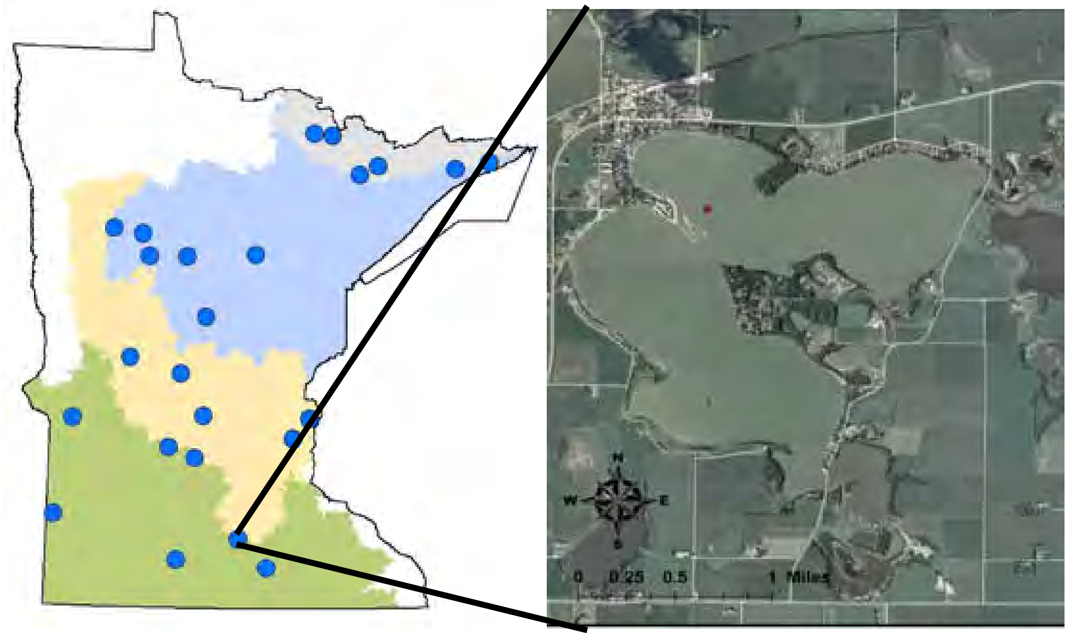
Sentinel Lake Assessment Report
Madison Lake (07-0044)
Blue Earth County, Minnesota



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&
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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 the necessary information to detect undesirable changes in Minnesota Lakes (Valley 2009). To increase our ability to predict the 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 the 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 the summer months only. "Shallow" lakes are defined as mixing continuously throughout the 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 funded by the ETF.

Madison is an important local resource, and is one of the largest and deepest lakes in Blue Earth County. It provides varied recreational opportunities including fishing, swimming, boating, sailing and skiing. It is a highly developed lake and, as such, makes a substantial contribution to the local economy. Landuse records suggest a slight decline in the percent of land in agricultural uses and an increase in developed landuse in recent years.

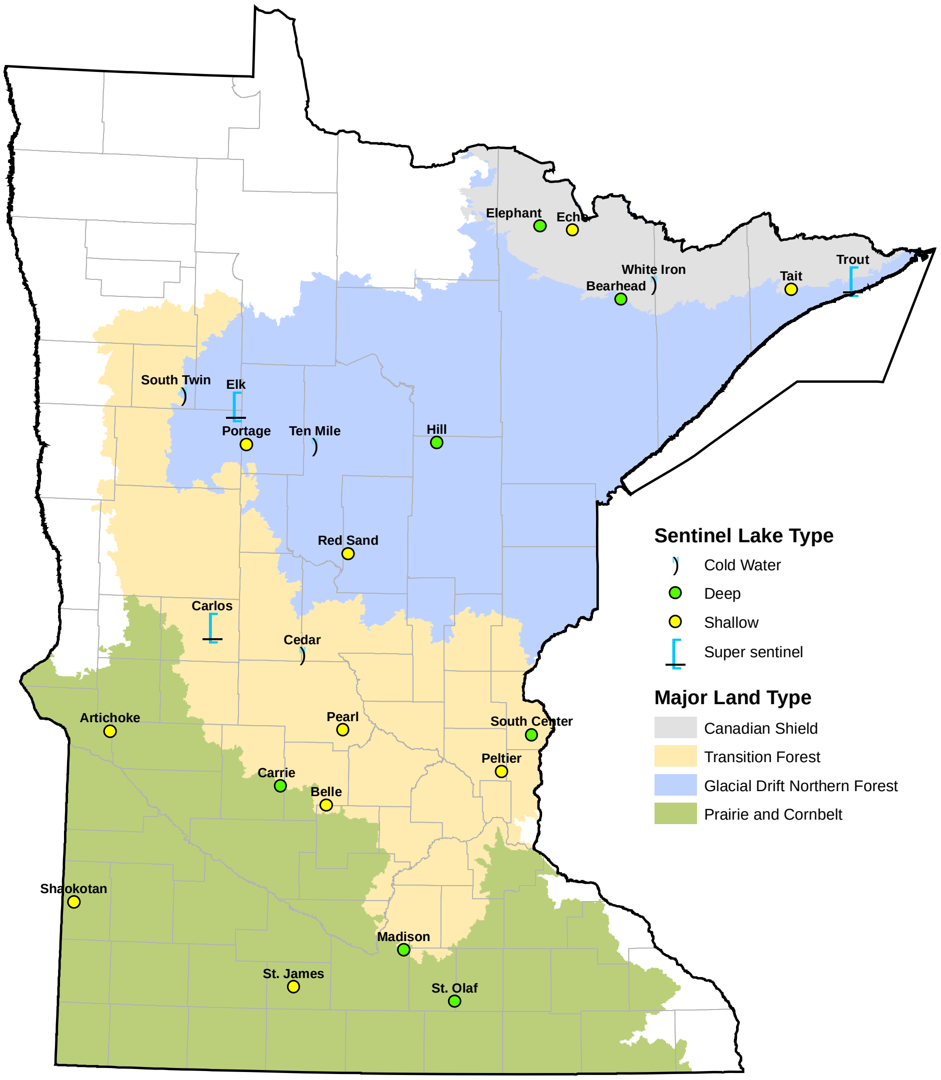
The modern-day water quality record indicates Madison has been eutrophic bordering on hyper eutrophic. In general, summer average total phosphorus is on the order of 65-95 micrograms per liter (µg/L), chlorophyll-a (chl-a) of 25 - 29 µg/L and Secchi of 0.8 – 1.1 meters in most summers. Severe nuisance blooms of blue-green algae are a common occurrence in most summers with individual chl-a measurements greater than 40 µg/L common in recent years. Based on these measurements, Madison was assessed as having elevated nutrient concentrations and was placed on the 2010 303(d) draft impaired waters list.

Game fish production (i.e., size and abundance) is relatively high despite relatively poor water quality conditions. River forage species that are adapted to turbid water conditions, combined with cover provided by curly-leaf pondweed seem to be important for sustaining quality populations of game fish. Improvements to water quality and native aquatic plants may lead to a decline in the biomass of river species and an increase in the biomass of lake species. It is unclear whether this change will have a net gain on game fish size and abundance in the lake. Long-term monitoring will be important to assess future trends in water quality, aquatic plants, and fish communities.

Nevertheless, gizzard shad, black bullhead, and common carp along with boom-bust cycles of curly-leaf pondweed are strong internal reinforcing forces maintaining the current poor water quality regime in Madison Lake. While watershed-based efforts to reduce external nutrient loading are essential to improving the water quality of Madison Lake, it will be difficult to overcome these internal resilience mechanisms that promote high internal loading of nutrients. In addition, future impacts of climate change that will alter hydrologic regimes need be considered as well if significant improvements to water quality and aquatic plant growth are to be made. Stopping further declines in water quality and aquatic plant growth may represent a more feasible management objective for Madison Lake.

Although curly-leaf pondweed presumably negatively impacts summer water quality and native aquatic plant growth in Madison, the species appears to be an important surrogate for providing cover for bass, sunfish, and northern pike. Policies that eliminate curly-leaf pondweed without replacements by native aquatic plants may have even worse impacts on water quality and fish habitat than if curly-leaf pondweed was left untreated.

Figure 1. Sentinel lakes locations and designations



Introduction

This report provides a relatively comprehensive analysis of physical, water quality and ecological characteristics of Madison Lake in Blue Earth, 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 analyses of various other sources of data for the lake. The water quality assessment focuses on data collected during the 2006 and 2008 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

1800's	Native American settlement on the lake
1880	Resort opens on Town Bay at Point Pleasant
1880	The east bay was dry and farmed for corn and potatoes
1927	Lake levels dropped because of tiling and drainage in lakes and sloughs along Le Sueur River
1929	The east bay is flooded
1939	Civilian Conservation Corps constructs a ditch between Madison and Mud Lake intended to be an additional inlet to Madison
1941	A wet spring and the improvements to the drainage at the outlet caused the lake to rise xx meters (5 ½ feet)
1955	The outlet was deepened and new culverts were put in between Madison and Mud Lake
1960	Paddlefish (Polyodon spathula) collected by commercial fishermen. Don Bluhm and Bud Biehn find an 80 pound paddlefish in a seine haul. The fish is returned to the water. Department of Conservation biologist and district manager, Jim Groebner, and Don Woods comment that the fish likely a carryover from before 1918
1961	Minnesota Department of Health investigated complaints untreated sewage to the lake
1966	Ditch # C-2 at 108N 25W were repaired, draining Indian and Alice Lakes to Madison bring lake level to its more stable current state
1970	Curly-leaf pondweed (*Potamogeton crispus*) first documented
1970	Gizzard shad (*Dorosoma cepedianum*) first documented. Fish are believed to have entered the lake during flooding in the middle 1960's
1972	Madison Lake was one of 80 Minnesota lakes studied by United States Environmental Protection Agency (USEPA) during the National Eutrophication Survey
1975	City of Madison Lake municipal sewer system goes into service. Discharging downstream of the lake to the Le Sueur River
1993	Forty-eight- inch culverts were replaced by 72 x59-inch culverts between Madison and Mud Lakes
2006	Madison Lake was one of 12 Blue Earth and McLeod County lakes included in a study on blue-green algal toxins in south central Minnesota.
2010	Sewer extension to Mankato Waste Water Treatment Facility will allow additional lake residents to be sewered

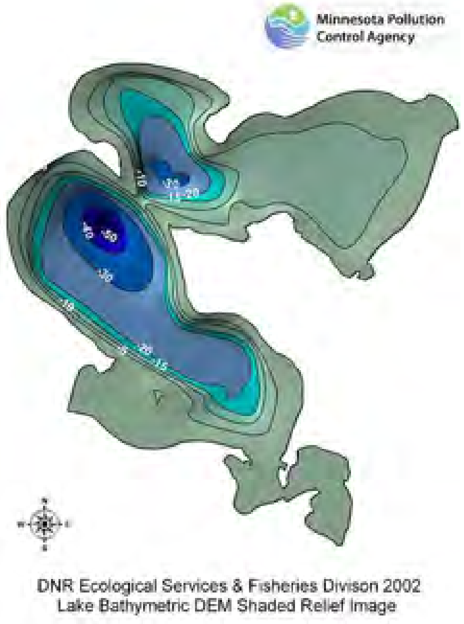
Background

Madison Lake is located in northeast corner of Blue Earth County on the south east edge of the city of Madison Lake, about 24 kilometers (15 miles) from Mankato MN. The lake was formed by irregular glacial deposition in till (Zumberge, 1952). According the current NRCS Blue Earth County soil survey soils around Madison Lake consist predominantly of poorly drained loamy soils such as Le Sueur clay loam, Cordova clay loam, Shorewood silty clay loam and Lester loam. It is a very popular lake with several parks, a fishing pier and three public accesses located on the east side of the lake.

Lake Morphometric and Watershed Characteristics

Madison Lake has as three distinct bays: a fairly large and shallow bay in the northeast, a smaller and deeper bay to the north, and the largest and deepest bay is in the southwestern portion the lake (Figure 2). A shallow narrows separates the northeast and southwest portions of the lake. Madison Lake's morphometric characteristics are summarized in Table 1. Percent littoral area refers to that portion of the lake that is 4.6 meters (15 feet) or less in depth, which often represents the depth to which rooted plants may grow in the lake. 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. Madison Lake has substantial aquatic plants that will be discussed later in detail.

Figure 2. Madison Lake bathymetric map



DNR Ecological Services & Fisheries Divison 2002
Lake Bathymetric DEM Shaded Relief Image

Table 1. Madison Lake bathymetric information[1]

Area	Hectares (Acres)	584 (1,443)
Littoral Area	%	50
Max. Depth	Meters (Ft).	18 (58)
Mean Depth	Meters (Ft).	3.9 (10)
Volume	Acre-Ft.	18,419

Madison Lake is part of the Minnesota River Basin, in the Le Sueur River Watershed. The lake has five inlets located around the lake. The only outlet is located in the southwest portion of the lake that drains to a small lake (Mud Lake). The contributing watershed drainage area includes several small lakes and wetlands. The total watershed area 3,061 hectares (11,167) resulting in a watershed to lake ratio of 7.7: 1. Watershed delineations are available at http://deli.dnr.state.mn.us/data_search.html "DNR watersheds - DNR Level 08 – All Catchments"

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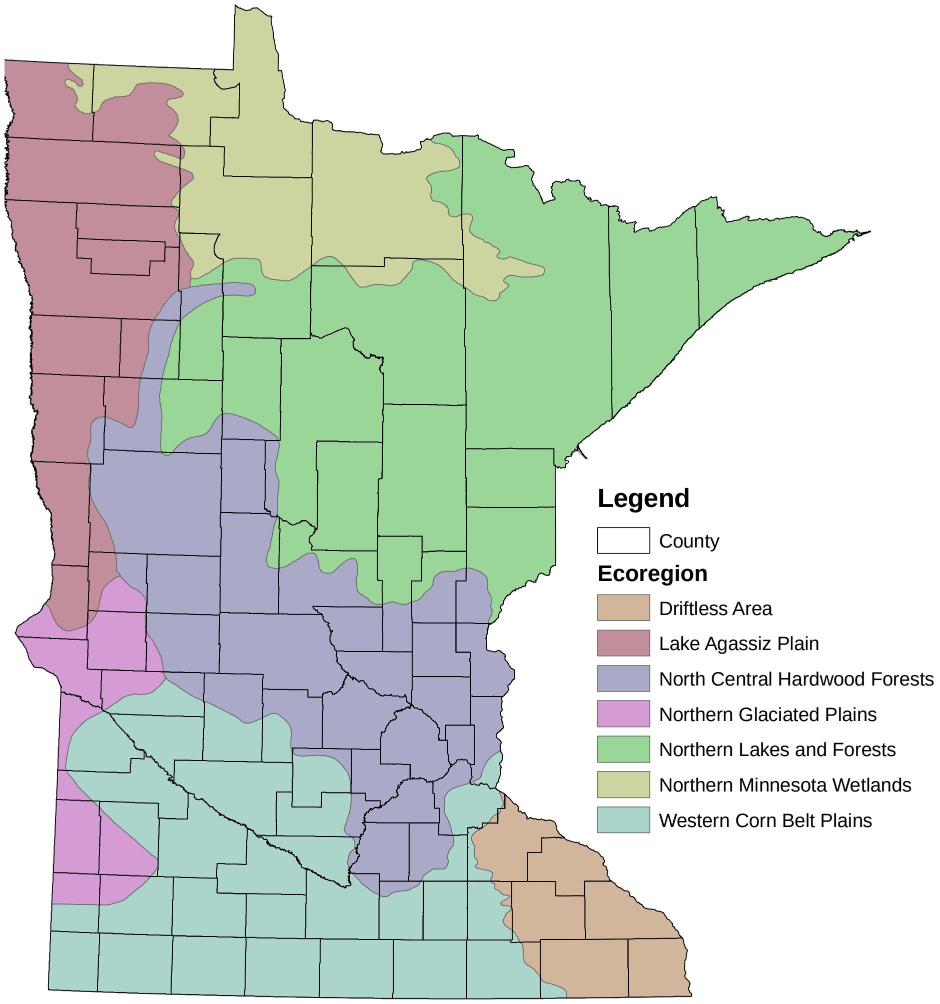
[1] Based on the 1:100,000 Lakes and Rivers Coverage and reflects the open water area in 2008, DNR

Ecoregion and Land Use Characteristics

Minnesota is divided into seven regions, referred to as ecoregions, as defined 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 the water quality and characteristics of other lakes. Madison Lake is located in the southern portion of the Central Hardwoods Forest (CHF) ecoregion near the border with the Western Corn Belt Plains (WCP) ecoregion (Figure 3). Since the lake is near the transition between the two ecoregions typical values from both ecoregions (CHF & WCP) will be used as a basis for comparison and predictive modeling.

