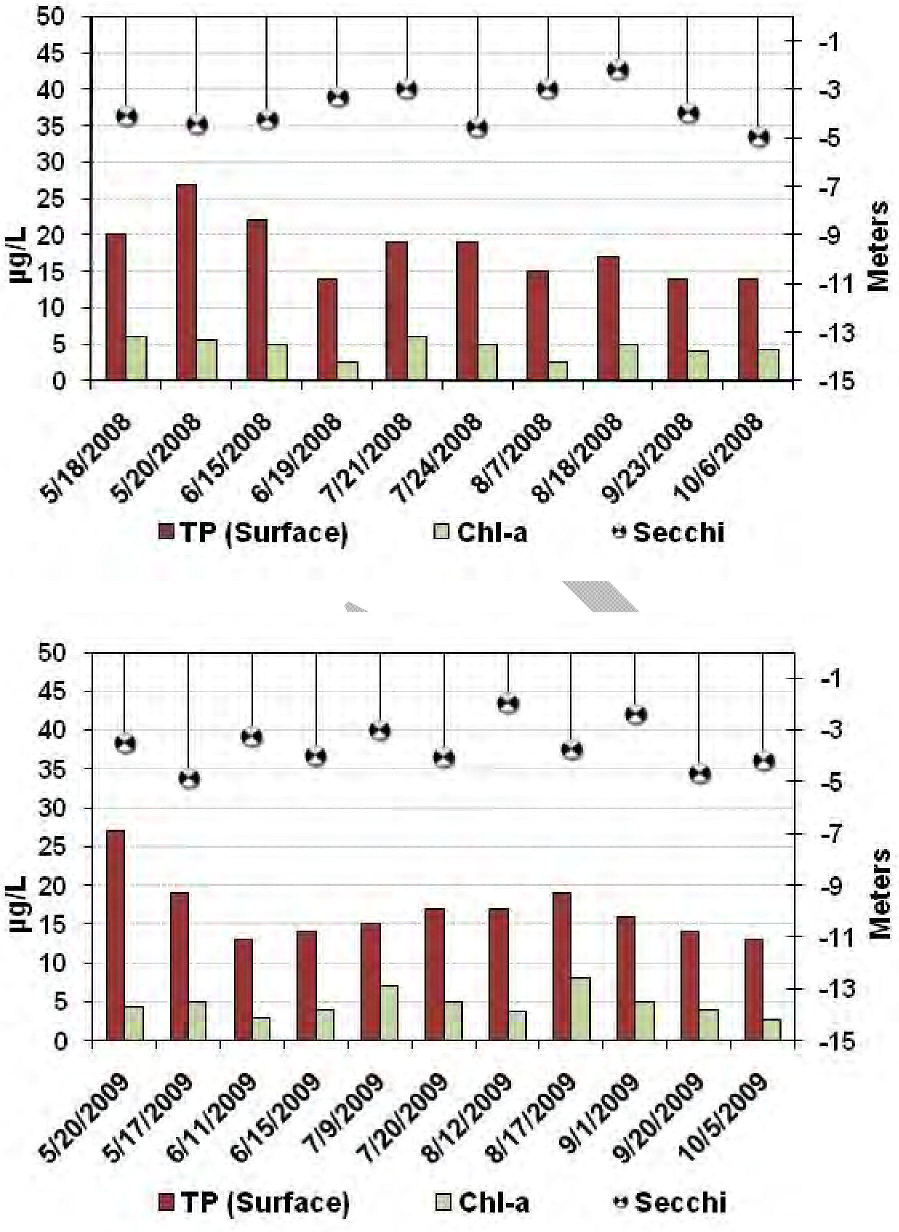
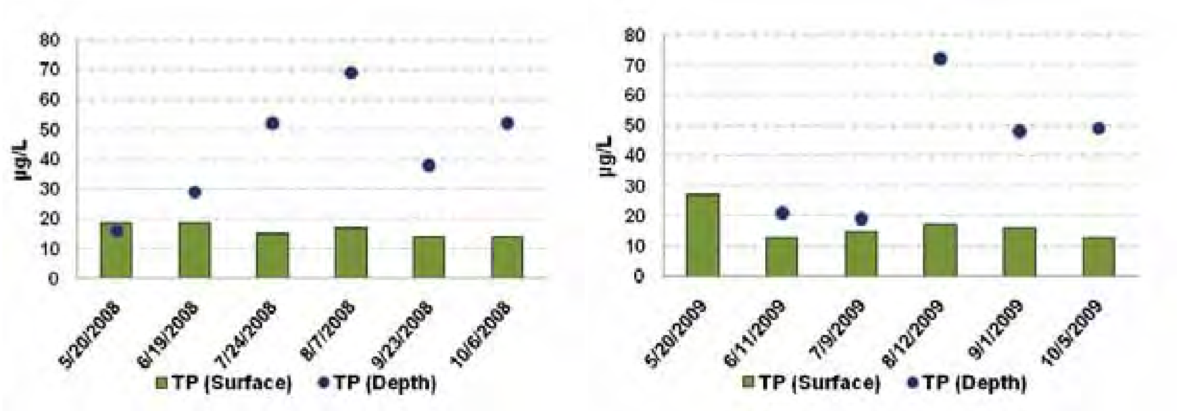


Figure 28. Surface and depth TP 2008 and 2009 at site 101.



Chlorophyll-*a*

Chl-*a*, a pigment found in algae, is used to estimate amount of algal production in a lake. In 2008 and 2009, chl-*a* values for Lake Carlos were between 2-7 ug/L indicating low algal productivity. (Figures 25 and 26). The range of reference lakes in the NCHF ecoregion is 5-22 ug/L. These values result in high water transparency for most of the summer. Clear water of Lake Carlos is a reason it is a popular recreation destination

Secchi disk transparency

Transparency is generally a function of the amount of algae in the water. Suspended sediments or color (due to dissolved organic material) may also reduce water transparency; however, total suspended solids (TSS) in Lake Carlos are within or below the typical range for NCHF lakes. Total suspended inorganic solids (TSIS) are rather low (Table 9), so it is unlikely TSIS limits transparency. Lake Carlos's 2008 mean Secchi was 3.7 m (12ft), exceeding the NCHF ecoregion range of 4.9 m – 10.5 m. Absence of algae and suspended solids results in excellent Secchi transparency throughout the lake.

Dissolved minerals and organic carbon

Dissolved minerals and organic carbon were measured in 2008 and 2009 as part of long-term monitoring of Lake Carlos and other Sentinel lakes. This includes some of the standard measures, such as TSS, alkalinity, conductivity and color (Table 9), as well as major cations, anions, silica, iron and organic carbon (Table 10). While several of these parameters have "typical" ecoregion-based concentrations (e.g. Table 9); some do not. For parameters without ecoregion–based comparisons, data from the 2007 NLA study were used to provide perspective on reported concentrations (Table 11). Since NLA lakes were selected randomly, they provide a reasonable basis for describing typical ranges and distributions at a state-wide level.

Table 9. Lake Carlos summer-mean water quality as compared to the ecoregion reference lake typical range.

Parameter	2008	2009	NCHF
# of lakes			43
Total Phosphorus (µg/L)	17.5	16.7	23 – 50
Chlorophyll mean (µg/L)	3.5	4.3	5 – 22
Chlorophyll maximum (µg/L)	6.0	7.0	7 - 37
Secchi Disk (feet)	12	12	4.9 - 10.5
(meters)	3.6	3.6	(1.5 - 3.2)
Total Kjeldahl Nitrogen (mg/L)	<.05	.73	< 0.60 - 1.2
Alkalinity (mg/L)	175	173	75 - 150
Color (Pt-Co Units)	5	5	10-20
pH (SU)	7.9	8.6	8.6 - 8.8
Chloride (mg/L)	35.7	37.5	4-10
Total Suspended Solids (mg/L)	2.4	9.4	2-6
Total Sus. Inorganic Solids (mg/L)	1.8	4.8	1-2
Conductivity (µmhos/cm)	422	437	300 - 400
TN:TP ratio	-	23:1	25:1 - 35:1

TSS values were low when compared to NCHF reference lakes. Most of the TSS can be attributed to organic suspended solids (TSS-TSIS), i.e. suspended algae. Water clarity in Lake Carlos is exceptional most summers because of low algae and low amounts of inorganic suspended solids; however, during periods of heavy rain and wind TSS and TSIS values may become elevated because of sediment resuspension. This was the case in 2009, resulting in higher than normal TSS for Carlos (Table 9).

The low color value indicates water is clear and has minimal dissolved organic carbon (DOC). As such, total organic carbon (TOC) is rather low and the majority of the TOC is in the DOC form, which is consistent with the state-wide data. Lakes that receive a majority of their water inputs from forest and wetland runoff often have correspondingly higher color and TOC values as a result of incompletely dissolved organic matter (plants, leaves, and other organic material).

Alkalinity and conductivity are higher than the typical range for NCHF lakes. Alkalinity values indicate hard, mineral rich, waters that are common throughout lakes in this area (Table 9). As a result, the increased amount of dissolved minerals increases conductivity of Lake Carlos.

Most cation and anion concentrations were stable across sampling events and years (Table10 Magnessium (Mg), Soduim (Na), Potassium (K) and Chloride (Cl) measurements are noted to be conservative and undergo only minor spatial and temporal changes (Wetzel 2001). Mg is required by algae to produce chl-*a* and Calcium (Ca) is used by rooted plants. Silica (Si), which is required by diatoms to form their “glass” shells, varied slightly from spring to fall. The slight decline in mid-summer to fall may be caused by a fall diatom bloom. Calcium (Ca) and magnesium (Mg) are dominant cations and concentrations of both are on the high end of the typical range of state-wide data (Table 11). The other major cation – sodium (Na) is much higher than typical NCHF and NLA ranges. Potassium (K) is on the upper end of the typical NLA range as well. Bicarbonate is the dominant anion, followed by chloride (Cl) and sulfate (SO_4). Chloride greatly exceeds the typical range for

NCHF reference lakes (Table 9); and statewide NLA data. Sulfate is within the relative range of NLA data. Average cation and anion balances (cation-anions expressed as a % of cations) for 2008 and 2009 were within 1% and 2%, which is well within values exhibited by the NLA lakes.

Table 10. Lake Carlos cation, anion, and organic carbon measurements.