Figure 3. Minnesota ecoregions as mapped by United States Environmental Protection Agency



Since land use within the watershed affects water quality significantly, it has proven helpful to summarize land use in simple categories and look at changes in land use over time. The latest land use summary (NLCD 2001) shows the Madison watershed is predominately agricultural (Table 2). Based on a comparison of three databases that represent land use for 1969, 1991, and 2001 developed use has increased while cultivated use has decreased. This comparison also suggests that the percent of water and wetlands has increased over time as well. There are ten feedlots noted in the watershed and most are located on or near watercourses that can potentially drain to the lake (Figure 4). Depending on land application practices and permit compliance, these feedlots are a potential source of excess nutrients to the lake. Overall, the most current land use mapping is consistent with a lake located near the transition of two ecoregions.

Figure 4. Madison Lake watershed and land use composition

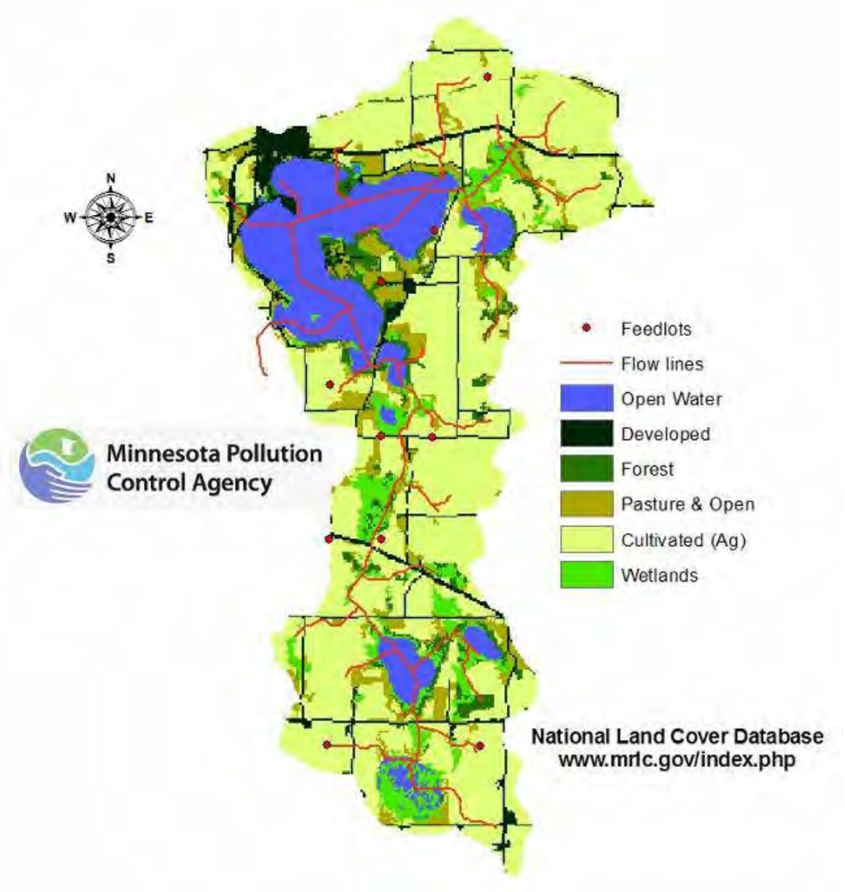


Table 2. Land use composition. Typical range based on interquartile range for North Central Hardwoods Forests ecoregion reference lakes.

Land use	% Land Use NLCD 2001	% Land Use GAP 1991	% Land Use LU 1969	WCBP typical land use percentage	NCHF typical land use percentage
Developed	9	5	4	0 – 16	2 - 9
Cultivated (Ag)	48	62	61	42 – 75	22 - 50
Pasture & Open	10	15	12	0 – 7	11 - 25
Forest	2	0.5	0.5	0 – 15	6 - 25
Water/ Wetland	31	21	22	3 - 26	14 - 30
Feedlots (#)	10	NA[4]	NA[4]		

Lake Level and Ice On/Off

The MDNR Division of Waters, with help from volunteers, has been regularly measuring water levels on Madison Lake since 1939. Lake levels increased 10 feet from 1939 to 1944 (following the severe drought of the 1930's) and have been generally stable, at about 1,016 feet about sea level, since that time (Figure 5). The two most recent droughts (1976 and 1988) are evident in the record as well. 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. Ice off records on Madison Lake are extensive, going back to 1927 (Figure 6). Ice off is typically early April and no distinct trend is evident in these data. This runs contrary to findings by Johnson and Stefan (2006), who documented long-term declines in ice-cover throughout Minnesota.

Figure 5. Madison Lake water levels history

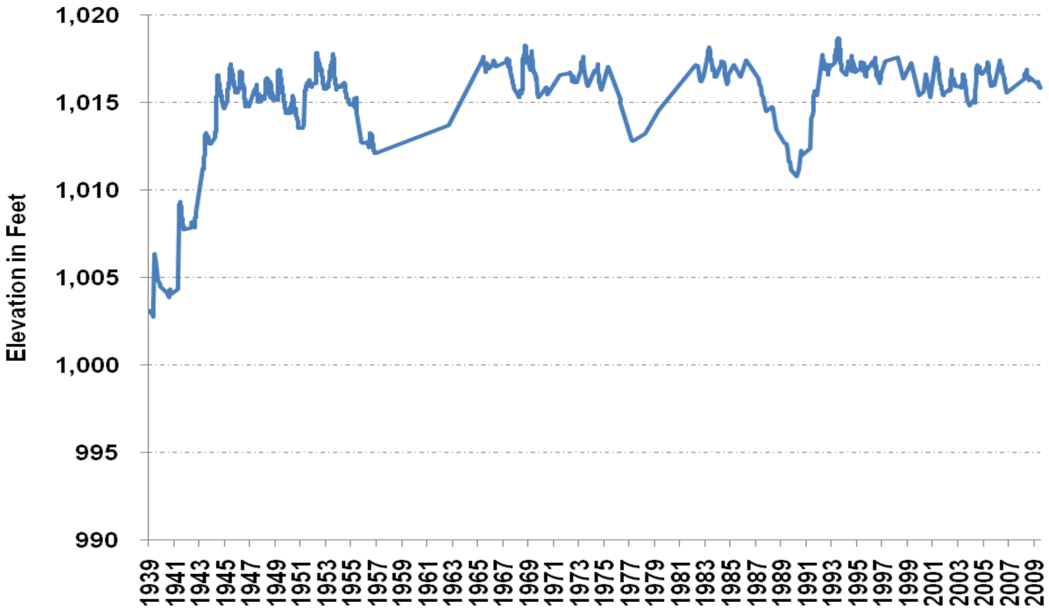
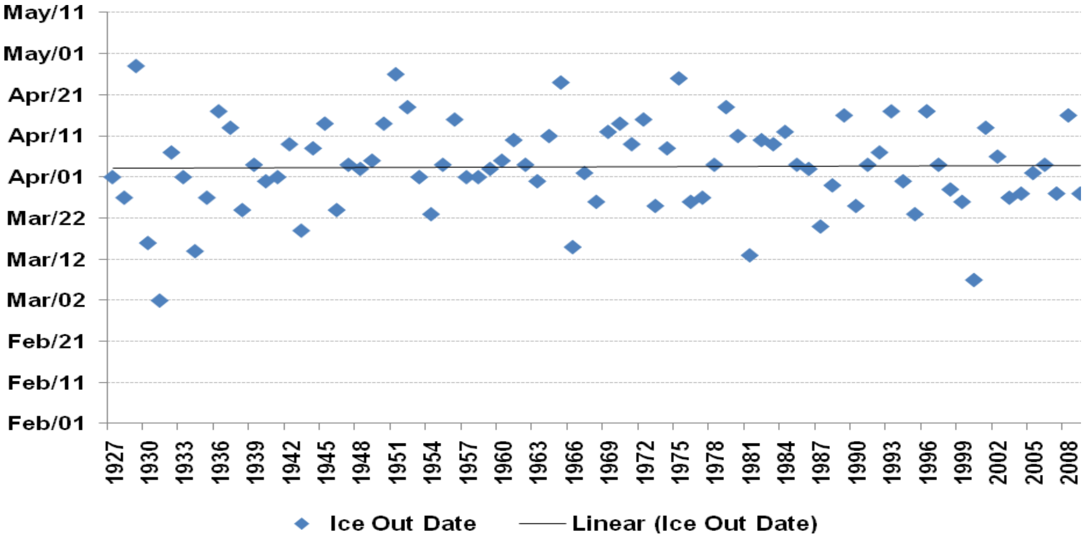


Figure 6. Madison Lake ice out dates



Precipitation and Climate Summary

Large rain events increase runoff into the lake and may influence in-lake water quality and lake levels. Rain gage records from Mankato show five of one-inch and one two-inch during water quality monitoring period of 2008 (Figure 7). No major rain event occurred prior to any of the 2008 sampling events (Figure 7). Total precipitation in 2008 was slightly below normal (Figure 8). The 2008 and 2006 annual precipitation was similar (Figure 9). Long-term precipitation records from the Mankato area indicate wetter condition in recent years and fair amount you yearly variation (Figure 9). This information was obtained through the State Climatology Office and can be found at http://climate.umn.edu/climatology.htm.

Figure 7. Summer 2008 rainfall and temperature based on records for Mankato, MN

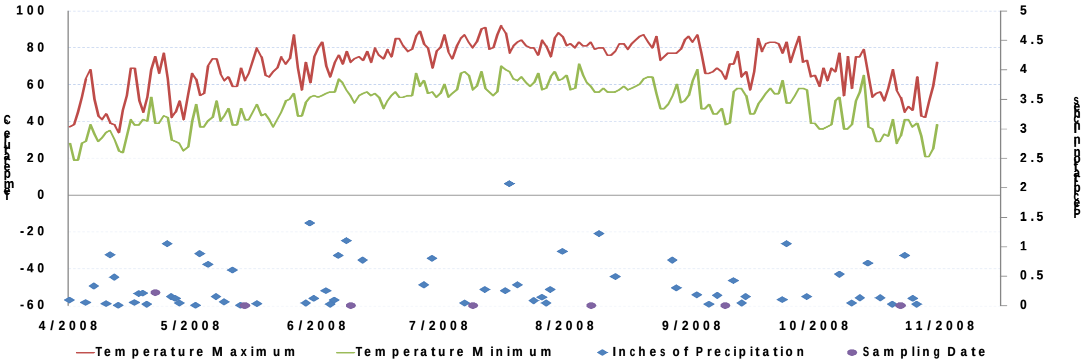


Figure 8. 2008 Minnesota water year precipitation and departure from normal

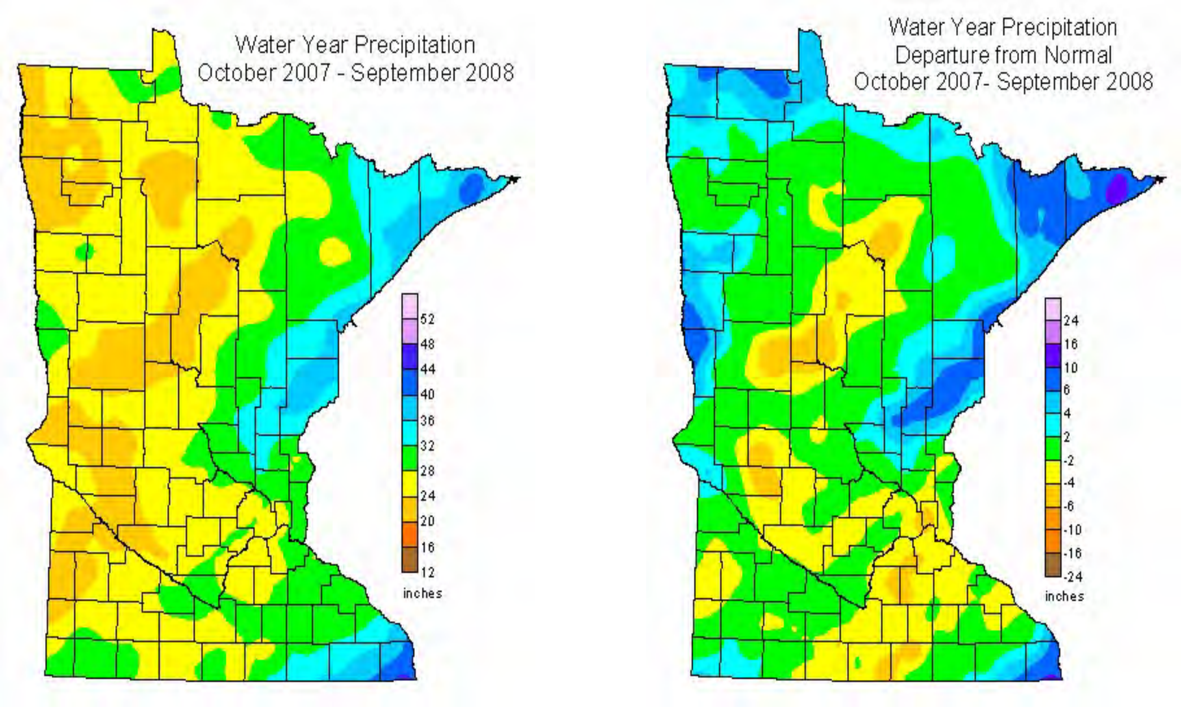
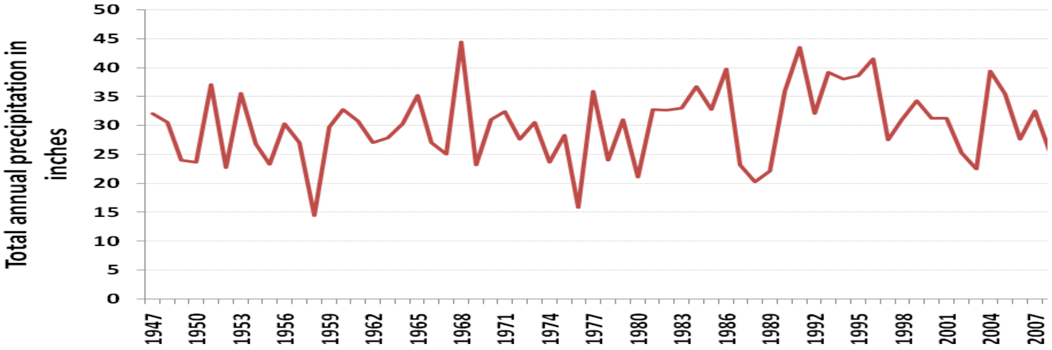