Date	mg/L	mg/L	mg/L	mg/L	µg/L	mg/L		mg/L	mg/L	mg/L	mg/L
	Ca	Mg	Na	K	Fe	Si		SO_4	Cl	TOC	DOC
5/20/2008	28.8	26.7	22.0	4.8	-	-		9.1	35.9	5.9	-
7/24/2008	27.2	26.7	22.0	4.6	-	-		9.2	35.4	6.1	-
10/6/2008	26.4	26.7	22.0	4.7	-	-		9.0	37.7	6.3	-
5/20/2009	31.6	27.4	22.5	4.6	18.2	8.1		9.1	37.7	6.3	5.8
7/9/2009	29.6	27.0	22.3	4.2	15.1	4.9		9.0	37.2	7.1	6.5
10/5/2009	27.3	27.1	22.5	4.6	18.6	6.7		9.2	37.6	6.5	6.2

Table 11. Annual mean values for cations, anions, and organic carbon. Interquartile range (referred to as typical range) based on 64 lakes included in the 2007 NLA study included for perspective.

Parameter[1]	Ten Mile	Ten Mile	NLA IQ Range		Ion balance	µeq/L	µeq/L
	2008	2009	2007			2008	2009
Ca (mg/L)	27.5	29.5	19.1 - 33.7		cations	1372	1472
Mg (mg/L)	26.7	27.2	6.7 - 26.9			2196	2237
K (mg/L)	4.6	4.5	0.9 - 4.8			118	115
Na (mg/L)	22.0	22.4	2.2 - 9.0			957	974
Fe (µg/L)	-	17.3	-		**sum**	**4643**	**4799**
Si (mg/L)	-	6.6	3.1-13.5				
Alk (mg/L	173.3	173.3	-		anions	3446	3446
SO_4 (mg/L)	9.1	9.1	2.2 - 14.1			190	190
Cl (mg/L)	36.3	37.5	1.5 - 18.4			1024	1058
DOC (mg/L)	-	6.2	-		**sum**	**4680**	**4713**
TOC (mg/L)	6.1	6.6	7.3 - 14.2				

Throughout the period of record, Cl values in Lake Carlos increased from 3.4 mg/L in 1948 to 37.5 mg/L in 2009 (Figure 29). The ecoregion range for Cl in the NCHF is 4-10 mg/L. Chloride is easily dissolved into solution and is not readily used by freshwater biota. Because it is conservative , concentrations increase as loading to the lake increases over time (Figure 30). Primary sources of Cl to Carlos likely include stormwater from spreading of salt on roadways during winter and effluent from ALASD wastewater discharge. High concentrations of Cl are found in lakes and tributaries which discharge into the western end of Lake Le Homme Dieu and ultimately into Lake Carlos. No adverse effects are known to biota at current Cl concentrations; however, if concentrations continue to increase it may be cause for concern.

Figure 29. Annual mean chloride concentrations.

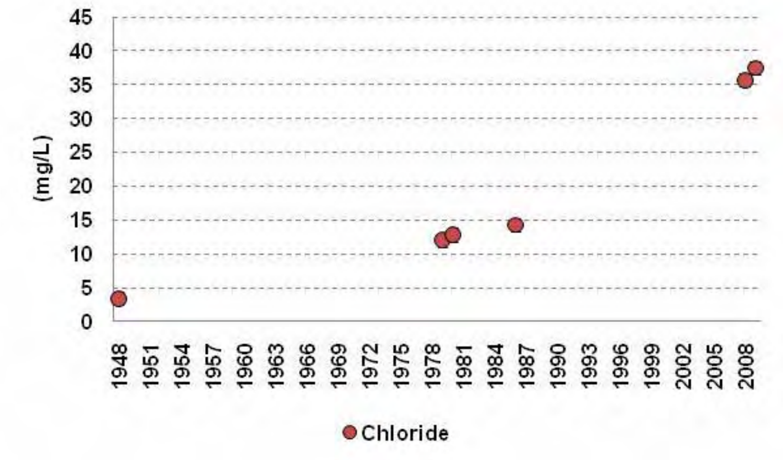
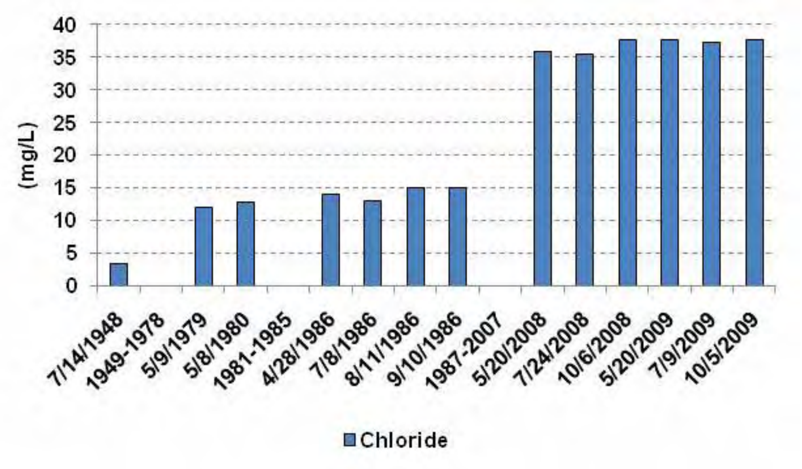


Figure 30. Chloride concentrations during sampling events.