Figure 9. Long-term precipitation trends



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 approximately 1 meter (m), then 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). Most recent MDNR Fisheries surveys follow guidelines outlined by DNR Special Publication 147 (MDNR 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

The MDNR, MPCA and volunteers going back to 1947 have collected water quality data for Madison Lake. In 2008, the lake was monitored monthly by the MPCA staff, as well as additional field observation, by the Citizen Lake Monitoring Program (CLMP) volunteer, Curt Kloss. Lake surface samples were collected by MPCA staff with an integrated sampler, a polyvinyl chloride 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 micrometer mesh Wisconsin zooplankton net. Phytoplankton (algae) samples were taken with an integrated sampler. Depth total phosphorous (TP) samples were collected with a Kemmerer sampler. Temperature and dissolved oxygen (DO) profiles and Secchi disk transparency measurements were also taken. Samples were collected at site 201 (Figure 15). Sampling procedures were employed as described in the MPCA Standard Operating Procedure for Lake Water Quality document, which can be found here: http://www.pca.state.mn.us/publications/wq-s1-16.pdf.

In 2006, Madison Lake was part of a targeted study that assessed blue-green algal toxins and water quality data from 12 eutrophic to hypereutrophic lakes in south central Minnesota. This report can be found at http://www.pca.state.mn.us/publications/reports/wq-lar3-11.pdf.

Laboratory analysis for all MPCA monitoring was performed by the laboratory of the Minnesota Department of Health (MDH) 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). MC samples underwent a triple freezing cell lysis procedure. The MC analysis conducted for this study is summarized as a quantification of microcystin congeners including nodularins. It has an assay method maximum quantifiable range of five µg/L, which requires dilution of samples when concentrations are above this range. This can result in reduced accuracy depending on the amount of dilution. Phytoplankton samples were analyzed at the MPCA using a rapid assessment technique.

Table 3. MDH Laboratory methods and precision estimates

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. Two replicate vertical tows were taken 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

MDNR fisheries managers utilize netting survey information to assess the status of fish communities and measure the efficacy of management programs. Presence, absence, abundance, physical condition of captured fishes, and community relationships among fish species within survey catch information provide good indicators of current habitat conditions and trophic state of a lake (Schupp and Wilson, 1993). These data are stored in a long-term fisheries survey database, which has proven valuable in qualifying and quantifying changes in environmental and fisheries characteristics over time.

Due to a relatively direct connection to the Le Sueur River, the fish community of Madison Lake comprises a number of riverine species (Table 4). Past fisheries surveys and commercial fishing records that document abundant populations of many of these species, combined with a water control structure at the lake's outlet that impedes fish movement, suggest Madison harbors self-sustaining populations of several of these species within the lake. For example, the gizzard shad (*Dorosoma cepedianum)* were first detected in 1970, but it is assumed they migrated up from the Le Sueur River during the flood of 1965. They have since been self-sustaining and Madison is the only inland lake in Minnesota to support the species. Gizzard shad are important forage species for sustaining predators in large rivers, but they can have harmful effects on lake habitats and native fish communities if they displace native prey species. Specifically, gizzard shad can quickly outgrow the mouth (gape) size of juvenile largemouth bass (*Micropterus salmoides)*, thus affecting largemouth bass recruitment (Garvey and Stein 1998). Because there are numerous other prey species present in Madison Lake, gape-limitation may not be a limiting factor for juvenile largemouth bass. Still, through their prolific reproduction and omnivorous feeding habits and subsequent excretion, they can mobilize nutrients previously "locked up" and make them available for algae growth (Schaus et al. 1997). Common carp (*Cyprinus carpio*), which are also abundant in the lake, similarly impact water quality and aquatic plants through their feeding and spawning activities (Lougheed et al. 1998, Jackson et al. 2010). Thus these species indirectly influence lake species dependent on aquatic plants such as northern pike (*Esox lucius)*, bass (*Morone chrysops, Micropterus salmoides*), and bluegill (*Lepomis macrochirus*).

Turbid water, sparse summer aquatic plant growth, and a warming climate likely favors continued persistence of gizzard shad and other river species in Madison. If future efforts to reduce nutrient loading are successful at improving water clarity and aquatic plant growth throughout the year (e.g., reductions in curly-leaf pondweed and increases in native plants that grow all summer), the relative contribution of river species in surveys should decline in favor of more abundant populations of traditional lake species such as northern pike, largemouth bass, and bluegill. However, despite the harmful impacts of curly-leaf pondweed (*Potamogeton crispus*) on water quality and native aquatic plants (see Aquatic Plant Assessment), in the absence of other aquatic plant cover, curly-leaf pondweed seems to provide an important surrogate for habitat for northern pike, largemouth bass, and bluegill. These species are not likely to persist if curly-leaf pondweed is eliminated without the replacement of other aquatic plant species.

Despite a diverse community of non-game river fish, the lake has a relatively species-poor community of lake species when compared with clearer lakes in central and northern Minnesota; however, the lake is of average diversity when compared with other productive southern Minnesota lakes. Index of biotic integrity (IBI) scores in Madison Lake in 2008 and 2009 were 45 and 46 respectively (out of a maximum of 160). The lake harbors many species considered "tolerant" to pollution such as carp and black bullhead, and likely no species considered intolerant (Table 4). Iowa darter (*Etheostoma exile*), an intolerant species more common to lakes with high water quality and aquatic plants, were believed to have been sampled in 1985; however, IBI surveys in 2008 and 2009 that targeted nearshore habitats failed to detect this species, suggesting the species was either misidentified in 1985, exists at undetectable population levels, or has been extirpated.

Table 4. Percent frequency of occurrence of aquatic plant species at depths ≤ 15 feet sampled during point-intercept surveys competed 11 August 2008 and 29 June 2009 on Madison Lake, Blue Earth County, MN. Thermal guilds were classified by Lyons et al. (2009) and environmental tolerances were categorized by Drake and Pereira (2002).

Common name	Species name	Habitat guild	Trophic guild	Thermal guild	Environmental tolerance	First documented
Bluegill sunfish	*Lepomis macrochirus*	Lake	Insectivore	Warm	Neutral	1920
Emerald shiner	*Notropis atherinoides*	Lake	Insectivore	Warm	Neutral	1955
Golden shiner	*Notemigonus crysoleucas*	Lake	Insectivore	Warm	Neutral	1947
Green sunfish	*Lepomis cyanellus*	Lake	Insectivore	Warm	Neutral	1947
Iowa darter	*Etheostoma exile*	Lake	Insectivore	Warm	Intolerant	1985
Johnny darter	*Etheostoma nigrum*	Lake	Insectivore	Cool-warm	Neutral	1982
Logperch	*Percina caprodes*	Lake	Insectivore	Warm	Neutral	2008
Pumpkinseed sunfish	*Lepomis gibbosus*	Lake	Insectivore	Warm	Neutral	1947
Spottail shiner	*Notropis hudsonius*	Lake	Insectivore	Warm	Neutral	1974
Yellow perch	*Perca flavescens*	Lake	Insectivore	Cool-warm	Neutral	1913
Black bullhead	*Ameiurus melas*	Lake	Omnivore	Warm	Tolerant	1947
Bluntnose minnow	*Pimephales notatus*	Lake	Omnivore	Warm	Neutral	2008
Brown bullhead	*Ameiurus nebulosus*	Lake	Omnivore	Warm	Neutral	1947
Fathead minnow	*Pimephales promelas*	Lake	Omnivore	Warm	Tolerant	1947
White sucker	*Catostomus commersonii*	Lake	Omnivore	Cool-warm	Tolerant	1948
Yellow bullhead	*Ameiurus natalis*	Lake	Omnivore	Warm	Neutral	1947
Black crappie	*Pomoxis nigromaculatus*	Lake	Predator	Warm	Neutral	1913
Bowfin	*Amia calva*	Lake	Predator	Warm	Neutral	1947
Largemouth bass	*Micropterus salmoides*	Lake	Predator	Warm	Neutral	1918
Northern pike	*Esox lucius*	Lake	Predator	Cool-warm	Neutral	1933
White Crappie	*Pomoxis annularis*	Lake	Predator	Warm	Neutral	1947
Common carp	*Cyprinus carpio*	Lake/River	Omnivore	Warm	Tolerant	1947
Walleye	*Sander vitreus*	Lake/River	Predator	Cool-warm	Neutral	1910
Bigmouth Buffalo	*Ictiobus cyprinellus*	River	Insectivore	Warm	Neutral	1947
Creek chub	*Semotilus atromaculatus*	River	Insectivore	Cool-warm	Tolerant	2008
Quillback	*Carpiodes cyprinus*	River	Insectivore	Warm	Neutral	1982
Freshwater drum	*Aplodinotus grunions*	River	Omnivore	Warm	Neutral	1947
Gizzard shad	*Dorosoma cepedianum*	River	Omnivore	Warm	Neutral	1970
Paddlefish[a]	*Polydon spathula*	River	Planktivore	Warm	Intolerant	1960
Channel catfish	*Ictalurus punctatus*	River	Predator	Warm	Neutral	1974
Longnose gar	*Lepisosteus osseus*	River	Predator	Warm	Neutral	1955
Shortnose gar	*Lepisosteus platostomus*	River	Predator	Warm	Neutral	1947
White bass	*Morone chrysops*	River	Predator	Warm	Neutral	1947

[a] Likely an ancient holdover from a pre-1918 migration that became landlocked. A commercial, anecdotally noted population existed prior to 1918. It is highly unlikely that Madison harbors a self-sustaining population of paddlefish today.

Fish species assessments

Gabelhouse (1984) established a length-categorization system to assess fish stocks, the proportional stock density (PSD), which measures the proportion of fish at young stock size, and relative stock densities (RSD), which measure fish proportions at larger sizes grouped into preferred (P), memorable (M), and trophy (T). Consult Figure 10 for a summary of historical catches of each major species documented in Madison Lake over its surveyed history.

Madison Lake black crappie (*Pomoxis nigromaculatus)* abundance declined since the 2008 assessment from 46.73 fish per gill net to 21.92, below the long-term average. Mean size increased since 2008, in typical inverse proportionality to decreased net catches; at this time mean size is larger than the long-term average. Seventy-four percent of black crappie sampled were at or above stock size, while 13 percent were larger than the preferred length of 25.4 cm (10 inches).

White crappie exhibit more irregular trends in abundance in Madison Lake. While white crappie (*Pomoxis annularis*) abundance is diminishing in historical contrast to black crappie in area lakes and within lakes of the same lake class, white crappie populations on Madison appear stable. If population trends from the last twenty years continue, Madison Lake white crappie should see a short-term population spike in coming years. Average size is fair, at around four to the pound. Sixty percent of white crappie sampled were at or above stock size, while 10 percent were larger than the preferred length of 25.4 cm (10 inches).

Yellow perch **(***Perca flavescens*) in Madison Lake fill a role as a forage species rather than as an established and sought after game fish species. Average size is small by angling standards; only 15 percent of yellow perch sampled were at or above a stock size and no fish were sampled above the preferred length of 25.4 cm (10 inches). Recruitment of yellow perch is often highly variable from year to year. Although yellow perch are highly important for game fish in many Minnesota lakes, Madison Lake has several other forage species present in the lake (e.g., bluegill, gizzard shad, freshwater drum, black bullhead, minnows). Consequently, the probability that predators in the lake will frequently encounter suitable-sized prey during foraging bouts is high.

Bluegill abundance trends over the netting history of Madison Lake show a rising and falling oscillation. Abundance declined from 2008 to 2009, and if historical netting trends continue, abundance should bottom out soon and then sharply rise. Fish average four to a pound; 74 percent of bluegill sampled were at or above stock size, while 2 percent were larger than the preferred length of 8 inches. Most fish are in the five to seven inch range.

Largemouth bass showed good distribution of sizes. A historical record is incomplete, as electrofishing has only recently been used as a more effective sampling gear than passive net gears. The 2009 catch was 50 fish, nearly identical to the 2008 catch of 48 fish. Total weight and pounds per hour on time was roughly double in 2009 compared to 2008. Length frequency tables are nearly identical; the large average fish size and weight per unit effort in 2009 is likely explained by the capture of six individuals larger than 17 inches total length compared to none in 2008. Forty-eight percent of largemouth bass sampled were at or above stock size, 26 percent were at or above the preferred size of fifteen inches, and 4 percent were at or above the memorable size of twenty inches.

Common carp abundance has been variable across time and most individuals are relatively large. All fish sampled in gill nets in 2009 were larger than the stock size of 40.6 cm (16 inches), 37 percent were larger than the preferred length of 53 cm (21 inches), and 11 percent were larger than the memorable size of 66 cm (26 inches). Significant new carp recruitment to Madison Lake may occur from connected lakes or backwaters following a winterkill (Bajer and Sorensen 2009). Carp biomass in Madison Lake has been sufficiently high to support a viable commercial fishery (Figure 11). Harvest of carp by commercial fishers over time has been opportunistic and dependent on commercial markets but has averaged 14,061 kg (31,000 lbs) since 1980. Trends (or lack thereof) in harvest may have more to do with market conditions than changes in populations.

White bass in Madison do not seem to exhibit the periodic population booms observed in other southern Minnesota lakes where the species is present. In the nearby Cannon River system of connected lakes, white bass can make up the majority catch by abundance and biomass. In Madison, net catches of white bass are low, averaging less than one fish per net. Most net catches are too low to characterize the size distribution of fish.

Black bullhead (*Ameiurus melas*) abundance in the last twenty-five years has been at average levels compared with other similar lakes. The long-term gill net average is 10.81. Black bullhead in Madison Lake, have a relatively large size structure. Ninety Seven percent of black bullhead were larger than the stock size, 45 percent were larger than the preferred size of 12 inches, and 2 percent of the catch were in the memorable size of 15 inches.

Yellow bullheads (Ameiurus natalis) have, in the last decade, been detected at very low levels, below the long-term average of two fish per gill net. Size trends are stable; most fish are in the 25.4 to 35.6 cm (10 to 14 inch) range. All fish sampled in 2009 were larger than the stock size and 55 percent were larger than the preferred size of 30.5 cm (12 inches).

The northern pike population has been relatively stable at low levels in the last twenty five years, adhering closely to a long-term average of three fish per gill net; however, northern pike average size has been large since gizzard shad became established in the lake. Eighty-six percent of pike sampled in 2009 were larger than the stock size of 53.3 cm (21 inches), 54 percent of pike were larger than the preferred size of 71 cm (28 inches), and 14 percent were larger than the memorable size of 86.4 cm (34 inches). In the last two years of SLICE gill netting, a few fish approaching the 102 cm (40 inch) range were caught. Despite supporting trophy-sized northern pike, low overall abundance (and likely low catch rates) limits the recreation potential of a northern pike fishery.

Walleye (*Sander vitreus*) continue to be the management emphasis on Madison Lake. Abundance trends for walleye have been stable, with a long-term average around seven fish per gill net, which is in the upper quartile for class 24 lakes. Walleye in Madison are generally in the angler’s preferred slot length, from 51 cm (20 inches) and beyond. Ninety-five percent of walleye are larger than stock size of 38 cm (15 inches), 60 percent of walleye are larger than the preferred size of 51 cm (20 inches), and 12 percent are in the memorable size, greater than 64 cm (25 inches).

The upshot from the assessment of the fish community in Madison Lake is that game fish production (i.e., size and abundance) is relatively high despite relatively poor water quality conditions. River forage species that are adapted to turbid water conditions, combined with cover provided by curly-leaf pondweed seem to be important for sustaining quality populations of game fish. Improvements to water quality and native aquatic plants may lead to a decline in the biomass of river species and an increase in the biomass of lake species. It is unclear whether this change will have a net gain on game fish size and abundance in the lake. Long-term monitoring will be important to assess future trends in water quality, aquatic plants, and fish communities.

Figure 10. Historical net summary of catches in summer gillnets (GN) or trapnets (TN).

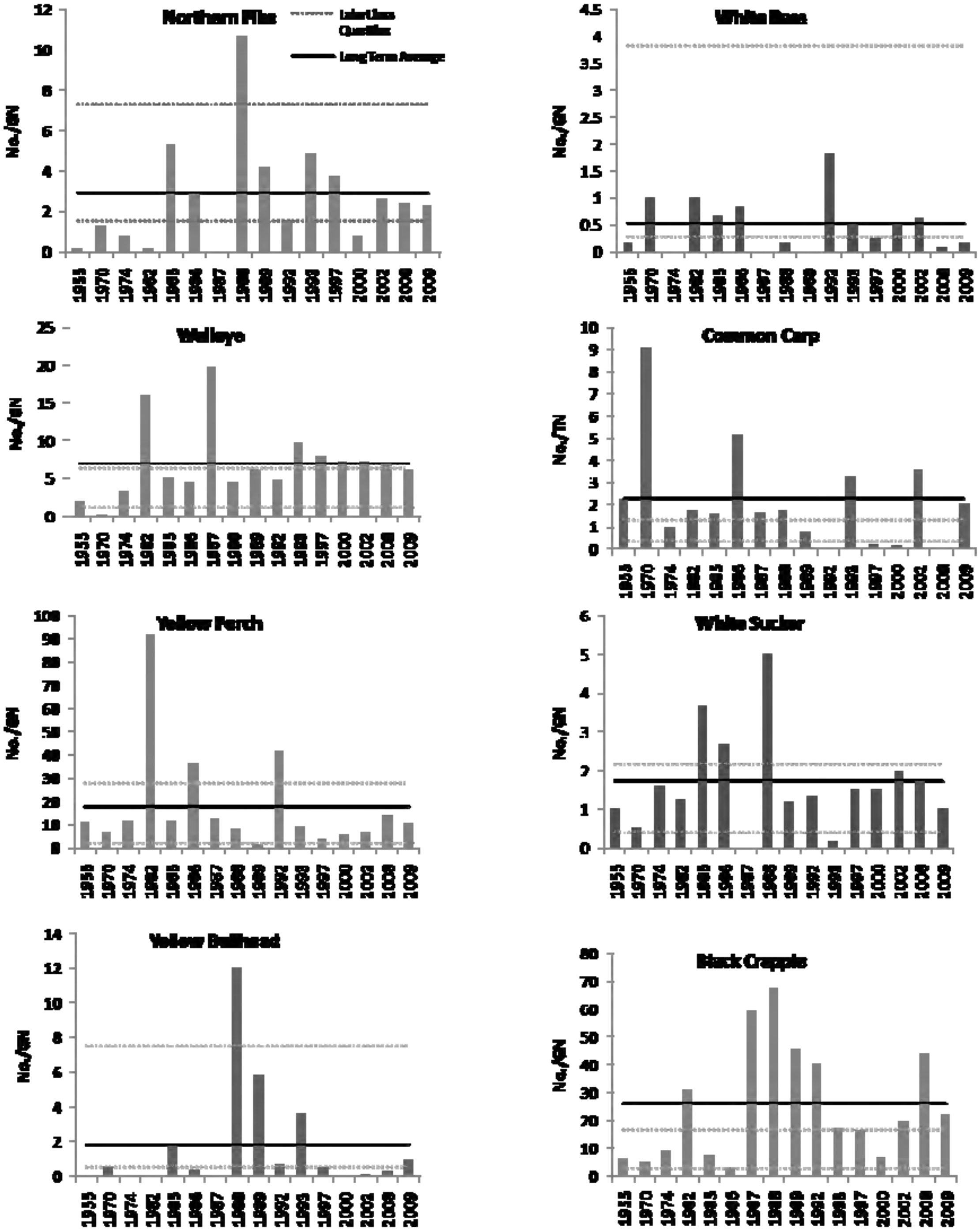


Figure 10. continued

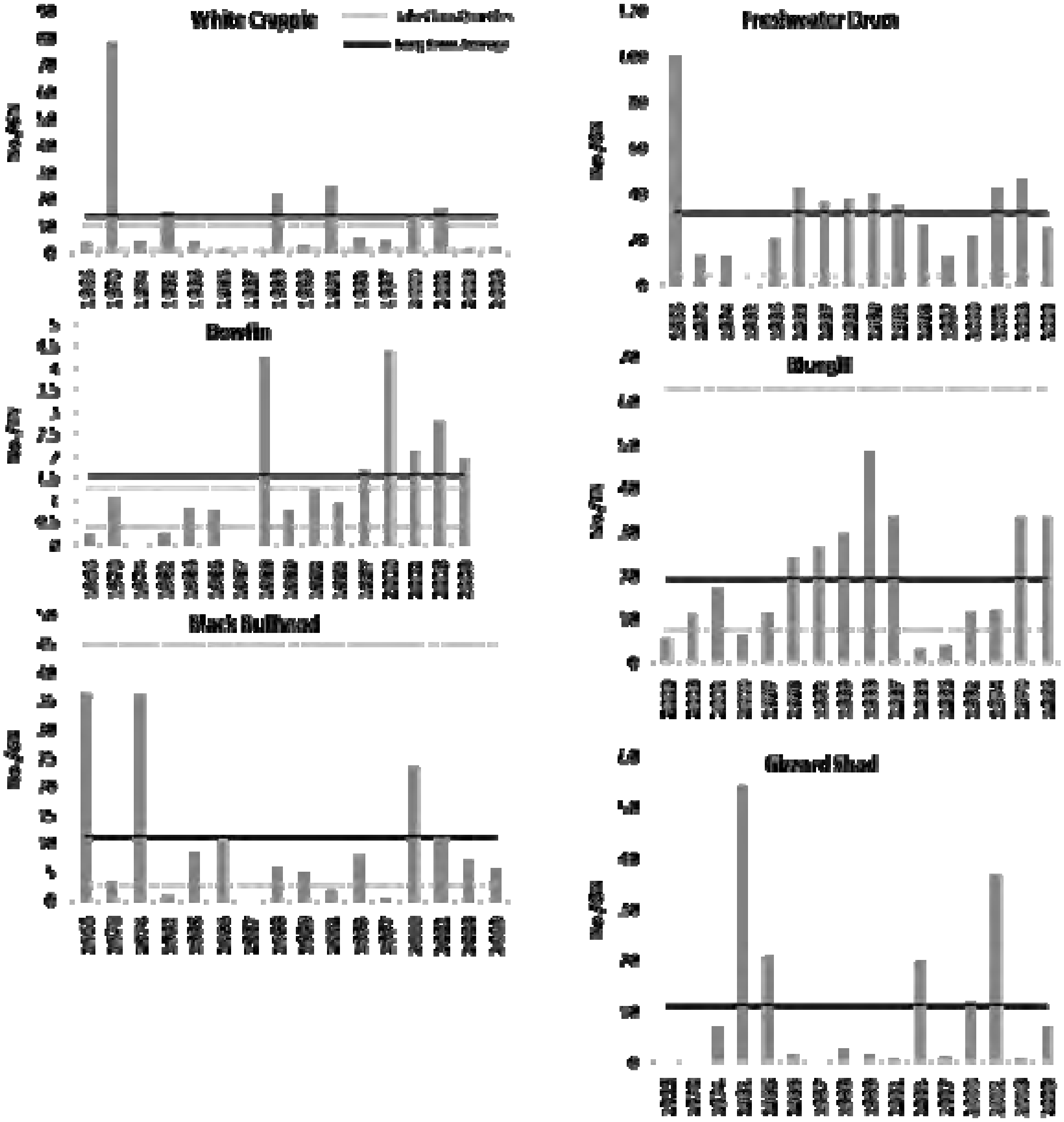
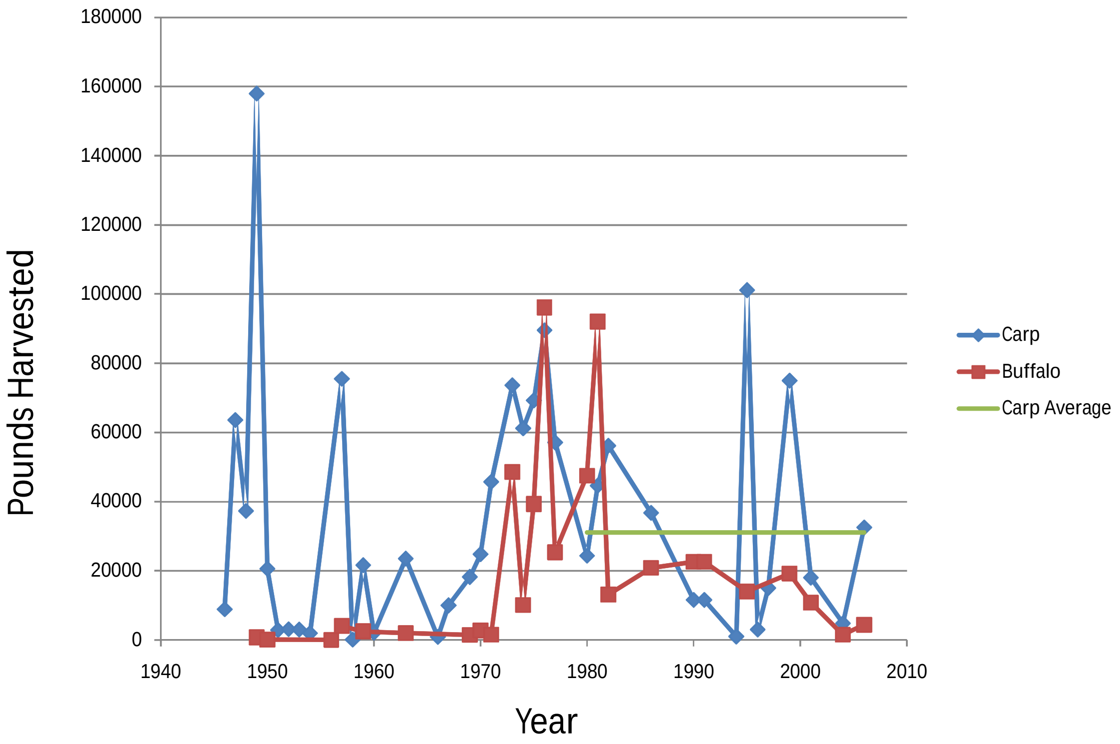