Phytoplankton (algae)

Algal communities shift throughout the seasons in response to changes in nutrient supply, sunlight and temperature. Nutrient levels remained low throughout the year, limiting algal production in Lake Carlos. Transition in phytoplankton assemblage for Lake Carlos in 2008 at sites 101 and 102 is depicted in Figure 31. Diatoms are most abundant in cool water conditions usually during spring and fall turn over. Since water temperatures remain cooler at depth, diatoms persist throughout summer and are an indication of good water quality. As water temperatures warm and silica supplies decline (Table 10), diatom production slows and dinoflagellates become present. By mid-summer, blue-green algae thrive in high water temperatures and are able to outcompete other species of algae because of its larger size and ability to move vertically through the water column. Based on Figure 32, blue-greens became dominant in June and remained dominant through the fall sample collection in October, even though water temperatures were cool. Yellow-brown algae were significant in May and October at site 101 and present in low densities at site 102. Blue-green algae (*Microcystis),* dinoflagellate (*Ceratium*), and diatoms (*Asterionella* and *Fragilaria*) are shown from Lake Carlos in Figure 33.

Figure 31. Phytoplankton assemblage in Lake Carlos at site 101.

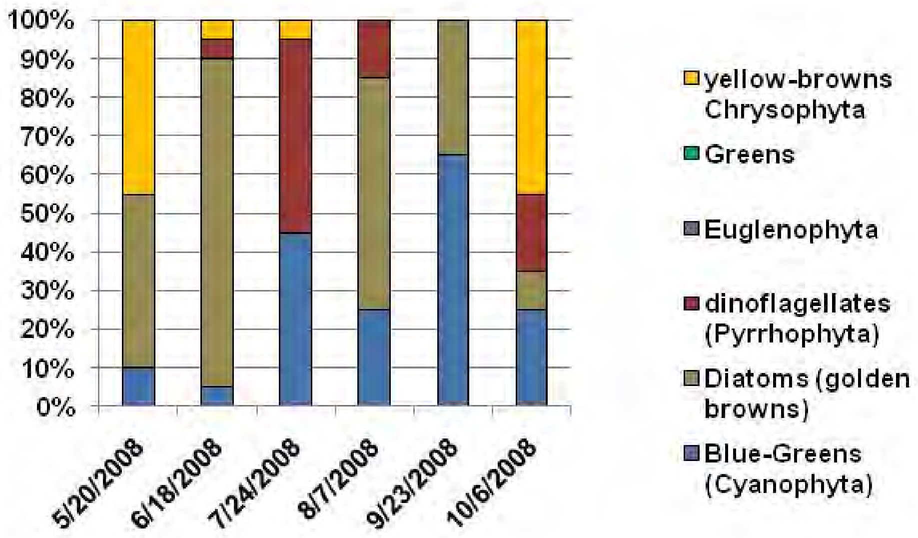


Figure 32. Phytoplankton assemblage in Lake Carlos at site 102.

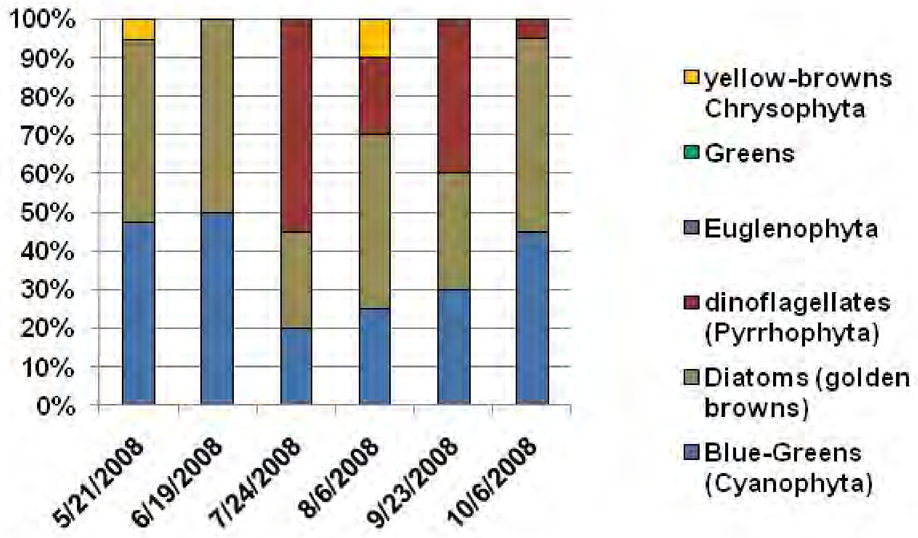
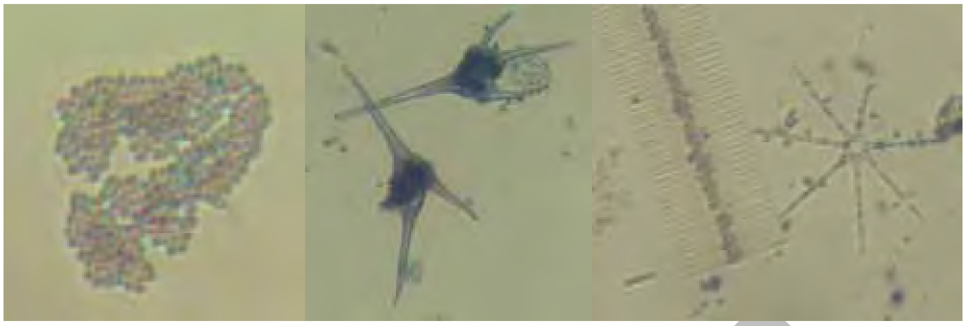


Figure 33. Phytoplankton found in Lake Carlos.