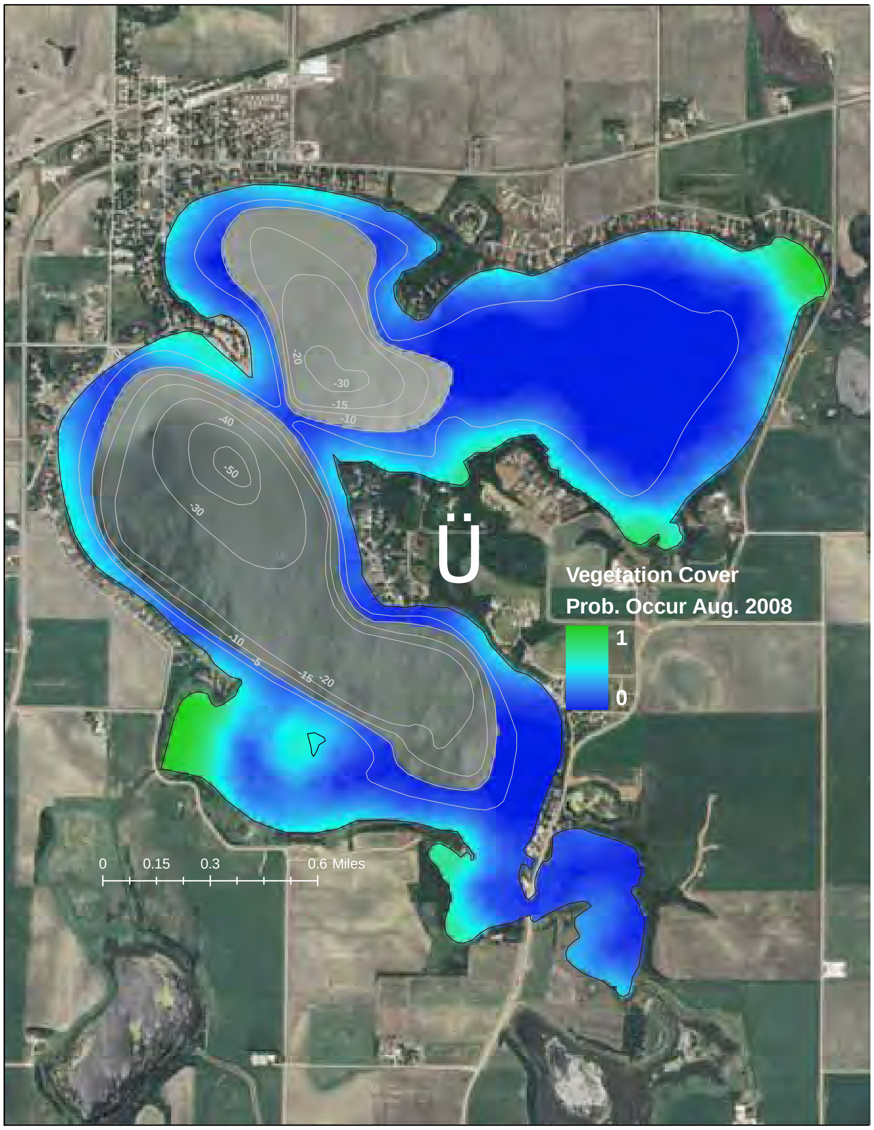
Figure 11. Pounds of carp and buffalo (*Ictiobus cyprinellus*) commercially harvested or removed by contractors or MDNR over time



Aquatic Plant Assessment

Emergent and submersed aquatic plants were rare in the August 2009 survey (Figure 12) and have been rare throughout the surveyed history of Madison Lake. Initial surveys in 1947 documented sparse aquatic plant growth due to carp activity but still noted that coontail (*Ceratophyllum demersum*), Canada waterweed (*Elodea canadensis*), and sago pondweed (*Stuckenia pectinata*) occurred at some frequency. Other common species noted in successive surveys included the invasive curly leaf pondweed (*Potamogeton crispus*; discussed in more detail below), and northern watermilfoil (*Myriophyllum sibiricum).* Emergent species such as bulrush (*Scirpus* spp.) and cattail (*Typha* spp.) have always been present, but sparse.

Figure 12. Probability of occurrence of aquatic vegetation in Madison Lake estimated using indicator kriging on point-intercept plant survey data from 11 August 2008.



Today, the aquatic plant community in Madison is relatively species-poor compared with less disturbed lakes in non-agricultural or urban areas, but is quite typical of nutrient-rich lakes in the WCP ecoregion. No species had summer frequencies of greater than 10% (Table 5). Still, the lake supports some muskgrass or *Chara* sp., which is a benthic plant that is highly desirable from a fish habitat and water quality standpoint and somewhat rare in lakes as productive as Madison. Besides offering quality physical habitat for fish, muskgrass is an important plant for maintaining clear water. In turn, clear water promotes muskgrass (Kufel and Kufel 2002; Ibelings et al. 2007); however, mechanisms reinforcing Madison's poor water quality regime including curly-leaf pondweed, carp, and gizzard shad will likely continue to overwhelm any positive benefits of muskgrass.

Table 4. Percent frequency of occurrence of aquatic plant species at depths ≤ 15 feet sampled during point-intercept surveys competed 11 August 2008 and 29 June 2009 on Madison Lake, Blue Earth County, MN.

Common name	Species name	Growth form	Frequency (%)	
			2008	2009
All rooted plants			24.7	58.8
Muskgrass	*Chara sp.*	Submersed	9.1	8.5
Sago pondweed	*Stuckenia pectinata*	Submersed	8.6	10.9
Filamentous algae			6.1	9.1
Coontail	*Ceratophyllum demersum*	Submersed	5.6	6.1
Northern watermilfoil	*Myriophyllum sibiricum*	Submersed	5.3	4.6
Bushy pondweed	*Najas flexilis*	Submersed	4.2	1.5
Clasping-leaf pondweed	*Potamogeton richardsonii*	Submersed	3.9	1.3
Curly-leaf pondweed[a]	*Potamogeton crispus*	Submersed	2.3	43.7
Canada waterweed	*Elodea canadensis*	Submersed	2.3	0.5
Floating-leaf pondweed	*Potamogeton natans*	Floating-leaf	1.6	0
Greater duckweed	*Spirodela polyrhiza*	Free Floating	0.9	0
Water star-grass	*Heteranthera dubia*	Submersed	0.8	0
Cattail group	*Typha sp.*	Emergent	0.6	0.2
River bulrush	*Scirpus fluviatilis*	Emergent	0.5	0
Lesser duckweed	*Lemna minor*	Free Floating	0.3	1.5
Hardstem bulrush	*Scirpus acutus*	Emergent	0.3	0.2
Star duckweed	*Lemna trisulca*	Submersed	0.2	0
Softstem bulrush	*Scirpus validus*	Emergent	0.2	0
Burreed group	*Sparganinm sp.*	Emergent	0.2	0
Water moss	*Drepanocladus sp.*	Free Floating	0	1.2
Small pondweed	*Potamogeton pusillus*	Submersed	0	6.6
Naiad group	*Najas sp.*	Submersed	0	0.2

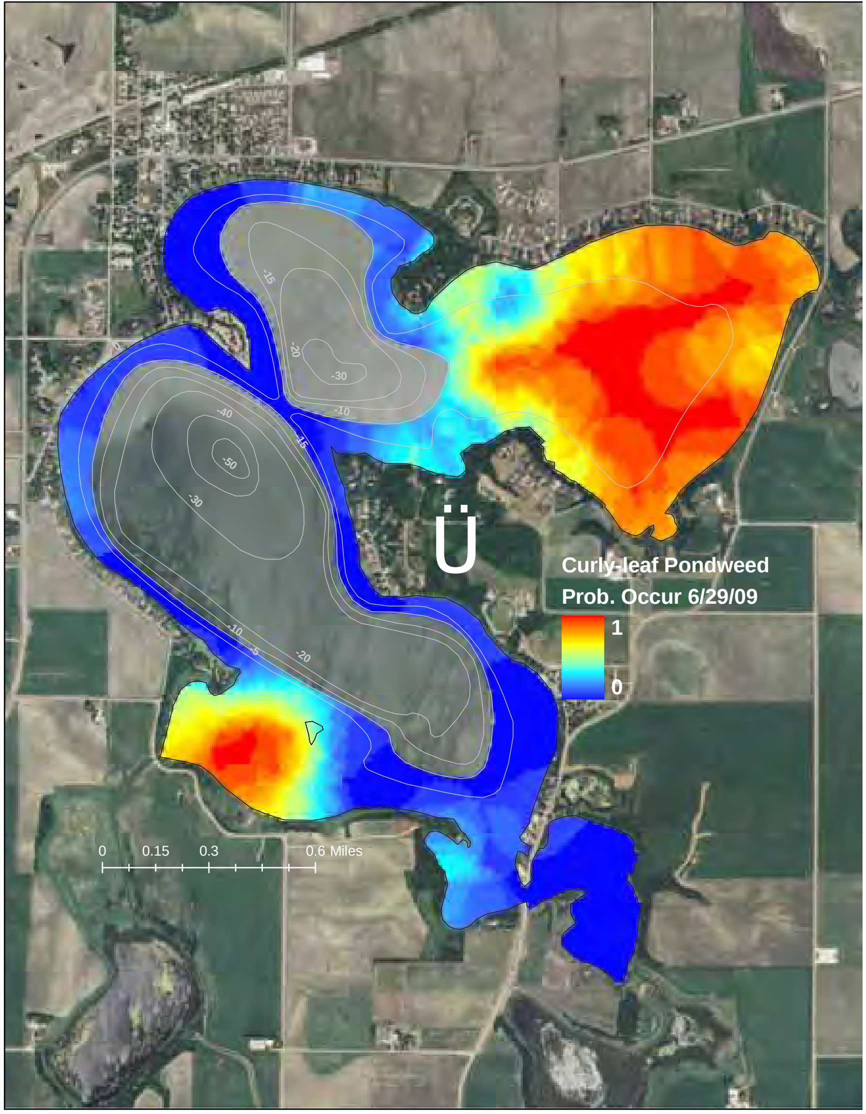
Curly-leaf pondweed

In 1970, the invasive curly-leaf pondweed was first noted and has been a common species observed ever since. Curly-leaf pondweed is a non-native invasive submerged aquatic plant that is widespread throughout the southern part of the state. The exact date of introduction into Minnesota is unknown, but it is believed to have been present in Minnesota lakes since the early 1900's 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 nutrients (exact quantity unknown), can 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. Curly-leaf pondweed (Figure 13) cover was assessed on June 29, 2009 (Figure 14) during point-intercept vegetation surveys. Although, this date was past peak abundance, plant stems were still present at presumably all colonized areas thus areal cover could be quantified. Estimates from kriging interpolation (Isaaks and Srivastava 1989) of point-intercept sample data predicted that curly-leaf pondweed covered 408 acres (28%) less than 25.4 (10 feet) in Madison Lake (e.g., area of 15-m grid cells with probability of occurrence ≥ 0.5; Fig. 14). Most of this growth occurred in the northeast and southwest areas of the lake. Surveys in August of the year before, demonstrate an absence of plants and lower overall cover (83 acres) of aquatic plants after senescence of curly-leaf pondweed (Figure 12). Given the high cover and abundance of curly-leaf pondweed, and algae blooms that follow senescence, Madison may have already crossed a threshold that will make improvements to water clarity quite difficult.

Figure 13. Curly-leaf pondweed photo from the northeast basin June 2006

Figure 14. Probability of occurrence of curly-leaf pondweed in Madison Lake estimated using indicator kriging on point-intercept plant survey data from 29 June 2009.



Summary of nearshore human impacts on aquatic plant communities

Historical lake surveys often documented that removal of emergent vegetation by recently developed shorelines was common and impacting nearshore habitats; however, actual losses have not been documented over time.

Approximately 200 dock structures were enumerated from aerial photos acquired from the Farm Service Administration in summer 2008 (one dock for every 100 m of shoreline). By rule, lakeshore owners are allowed to remove a 232 square meter (2500 square foot) area of submersed aquatic plants without a permit. If we assumed that all who owned a dock also removed 232 square meter (2500 square foot) of aquatic plants, then the lakeshore owners have the option to remove up to 2.6 hectares (6.5 acres) aquatic plants (1.5% of the area of vegetation growth) without a permit. The actual amount of plant removal is probably less. Furthermore since 2004, only one lakeshore owner has been permitted to remove, using chemical herbicides, more vegetation than is already allowed without a permit. The cumulative removal allowed by these permits was only 0.16 hectares (0.4 acres). Consequently, current aquatic plant removal activities probably have a very small impact on fish habitat. Minimal removal of aquatic plants will be required for future gains in fish habitat in Madison Lake.

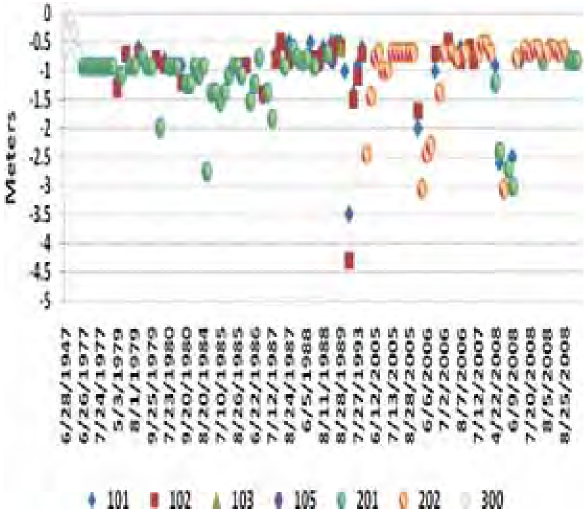
Water Quality

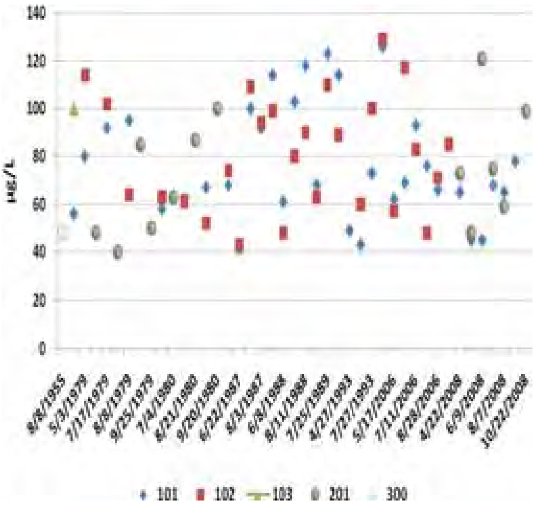
Sampling locations

Over the lake's history, several locations have been monitored for water quality (Figure 15). The majority of the monitoring has been done at two deep sites on the lake: sites 101, 202, 201 and 102. No apparent differences are noted in the transparency or TP among the different sampling sites (Figure 16 and 17). Based on this site comparison, additional water quality analysis in this report did not take site location into account.

Figure 15 Madison Lake monitoring locations

Figure 16. Madison Secchi transparency comparison among sites
Figure 17. Madison total phosphorus comparison among sites





2006 and 2008 summer mean values

Standard summer-mean water quality data for 2006 and 2008 are presented in Table 6, along with ecoregion ranges for many parameters (raw results are provided in Appendix A. In general, most water quality parameters indicate the lake is eutrophic and is typical for a lake within the WCP ecoregion. In recent years, as a part of the Sentinel lake monitoring and special studies, some additional quality parameters have been measured on Madison Lake including: dissolved minerals, organic carbon, and algal toxin.

Table 5. Madison Lake 2008 and 2006 water quality summer means (June – September) and ecoregion reference lake typical (IQ) range

Parameter	2006	2008	NCHF	WCBP
# of lakes			43	16
Total Phosphorus (µg/L)	80.8 ± 11	76.3 ± 5	23 – 50	65 - 150
Chlorophyll mean (µg/L)	47 ± 5	28 ± 7	5 – 22	30 - 80
Chlorophyll maximum (µg/L)	67	70.9	7 - 37	60 - 140
Secchi Disk (feet)	0.85 ± .06	1.3 ± 0.2	4.9 - 10.5	1.6 - 3.3
(meters)			(1.5 - 3.2)	(0.5 - 1.0)
Total Kjeldahl Nitrogen (mg/L)	1.8 ± 0.1	1.3 ± 0.14	< 0.60 - 1.2	1.3 - 2.7
Nitrite + Nitrate-N (mg/L)	-	0.37 ± 0.05	<0.01	0.01 - 0.02
Alkalinity (mg/L)	144 ± 2	140 ± 10	75 - 150	125 - 165
Color (Pt-Co Units)	18 ± 2	20 ± 0	10 - 20	15 - 25
pH (SU)	8.7 ± 0.1	8.4 ± 0.1	8.6 - 8.8	8.2 - 9.0
Chloride (mg/L)	20.6 ± 0.2	24 ± 0.1	4 - 10	13 - 22
Total Suspended Solids (mg/L)	10.0 ± 1	7.6 ± 2.4	2 - 6	7 - 18
Total Sus. Inorganic Solids (mg/L)	2.1 ± .04	2.8 ± 0.06	1 - 2	3 - 9
Conductivity (µmhos/cm)	267.5 ± 67	323 ± 21	300 - 400	300 - 650
Total nitrogen:Total phosphorus ratio	-	-	25:1 - 35:1	17:1 - 27:1
Pheophytin mg/L	8.8 ± 2	4.7 ± 1.5	-	-
Pheophytin %	17 ± 4		-	-
Temperature (C°)	23.3 ± 1.3	18.4 ± 2.1	-	-
DO mg/L	8.6 ± 2.6	10 ± 0.5	-	-
Oxidation Reduction Potential ORP mV	270 ± 31	317 ± 31	-	-

Temperature stratification

Temperatures profiles (measurements taken at 1 meter increments) help depict thermal stratification (temperature change with depth). Thermal stratification, or lack of, can have a significant effect on lake water quality. Temperature profiles from 2008 at site 201show a slight thermocline (zone of maximum temperature change) present in early July that increased in depth through August (Figure 18 and 19). The thermoclines observed in 2008 began in 7.5 meters at site 201. In 2006, a distinct thermocline was present in mid-June beginning at about 9.5 meters of depth. Temperature stratification was observed at site 201in 2006 from June- September with peak thermocline observed on August 7 (temperatures ranged 7°C between 6 and 10 meters of depth). In general, 2006 water temperatures were warmer in spring/early summer compared to 2008. This allowed for deeper and longer period of stratified conditions. This comparison for 2006 and 2008 indicates that stratification patterns may vary from year to year in Madison Lake, likely as a function of air temperature, wind intensity, direction and other climate factors.

Figure 18. 2006 and 2008 temperature profiles

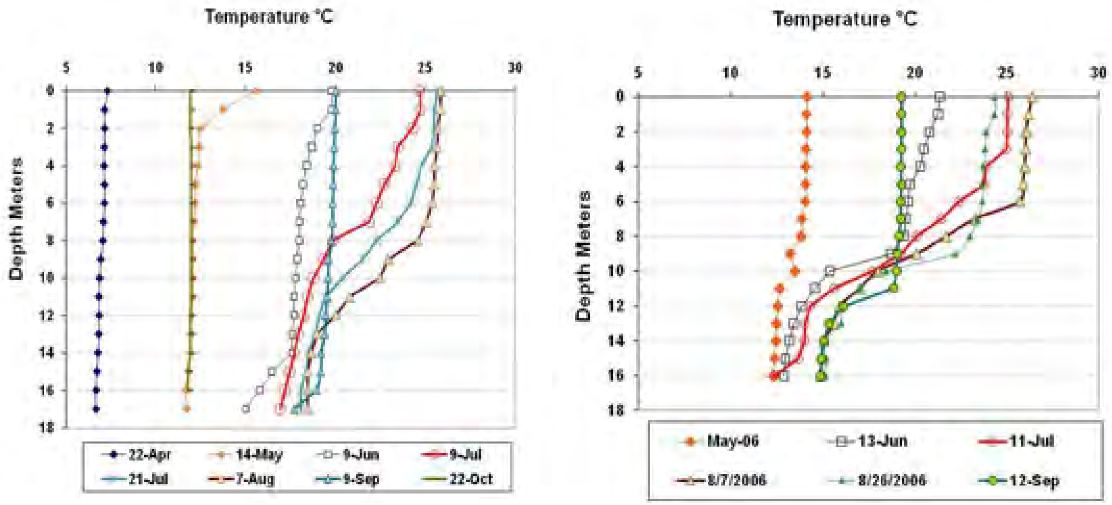
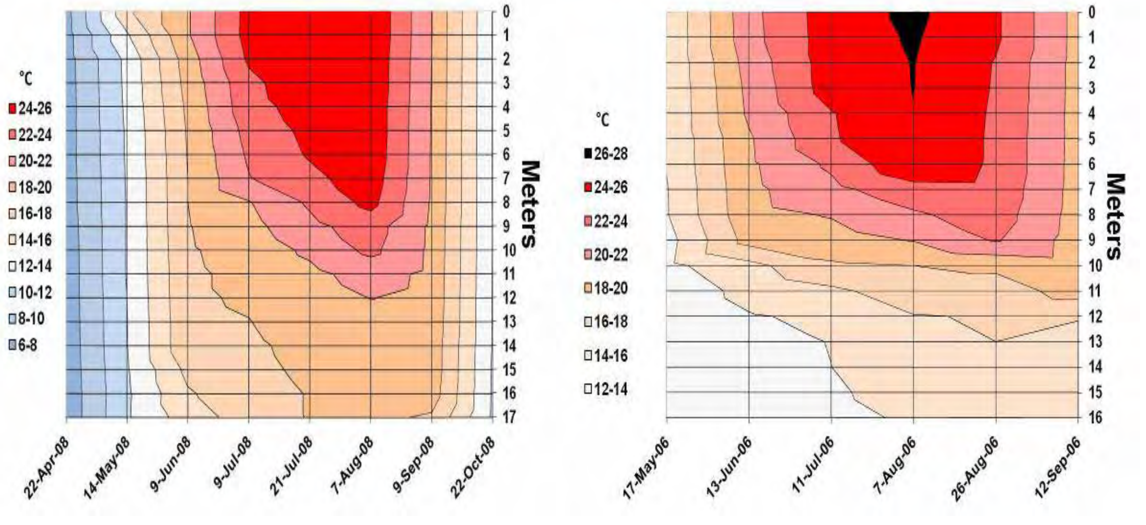


Figure 19 2006 and 2008 interpolated temperature isopleths



Dissolved oxygen stratification

In 2008, DO levels were well-mixed through the water column in April and May (Figure 20 and 21). In early June 2008, DO declined with depth, reaching anoxic (≤ 2 milligrams per liter - mg/L) at about 15 meters (Figure 18 and 19). The hypoxic zone increased significantly by July, climbing to five meters from the surface. By September 2008, fall mixing was underway (Figure 18 and19) and DO was replenished throughout much of the bottom waters of the lake. In 2006, anoxic conditions were seen at each monitoring event from May through September. The increased extent and duration of the anoxic condition during 2006 was likely driven by the early onset and stability of the thermocline. Anoxic conditions accelerate the release of phosphorus into the water column from sediments. The comparison of the two years shows not only that the DO regime can vary from year to year (Figures 20 and 21) but also can change rather rapidly in response to mixing events (Figure 18 and 19).

Figure 20. 2006 and 2008 dissolved oxygen profiles

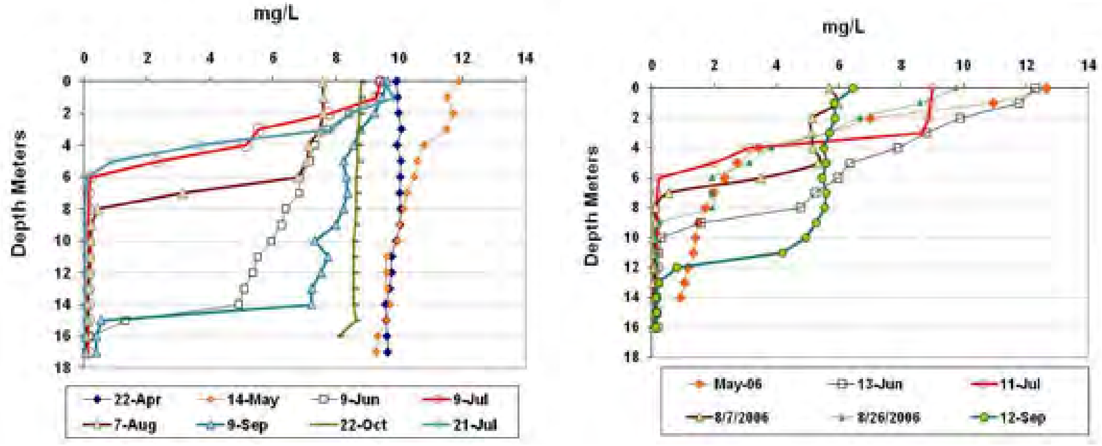
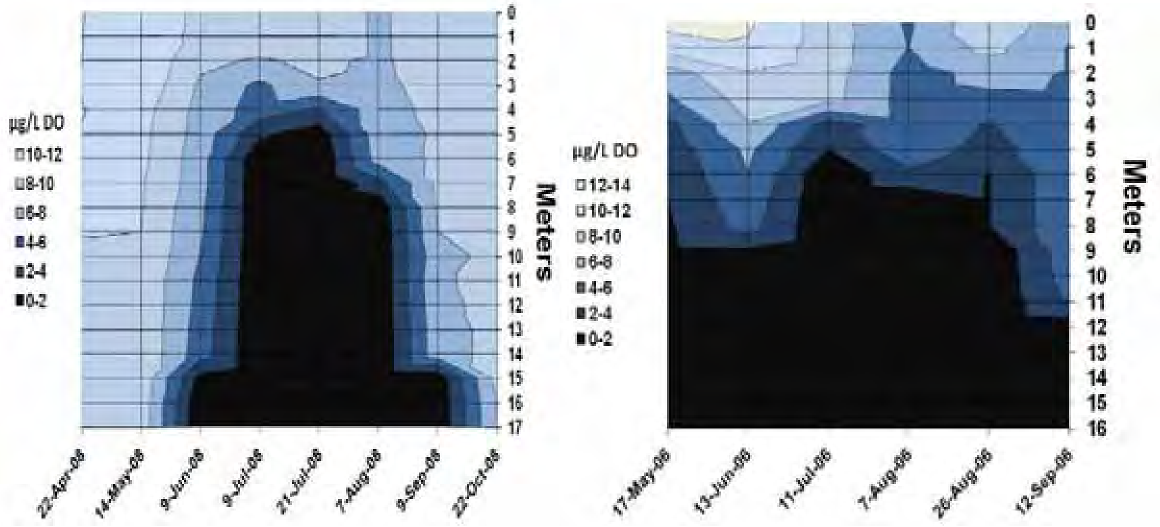


Figure 21. 2006 and 2008 interpolated dissolved oxygen isopleths



Total phosphorus

TP averaged above the NCHF ecoregion and within the WCBP ecoregion reference lake interquartile range (Table 6). TP was slightly higher (but not significantly different) in 2006 compared to 2008 (Figure 22). The seasonal TP trend was similar in 2006 and 2008 exhibiting midsummer decrease in surface TP as thermoclines developed (Figures 18 and 119). Another factor that may contribute to late summer increase of TP is the curly-leaf pondweed die-off (e.g. July 2006). Not only is TP released from decomposing curly-leaf pondweed, but sediments are less stable in the absence of curly-leaf pondweed. Increased in phosphorus below the thermocline was evident during both seasons as well (Figure 23). When stratification diminishes in fall, surface TP increased in both years as elevated hypolimnetic TP mixes with surface waters (Figure 23).

Chlorophyll-*a*

The summer averages during both monitoring seasons were within the interquartile range of the WCBP, but above the NCHF range. Chl-a levels correlated well with TP during both monitoring periods (Figure 22). During the warmer and more nutrient rich summer of 2006, chl-a levels were higher than 2008 (Figure 21). Nuisance blooms (chl-a >30 µg/L) were common in both summers, but most pronounced in 2006 (Figure 22).

Secchi disk transparency

Transparency depths correlated well with chl-a during both seasons (Figure 22) The 2008 transparency was notably deeper in May and June as compared to 2006. The higher transparency in 2008 was a function of lower chl-a (Figure 22). Several factors likely contributed to the lower chl-a including lower TP and extensive growth of curly-leaf pondweed. Curly-leaf pondweed provides refuge for zooplankton that feed on algae and serves to stabilize sediments, which may temporarily minimize internal P recycling.

Figure 22 Madison Lake 2008 and 2006 TP and chl-a concentrations, & Secchi depth

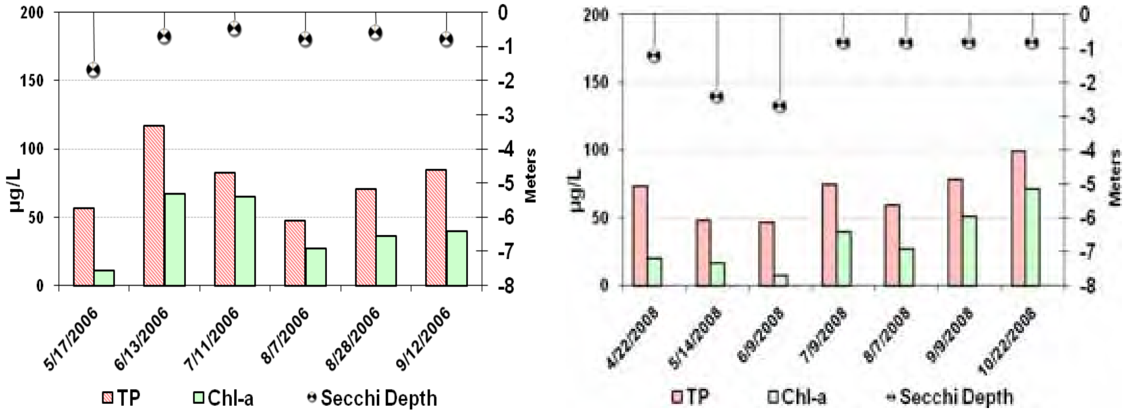
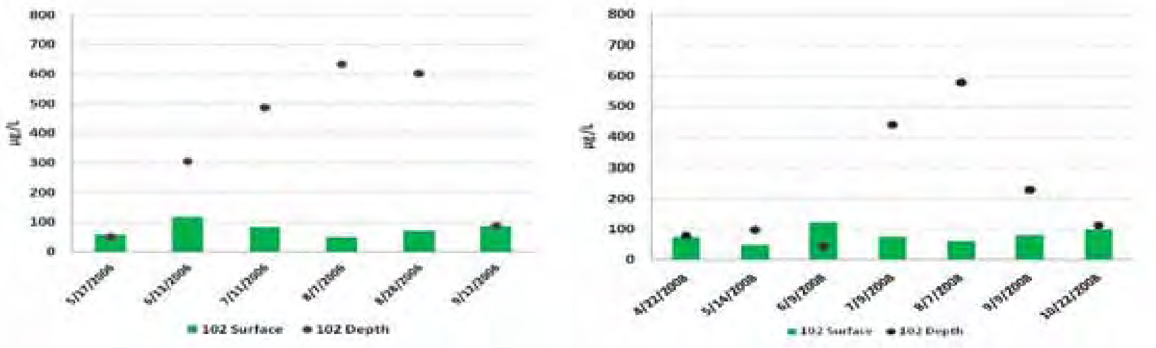