Blue-Green *Microcystis*, **Dinoflagellate** *Ceratium*, and **Diatoms** *Asterionella and Fragilaria*

Zooplankton

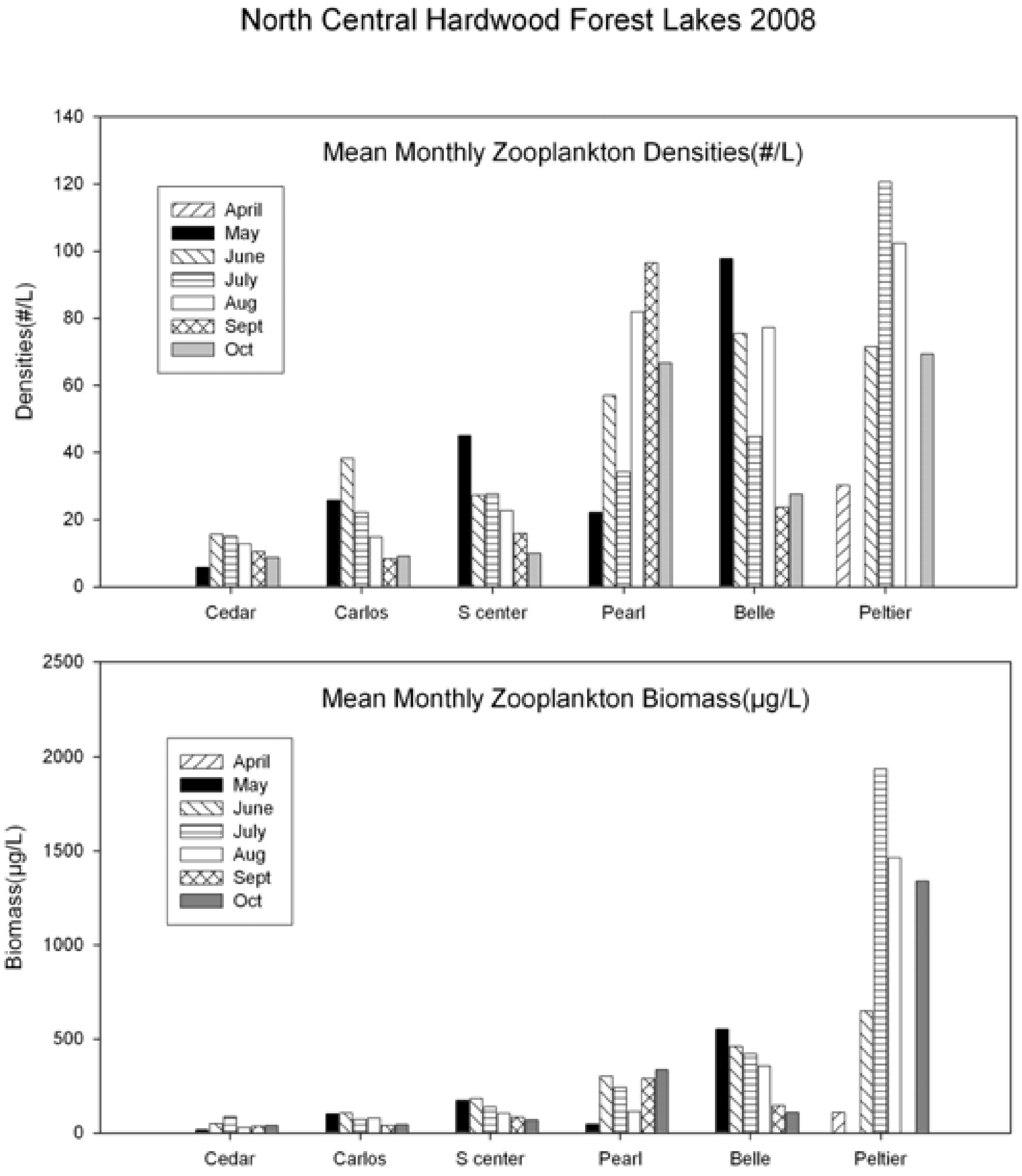
Zooplankton samples were analyzed by Jodie Hirsch at the MDNR. A summary report including information for all Sentinel lakes (Hirsch 2009) is the basis for the following comments on Lake Carlos.

Lake Carlos had the second lowest mean annual density and mean annual biomass of zooplankton of any of the NCHF lakes and was among the lower overall values for all 24 Sentinel lakes (Table 12); however, total number of taxa was on the high end among the NCHF lakes. Hirsch (2009) found that as lake productivity increased (e.g. TP or chl-*a*), relative abundance (biomass) of zooplankton increased in all 24 Sentinel lakes. Lake Carlos appears to have the highest zooplankton biomass and densities in June which then slowly decrease through the open water season (Figure 34). Low primary productivity and sterile waters limit zooplankton productivity. Absence of dense macrophyte beds reduce habitat and allow fish to readily feed on zooplankton. Many young-of-the- year fish utilize zooplankton as their primary food source once they obtain a large enough gape size. This may likely be the reason for reduction in zooplankton biomass throughout the summer.

Table 12. Mean annual zooplankton densities (#/L), biomass (µg/L) and total number of taxa for each of the sentinel lakes sampled in 2008. Lakes are arranged by ecoregion (Sentinel lake groupings).