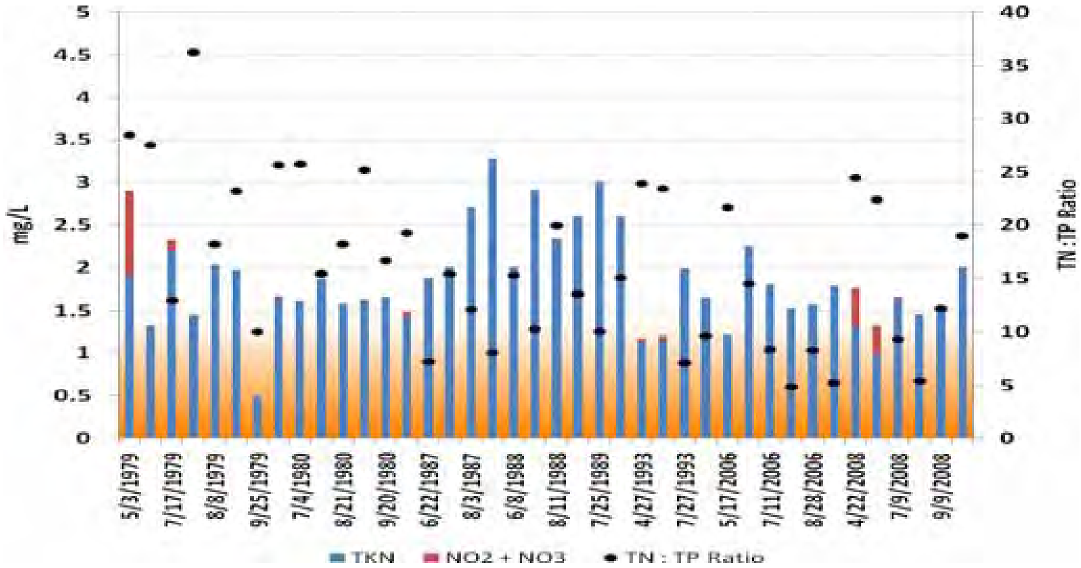
Figure 23 Madison Lake 2008 and 2006 surface and depth TP comparison



Nitrogen

Nitrogen is an essential for plant and algal growth and in some instances (e.g. when TP is very high) nitrogen may limit the growth of algae. There are several forms of N, but the most commonly measured are Total Kjeldahl Nitrogen (TKN) and nitrite + nitrate as nitrogen. The sum of these two measures is referred to as total nitrogen (TN). If the TN: TP ratio is greater than 10:1, TP tends to be the limiting nutrient, and if the TN: TP ratio is less than 5:1, nitrogen may be limiting (Chiaudani et al. 1974). The long-term TN:TP ratio of Madison Lake averaged 16.5:1 and based on 40 comparisons of TP and TN, indicate the lake is typically phosphorus limited. In recent years, TN: TP ratios have been lower, primarily as a result of reductions in TN, which raises the possibility of at least short-term N limitation (Figure 24).

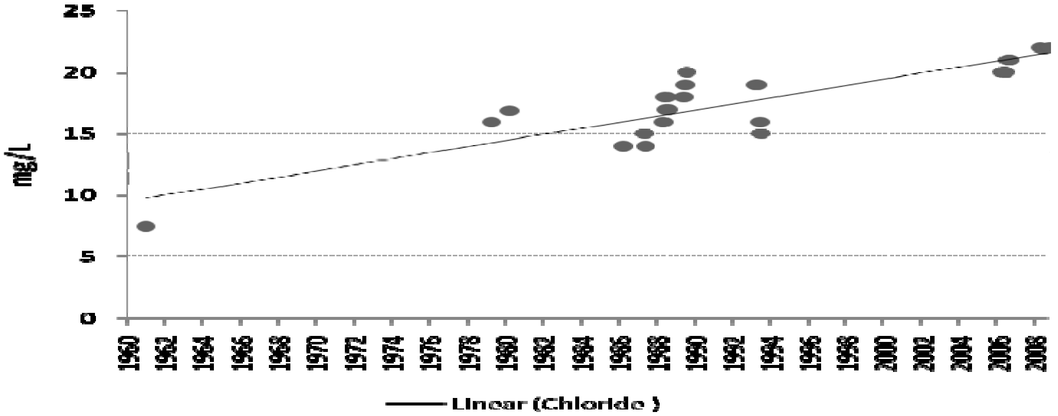
Figure 24. Long-term total nitrogen and TN : TP ratios for Madison Lake



Chloride

Chloride is considered a good indicator of anthropogenic impact on a lake. Road salt is often a large contributor to elevated chloride (Cl) in lakes. For example, Northern Lakes and Forests (NLF) ecoregion lakes with limited road networks and road salting in their watersheds often exhibit Cl on the order of 1-2 mg/L and NCHF reference lakes (outside of major metropolitan areas) are often in the 4-10 mg/L range. Based on data from 2006 and 2008 Cl is at or above the typical range for NCHF and WCBP lakes (Tale 6). Based on data from 1960-2008 Cl has increased over time (Figure 25).

Figure 25 Madison Lake long-term chloride measurements



Dissolved minerals and organic carbon

Dissolved minerals and organic carbon were measured in 2008 and 2009 as part of the long-term monitoring of Madison and other Sentinel lakes (Table 7). This includes some of the standard lake assessment measures of total suspended solids (TSS), alkalinity, conductivity and color (Table 6), as well as major cations, anions, and organic carbon. While several of these parameters have "typical" ecoregion-based concentrations, some do not. For parameters without ecoregion–based comparisons, data from the 2007 National Lakes Assessment (NLA) study were used to provide perspective on reported concentrations (Table 7). Since the NLA lakes were selected randomly, they provide a reasonable basis for describing typical ranges and distributions at the statewide level. Chloride was the only parameter that was outside the NLA range.

Alkalinity

Alkalinity and conductivity are in the typical range for NCHF and WCBP lakes and are indicative of hard water (Table 6). Most cation and anion concentrations were quite stable across sample events (Table 7), with the exception of calcium (Ca), which is consistent with the literature. Magnesium (Mg), sodium (Na), potassium (K) and Cl are noted to be relatively conservative and undergo only minor spatial and temporal change (Wetzel 2001). Mg is required by algae to produce chl-a, and Ca is used by rooted plants. The mid-summer decline in Ca was likely in response to the excessive growth of curly-leaf pondweed and other rooted plants in spring and summer.

Ions

Ca and Mg are the dominant cations. Ca results varied some, while Mg levels were stable through the two years of monitoring. Concentrations of both averaged within the typical range of the statewide data (Table 8). The other two major cations –Na and K are well within, or close to, the typical range as well. Bicarbonate (measured as alkalinity) is the dominant cation, followed by Cl and sulfate (SO_4). Cl is near the typical range for NLF reference lakes (Table 6) and the statewide NLA data (Table 8). Elevated Cl is most often attributed to application of road salt on roads in the watershed. Sulfate is within the typical range of the NLA data (Table 8). The average cation and anion balances (cation-anions expressed as a % of cations) was neat 1% for both 2008 and 2009 (Table 8), which is well within values exhibited by the NLA lakes.

Suspended solids

TSS is within the typical range for NCHF and WCBP reference lakes (Table 6) and most of the TSS can be attributed to organic SS (TSS-TSIS), i.e. suspended algae. Color values averaged within the NCHF and WCBP reference values for both years (Table 6). This indicates the water has natural dissolved color associated with 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 statewide data (Table 8). 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).

Table 6. Madison Lake 2008 and 2009 Ion results

	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Fe µg/L	Si mg/L	SO_4 mg/L	Cl mg/L	TOC mg/L	DOC mg/L
4/23/2008	36	21	7.9	4.3			9.27	22	10	
7/28/2008	27	21	8.3	4.1			9.04	21.9	13	
10/21/2008	34	22	11	4.6			8.41	22	11	
7/17/2009	25	21	8.9	4.2	45.1	4.9	7.46	23.5	15	13
10/15/2009	29	21	9.2	4.6	57.8	11	6.68	25.6	12	11

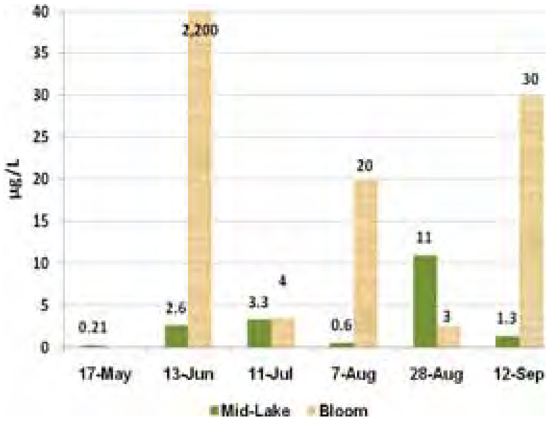
Table 7 Annual mean values for cations, anions, and organic carbon. Interquartile range (referred to as typical range) based on 64 lakes included in the 2007 NLA study included for perspective

Parameter	Madison	Madison	NLA IQ Range	µeq/L	µeq/L
	2008	2009	2007	2008	2009
Ca (mg/L)	32.3	27	19.1 - 33.7	1597	1347
Mg (mg/L)	21.3	21	6.7 - 26.9	1752	1727
K (mg/L)	4.3	4.4	0.9 - 4.8	187	191
Na (mg/L)	9.1	9.1	2.2 - 9.0	135	131
Cation Sum				3,671	3,396
Alk (mg/L)	143.3	135		2,860	2,700
SO4 (mg/L)	8.9	7.07	2.2 - 14.1	185	23
Cl (mg/L)	22.0	24.6	1.5 - 18.4	621	691
Anion Sum				3,666	3,414
Fe (µg/L)		51			
DOC (mg/L)		12			
TOC (mg/L)	11.3	13.5	7.3 - 14.2		
Si (mg/L)		7.9	3.1-13.5		

Algal toxins (microcystin)

As a part of the 2006 special study, microcystin (MC) was measured consistently at a primary mid-lake site and in nearshore blooms. MC at nearshore bloom sites were above the World Health Association (WHO) high risk category for recreational water on three occasions (Figure 26). One sample collected on June 13’ 2006, was gathered from a dense algal scum in the midst of a dense emergent plant bed (Figure 27). The toxin concentration in that sample was (2200 µg/L) well over the WHO high risk threshold of 2,000 µg/L.

Figure 26. Madison Lake 2006 microcystin results **Figure 27. June algal scum photo**



Phytoplankton (algae)

Chl-a, which provides an estimate of algal biomass, is often used to describe algal bloom intensity and frequency; however, it is often important to understand which algal forms contribute to the blooms and how the dominance of the various forms changes from spring to fall. For this purpose, algae samples were collected and analyzed during the 2006 and 2008 monitoring seasons (Figure 28 and 29). Algal composition and trends were similar during both 2006 and 2008 sampling seasons. Diatoms were dominant in May in both years. Diatoms prosper under cool well-mixed conditions in the spring when both nutrients and silica are abundant. They typically die back by June in response to declining silica concentrations and warming of the lake. Following the diatoms, blue-green algae became dominate in June and remained dominant throughout the remainder of the summer in both years. The blue-green taxa most commonly identified were *Anabaena*, *Microcystis* and *Aphanizomenon*—all of which have the ability to produce algal toxins.

Figure 28. Algal composition for Madison Lake in 2008

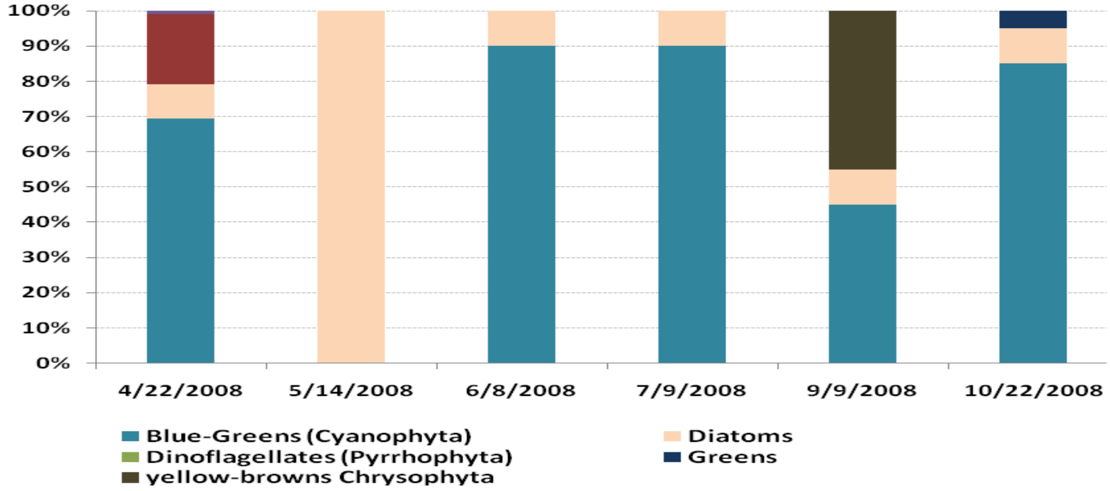
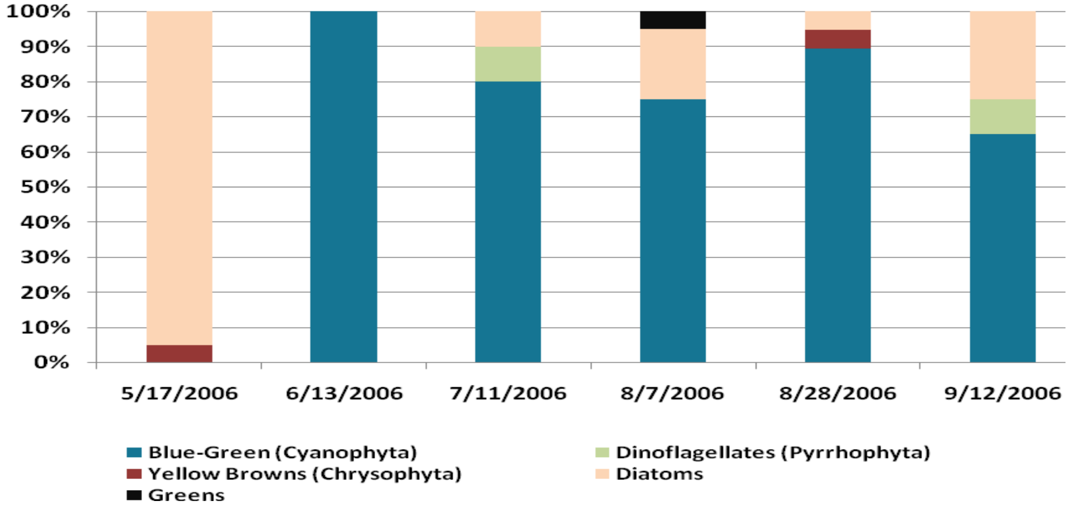


Figure 29. Algal composition for Madison Lake in 2006



Zooplankton

Zooplankton samples were analyzed by Jodie Hirsch at the MDNR. A summary report was prepared that included information for all the Sentinel lakes and that report (Hirsch 2009) is the basis for the following comments on Madison Lake. Zooplankton biomass remained relatively high in April –June, but declined in July and remained low until fall overturn in October (Figure 30). Madison Lake in 2008 was fairly typical as compared to other NCHF Sentinel lakes, but had low populations compared to other WCBP lakes (Table 9). The decline in July coincides with senescence of curly-leaf pondweed. Loss of daytime refuge and predation by juvenile fish contributes to seasonal declines in zooplankton.