Sentinel lakes zooplankton 2008	Mean annual densities (#/L)	Mean annual biomass (µg/L)	Total # taxa
Western Cornbelt Plains (WCBP & NGP)			
Artichoke	139.64	724.05	12
Shaokotan	107.55	1070.97	11
St. James	62.73	108.56	10
St. Olaf	60.23	336.20	15
Carrie	56.41	254.21	13
North Central Hardwood Forest (NCHF)			
Peltier	78.75	1098.39	12
Pearl	59.68	221.13	14
Belle	57.67	340.06	12
**Madison*	52.78	310.93	14
South Center	24.72	123.71	18
Carlos	19.66	73.49	16
Cedar	11.31	41.85	11
Northern Lakes and Forests (NLF)			
Portage	100.10	277.38	10
Red Sand	79.31	127.96	18
South Twin	25.83	54.93	12
Hill	17.73	147.29	11
Elk	16.95	47.10	12
Ten Mile	14.94	44.89	14
Border Lakes (NLF)			
Echo	37.03	89.68	12
Elephant	13.26	75.50	12
White Iron	10.00	38.64	14
Trout	6.28	29.52	13
Bearhead	5.15	38.37	14
Northern Light	1.03	4.16	13

Figure 34. Zooplankton mean monthly biomass and densities.



Trophic State Index and Long-term Trends

One way to evaluate trophic status of a lake and to interpret relationships among TP, chl-*a*, and Secchi disk transparency is Carlson's Trophic State Index (TSI) (Carlson 1977). TSI values are calculated as follows:

Total Phosphorus TSI (TSIP) = 14.42 ln (TP) + 4.15

Chlorophyll-*a* TSI (TSIC) = 9.81 ln (chl-*a*) + 30.6

Secchi disk TSI (TSIS) = 60 – 14.41 ln (SD)

TP and chl-*a* are expressed in µg/L and Secchi disk is in meters. TSI values range from 0 (ultra-oligotrophic) to 100 (hypereutrophic) in Table 13. Values for Lake Carlos are found in Figure 35. In this index, each increase of ten units represents a doubling of algal biomass. Comparisons of individual TSI measures provides a basis for assessing relationships among TP, chl-*a*, and Secchi (Figure 35). In general, the TSI values have been in fairly close correspondence with each other from 1990-present. Based on average TSI scores, Lake Carlos would be characterized as mesotrophic.

With regards to water quality data, Lake Carlos is quite data-rich (Figure 36). No distinct trend is evident from this ~30-year record. TP may have declined slightly; however, standard error bars suggest there is likely no significant difference among measurements from the 1970s as compared to the 2000s. Some minimal year-to-year variation in chl-a is evident, but chl-*a* has averaged approximately 5 µg/L during most summers. Secchi is a bit more variable; however, this may be a function of the numerous sites (and observers) measured over time. Recent measures are at or above the long-term mean for the lake.

Table 13. Lake categorization by Trophic State Index.

Productivity Category	**Oligotrophic**			**Mesotrophic**		**Eutrophic**		**Hypereutrophic**			
TSI Value	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**

Figure 35. Lake Carlos historic TSI values.

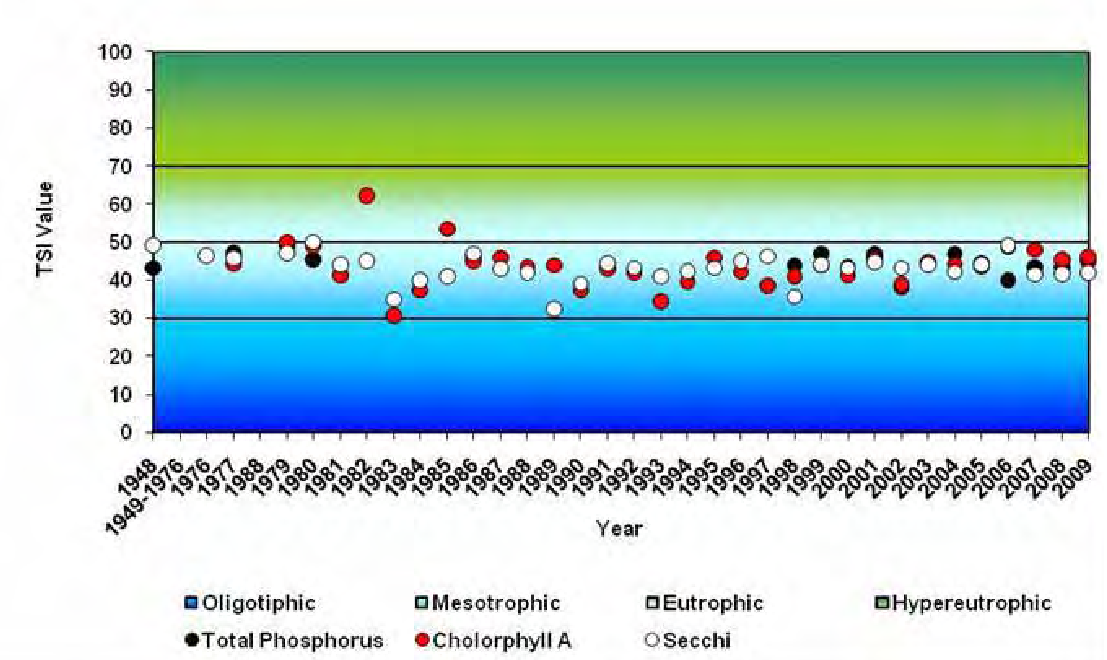
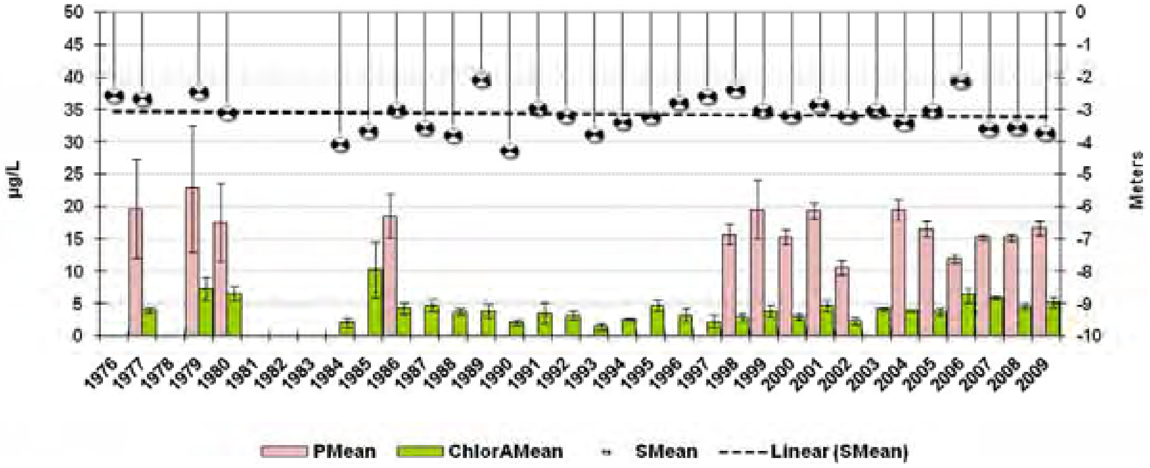