Figure 30. Mean annual zooplankton densities, biomass, and total number of taxa for each Sentinel lake in 2008

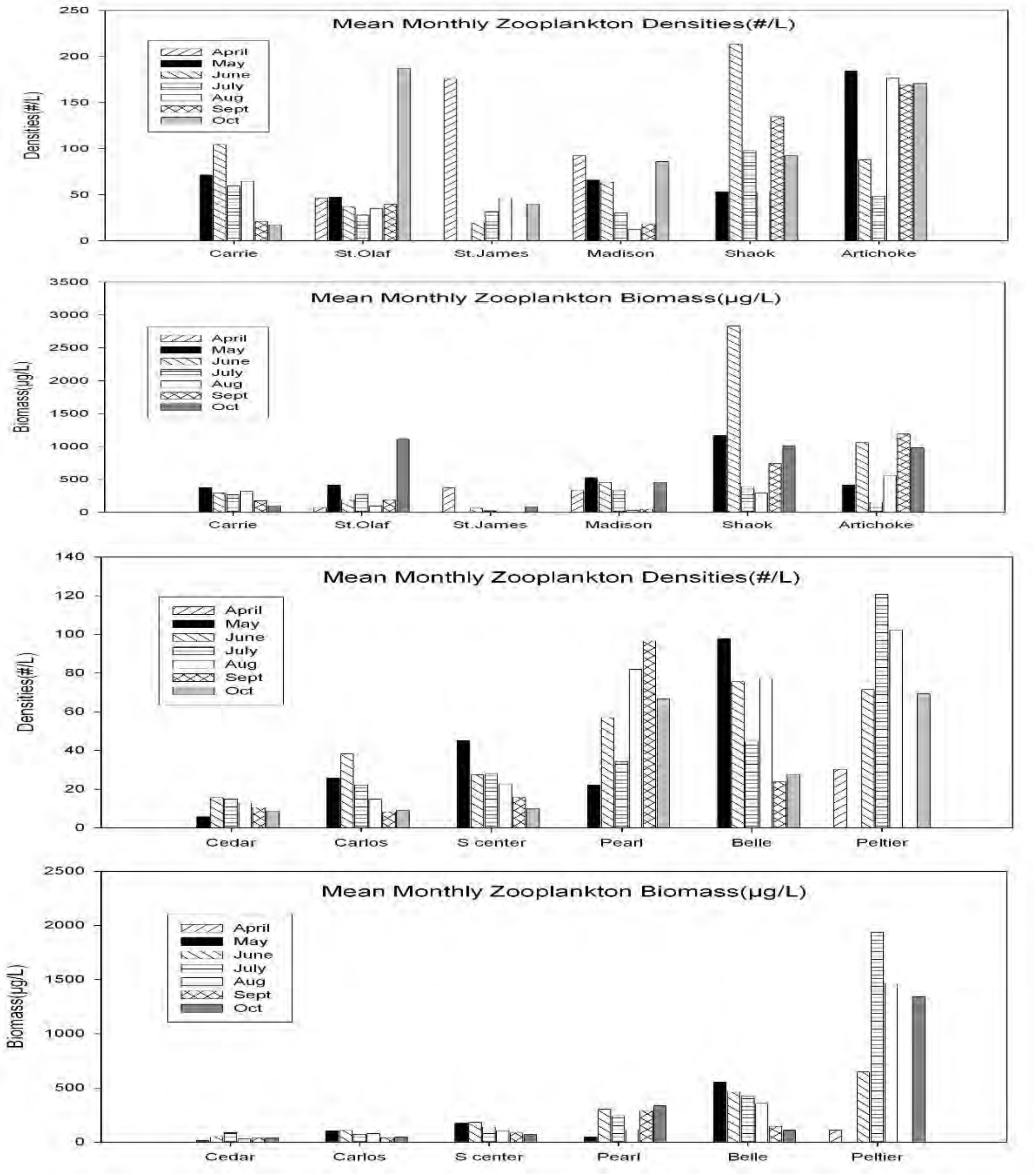


Table 8 Annual zooplankton densities (#/L), biomass (µg/L) and total number of taxa for each of the sentinel lakes sampled in 2008. Lakes are arranged by ecoregion (Sentinel lake groupings).

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

Trophic State

One way to evaluate the trophic status of a lake and to interpret the relationship between 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)

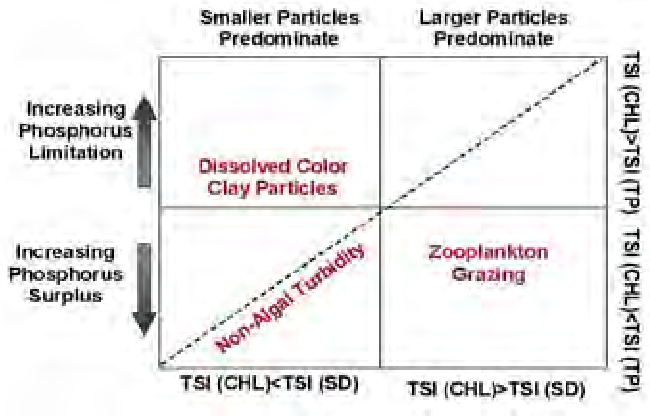
TP and chl-a are in µg/L and Secchi disk is in meters. TSI values range from 0 (ultra-oligotrophic) to 100 (hypereutrophic) (Table 10). In this index, each increase of ten units represents a doubling of algal biomass. Comparisons of the individual TSI measures provides a bases for assessing the relationship among TP, chl-a, and Secchi.

Table 9. 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

Variations in the individual trophic state indicators can be explained by several factors summarized in (Carlson 2005) and Figure 31. Secchi-TSI values from 2006 and 2008 were slightly lower than TP and chl-a. Based on Figure 31, this suggests the importance of zooplankton grazing, as well as the dominance of colony-forming blue-green algae (e.g. *Aphanizomenon*) that often allow for elevated transparency.

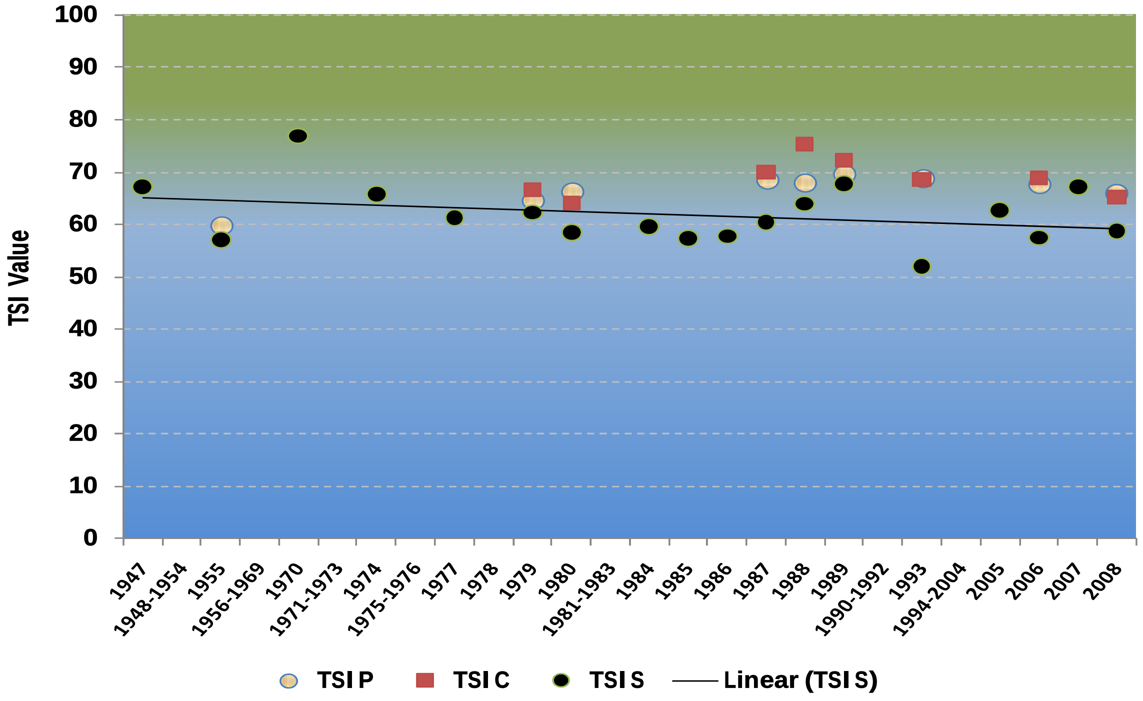
Figure 31. Possible explanations for deviations of the TSI



Trophic Status Trends

TSI calculations are often used to evaluate long-term trends in lake water quality. A review of data in STORET indicates there is a large amount of TSI data for Madison Lake going back to 1947 (Figure 32). In general, for trend assessment we seek a minimum of eight years of consistent data. Based on yearly TSI values no strong overall trend is apparent. Secchi exhibits a slight, but not significant, increase over time (Figure 31). The average TSI through the period of record (1947-2008) is 64 on Madison Lake, which would characterize it as eutrophic.

Figure 32. Madison Lake trophic status trend



Modeling

Numerous complex mathematical models are available for estimating nutrient and water budgets for lakes. These models can be used to relate the 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 the quality of the lake as a result of altering nutrient inputs to the lake (e.g., changing land uses in the watershed) or altering the flow or amount of water that enters the lake. To analyze the 2008 water quality of Madison Lake, the Minnesota Lake Eutrophication Analysis Procedures (MNLEAP) model (Wilson and Walker, 1989) was used. A comparison of MNLEAP predicted vs. observed values is presented in Table 11).

MNLEAP was developed by MPCA staff based on an analysis of data collected from the 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. Madison Lake data from 2008 (TP, chl-a, and Secchi)were used as the observed values Because Madison Lake is located in near the transition of the CHF and the WCP ecoregion, the model was run using both sets of ecoregion-based inputs. The observed TP, chl-a, and Secchi values for Madison Lake were close to those predicted from the MNLEAP model based on WCP inputs (Table 11). Based on Madison Lake's morphometry and watershed area and MNLEAP inputs Madison retains a high percentage of the P that enters the lake and its water residence time is approximately 3-4 years (Table 11). An equation developed by Vighi and Chiaudani (1985) suggests that background P for the lake is approximately 25 µg/L.

Table 10. MNLEAP model predictions

Parameter	2008 Madison Lake Observed	MINLEAP Prediction With WCP Ecoregion settings	MINLEAP Predictions with CHF Ecoregion settings
TP (µg/L)	76	79 (±32)	37 (±14)
Chl-*a* (µg /L)	31.5	39 (±27)	13 (±9)
Secchi (m)	0.95	0.9 (0.4)	1.7 (0.7)
P loading rate (kg/yr)	-	17,550	5,237
P retention (%)	-	0.86	0.78
P inflow conc. (µg/L)	-	566	172
Water Load (m/yr)	-	1.01	0.99
Outflow volume (hm^3/yr)	-	31.0	30.4
Residence time (yrs)	-	3.8	3.9
Vighi & Chiaudani		24.7	24.7

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. The 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 and updated every even-numbered year. In order for a lake to be considered impaired for aquatic recreation use, the average TP concentration must exceed the water quality standard for its ecoregion. In addition, either the chl-a concentration for the lake must exceed the standard or the Secchi data for the lake 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 for which Minnesota's water resources are assessed (e.g. mercury in fish tissue). If a water body is listed, a diagnostic TMDL study must be conducted to determine the sources and extent of pollution, and to establish pollutant reduction goals needed to restore the resource to meet the determined water quality standards for its ecoregion. The MPCA is responsible for performing assessment activities, listing impaired waters, and conducting TMDL studies in Minnesota.

Madison Lake's data were compared to the eutrophication water quality standards for deep lakes in the WCBP ecoregion (Table 12). They were found to exceed the TP and chl-a standards, and the lake was placed on the 2010 draft impaired waters list. A TMDL study on the lake is scheduled to be completed by 2014.

Table 11. Eutrophication standards by ecoregion and lake type

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
Madison Lake 2008	76	31	0.95
Madison Lake Long-term mean	83	56	1.0

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This information was obtained through the State Climatology Office and can be found at http://climate.umn.edu/climatology.htm.

Appendix

Select 2006 and 2008 Water Quality Data for Madison Lake

All water quality data can be accessed at: http://www.pca.state.mn.us/data/eda/STresults.cfm?stID=07-0044&stOR=MNPCA1

Parameter	Site	6/13/2006	7/11/2006	8/7/2006	8/28/2006	9/12/2006	6/9/2008	7/9/2008	8/7/2008	9/9/2008
Alkalinity, Total	102	150	140	140	140	150				
mg/L CaCO3	201							130		
Chloride	102	20	20	21	21	21				
mg/L	201							21.9		
Chlorophyll a,	101	36.8	76	44.1	37.6	30	9.91	45.6	40.7	50.8
corrected for pheophytin	102	66.9	64.7	27.2	35.9	39.7				
µg/L	201						7.23	39.5	27	
Color, Apparent	102	20	20	20	20	10		20	20	20
PCU	201							20		
Depth, Secchi Disk Depth	101	1	0.5	0.6	0.6	0.8	2.5	0.8	0.8	0.7
m	102	0.7	0.5	0.8	0.6	0.8				
	201						3		0.6	0.8
Nitrogen, Kjeldahl	102	2.25	1.8	1.53	1.57	1.78				
mg/L	201							1.65	1.45	
Phosphorus as P	101	69	93	76	66	85	45	68	65	70
mg/L	102	117	83	48	71	85				
	201						121	75	59	
Solids, Total Suspended (TSS)	102	11	12	6.4	8.8	12				
mg/L	201							10		