Figure 36. Lake Carlos historic phosphorus, chl-*a*, and Secchi trends.



Modeling

Numerous complex mathematical models are available for estimating nutrient and water budgets for lakes. These models can be used to relate flow of water and nutrients from a lake's watershed to observed conditions in the lake. Alternatively, they may be used for estimating changes in water quality of the lake as a result of altering nutrient inputs to the lake (e.g., changing land uses in the watershed) or altering flow or amount of water that enters the lake. Minnesota Lake Eutrophication Analysis Procedures (MINLEAP) model (Wilson and Walker, 1989) was used to assess water quality of Lake Carlos. A comparison of MINLEAP predicted vs. observed values is presented in Table 14.

MINLEAP is an empirical model developed by MPCA staff based on an analysis of data collected from ecoregion reference lakes. It is intended to be used as a screening tool for estimating lake conditions with minimal input data and is described in greater detail in Wilson and Walker (1989). The model predicts in-lake TP from these inputs and subsequently predicts chl-*a* based on a regression equation of TP and Secchi based on a regression equation based on chl-*a*. For analysis of Lake Carlos, MINLEAP was applied as a basis for comparing observed (2008) TP, chl-*a*, and Secchi values with those predicted by the model based on lake size, depth, and area of the watershed.

MINLEAP was calibrated to reflect concentrations from Lake Le Homme Dieu, Lake Darling, and small tributaries, which directly flow into Lake Carlos. It is important to realize that the basin and watershed complexity of Lake Carlos creates challenges in modeling when using a simple empirical model like MINLEAP. One of the primary problems is that the model cannot account for sedimentation (trapping) of P in upstream lakes like Le Homme Dieu and Darling.

Lake Carlos is located in the NCHF ecoregion and the model was run using NCHF ecoregion-based inputs. The typical NCHF stream P inflow concentration in MINLEAP is 147 ug/L. This stream inflow value resulted in an over estimate of in-lake P as compared to observed (Table 14). In order to yield a more accurate estimate of the P loading rate to Carlos, the stream P inflow concentration was calibrated based on measured values for Lake Le Homme Dieu and Lake Darling and the two main inlets to Lake Carlos. In-lake concentrations for both lakes were about 22 ug/L. Since there are other inflows to Lake Carlos, a slightly higher P value of 30 ug/L was used for calibration. This resulted in a predicted in-lake P, chl-*a* and Secchi that were not significantly different than observed (Table 14).

As part of the Sentinel lake project, the U.S. Geological Survey (lead: Dr. Richard Kiesling) are developing a sophisticated predictive, mechanistic lake model (CE-QUAL-W2) for Carlos to determine the interaction between nutrient cycling, primary production, and trophic dynamics in order to predict responses in deepwater thermal habitats for cold-water fish species. These models will be used to evaluate the response of Carlos to land use and climate change scenarios. For more information on this work and other related research visit http://www.dnr.state.mn.us/fisheries/slice/index.html.

Table 14. MINLEAP model results for Lake Carlos.

Parameter	2008 Lake Carlos Observed	MINLEAP Predicted NCHF Ecoregion	MINLEAP Calibrated NCHF Ecoregion
TP (µg/L)	18.0	48 (±16)	16.0 (±5)
Chl-*a* (µg /L)	3.5	18.6 (±11)	3.8 (±2)
Secchi (m)	3.6	1.4 (±0.6)	3.5 (±1.3)
P loading rate (kg/yr)	-	12,497	2,777
P retention (%)	-	0.68	0.52
P inflow conc. (µg/L)	-	151	34
Water Load (m/yr)	-	8.12	8.12
Outflow volume (hm^3/yr)	-	82.78	82.78
Residence time (yrs)	-	1.7	1.7
Vighi & Chiaudani		17.4	17.4

303(d) Assessment and Goal Setting

The federal Clean Water Act requires states to adopt water quality standards to protect waters from pollution. These standards define how much of a pollutant can be in the water and still allow it to meet designated uses, such as drinking water, fishing and swimming. Standards are set on a wide range of pollutants, including bacteria, nutrients, turbidity and mercury. A water body is “impaired” if it fails to meet one or more water quality standards.

Under Section 303(d) of the Clean Water Act, the state is required to asses all waters of the state to determine if they meet water quality standards. Waters that do not meet standards (i.e., impaired waters) are added to the 303(d) list which is updated in even-numbered years. In order for a lake to be considered impaired for aquatic recreation use, average TP concentration must exceed the water quality standard for its ecoregion. In addition, either chl-*a* concentrations for the lake must exceed the standard or Secchi data must be below the standard. A minimum of eight samples collected over two or more years are needed to conduct the assessment. There are numerous other water quality standards utilized to assess Minnesota’s water resources. An example is methyl-mercury found in fish tissues. If a water body is listed, an investigative total maximum load study (TMDL) study must be conducted to determine sources and extent of pollution, and establish pollutant reduction goals needed to restore the resource to meet water quality standards for its ecoregion. The MPCA is responsible for performing assessment activities, listing impaired waters, and conducting TMDL studies in Minnesota.

Lake Carlos was assessed relative to NCHF ecoregion standards for deep lakes (Table 15). Long-term and recent assessed (2008, &2009) summer-mean values for Lake Carlos meet water quality standards and Carlos fully supports aquatic recreational use. The high quality habitat and water quality in Lake Carlos is owed in big part to its great depth and upstream lakes that process upstream nutrient loading from Carlos’s large watershed; however, this resilience is not inexhaustible and unabated runoff from farm fields and urbanized portions of the watershed has the potential to impact Carlos and the lakes that comprise the overall chain of lakes. Expanded watershed best management practices including ditch and shoreland buffers, restored wetlands and grasslands, proper manure containment and disposal, improved waste water and septic treatment, rain gardens, and aquatic plant protection are probably the best immediate strategy to lessen local human impacts to Lake Carlos and other surrounding lakes.

Table 15. Eutrophication standards by ecoregion and lake type (Heiskary and Wilson, 2005). Lake Carlos 2008 and long-term means provided for comparison.

Ecoregion	TP µg/L	Chl-*a* µg/L	Secchi meters
NLF – Lake trout (Class 2A)	< 12	< 3	> 4.8
NLF – Stream trout (Class 2A)	< 20	< 6	> 2.5
NLF – Aquatic Rec. Use (Class 2B)	< 30	< 9	> 2.0
NCHF – Stream trout (Class 2a)	< 20	< 6	> 2.5
NCHF – Aquatic Rec. Use (Class 2b)	< 40	< 14	> 1.4
NCHF – Aquatic Rec. Use (Class 2b) Shallow lakes	< 60	< 20	> 1.0
WCBP & NGP – Aquatic Rec. Use (Class 2B)	< 65	< 22	> 0.9
WCBP & NGP – Aquatic Rec. Use (Class 2b) Shallow lakes	< 90	< 30	> 0.7
Lake Carlos 2008	**17.5**	**3.5**	**3.6**
Lake Carlos Long-term mean	**17**	**4.6**	**3.5**

References

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Appendix

MPCA Lake Surface Water Quality Data for Lake Carlos for 2008-2009

All water quality data can be accessed at: http://www.pca.state.mn.us/data/eda/STresults.cfm?stID=29-0250&stOR=MNPCA1

Lake Name	Lake ID	Sample Date	Site ID	Secchi	TP	Chl-*a*	Alkalinity	Chloride	TKN	Color, Apparent	TSS
				Meters	µg/L	µg/L	mg/L	mg/L	mg/L	PCU	mg/L
Carlos	21-0057	5/20/2008	101	3	19	5.62	180	35.9	0.72	5	2.4
Carlos	21-0057	6/19/2008	101	4.6	19	2.54			0.75		
Carlos	21-0057	7/24/2008	101	3	15	4.97	170	35.4	0.67	5	2.4
Carlos	21-0057	8/7/2008	101	2.2	17	2.53			0.61		
Carlos	21-0057	9/23/2008	101	4	14	4.05			0.66		
Carlos	21-0057	10/6/2008	101	5	14	4.2	170	37.7	0.66	5	1
Carlos	21-0057	5/20/2009	101	3.5	27	4.37	180	37.7	0.87	5	22
Carlos	21-0057	6/11/2009	101	3.3	13	3			0.58		
Carlos	21-0057	7/9/2009	101	3	15	7.02	170	37.2	0.71	5	3.6
Carlos	21-0057	8/12/2009	101	2	17	3.73			0.78		
Carlos	21-0057	9/1/2009	101	2.4	16	5.08			0.77		
Carlos	21-0057	10/5/2009	101	4.2	13	2.78	170	37.6	0.64	5	2.8
Carlos	21-0057	5/21/2008	102	4.5	16	3.85					
Carlos	21-0057	6/19/2008	102	4.9	14	2.27					
Carlos	21-0057	7/24/2008	102	2.75	15	3.52					
Carlos	21-0057	8/7/2008	102	2.2	16	2.69					
Carlos	21-0057	9/23/2008	102	3.1	14	5.16					

Carlos	21-0057	10/6/2008	102	4.9	18	4.45					
Carlos	21-0057	6/11/2009	102	3.4	16	2.78					
Carlos	21-0057	7/9/2009	102	3	17	3.2					
Carlos	21-0057	8/12/2009	102	1.8	22	4.49					
Carlos	21-0057	9/1/2009	102	2.4	16	5.58					
Carlos	21-0057	10/5/2009	102	4.7	14	2.95					