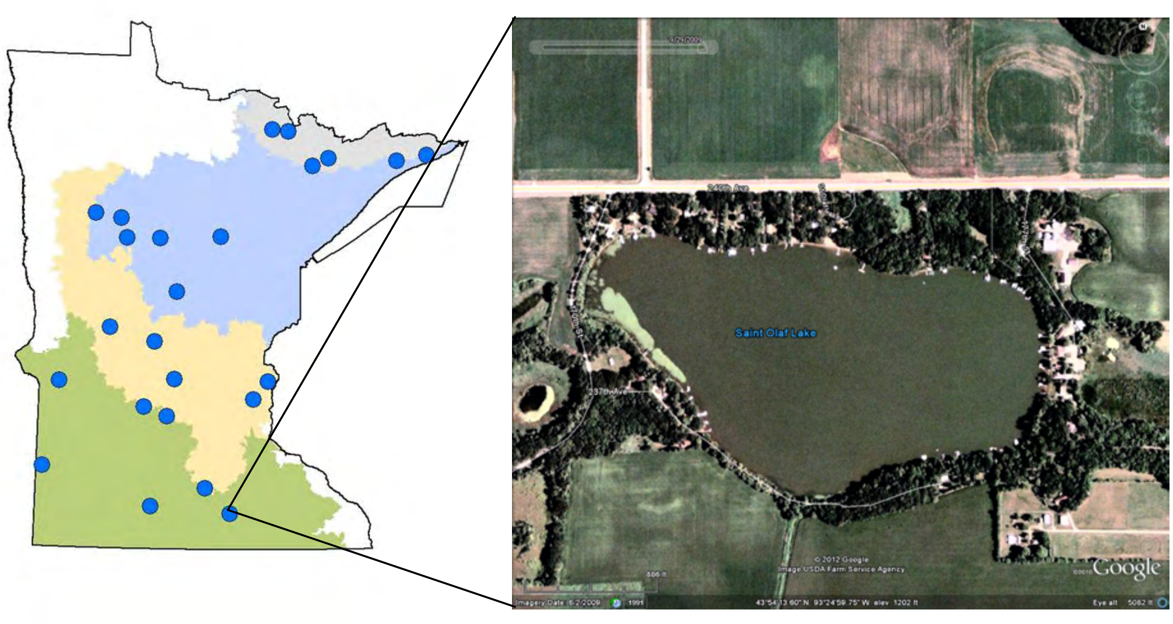
Sentinel Lake Assessment Report
St. Olaf Lake (81-0003)
Waseca County, Minnesota



Minnesota Pollution Control Agency

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Section of Fisheries

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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 2010). 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 typically do not stratify and are well mixed throughout most of the summer. "Cold Water" lakes are defined as lakes that 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.

Saint Olaf represents a deep lake in the Western Corn Belt Plains (WCBP) ecoregion. Saint Olaf is a 36-hectare (89 acre) lake, located about three miles northeast of the city of New Richland, Waseca County, within the Minnesota River basin watershed. The lake has a maximum depth of 10 meters (33 feet) and a mean depth of 4.4 meters (14.5 feet). The lake is 57 percent littoral with one public access. The total contributing watershed for St. Olaf Lake is quite small at 77 hectares (189 acres). The watershed is predominately cultivated; however the nearshore riparian area is ringed by homes and is somewhat wooded as well.

St. Olaf is a relatively deep lake for the WCBP ecoregion and is one of few southern Minnesota lakes that exhibit thermal stratification throughout the summer months. Based on recent water quality data (2008-2010), St. Olaf Lake is mildly eutrophic with total phosphorus (TP), chlorophyll-a (Chl-a), and Secchi values of: 35 micrograms per liter (µg/L), 21 µg/L, and 1.1 meters (3.6 feet) respectively. These values are better than the typical range for reference lakes in the WCBP ecoregion. While periodic nuisance algal blooms (Chl-a >20 µg/L) occur, severe nuisance blooms (Chl-a > 30 µg/L) are uncommon.

Pesticide samples were collected on four dates in 2009 and 2010 and analyzed at Minnesota Department of Agriculture. Detection frequency ranged from 25% to 100% for the various detected compounds. The St. Olaf lake watershed is highly cultivated and associated pesticide use is likely reflected in the pesticides detected. All pesticide detections in St. Olaf Lake are well below applicable water quality standards and benchmarks. The pesticide detections and concentration ranges in St. Olaf Lake are consistent with other lake sampling results of lakes located in highly cultivated areas in southern Minnesota.

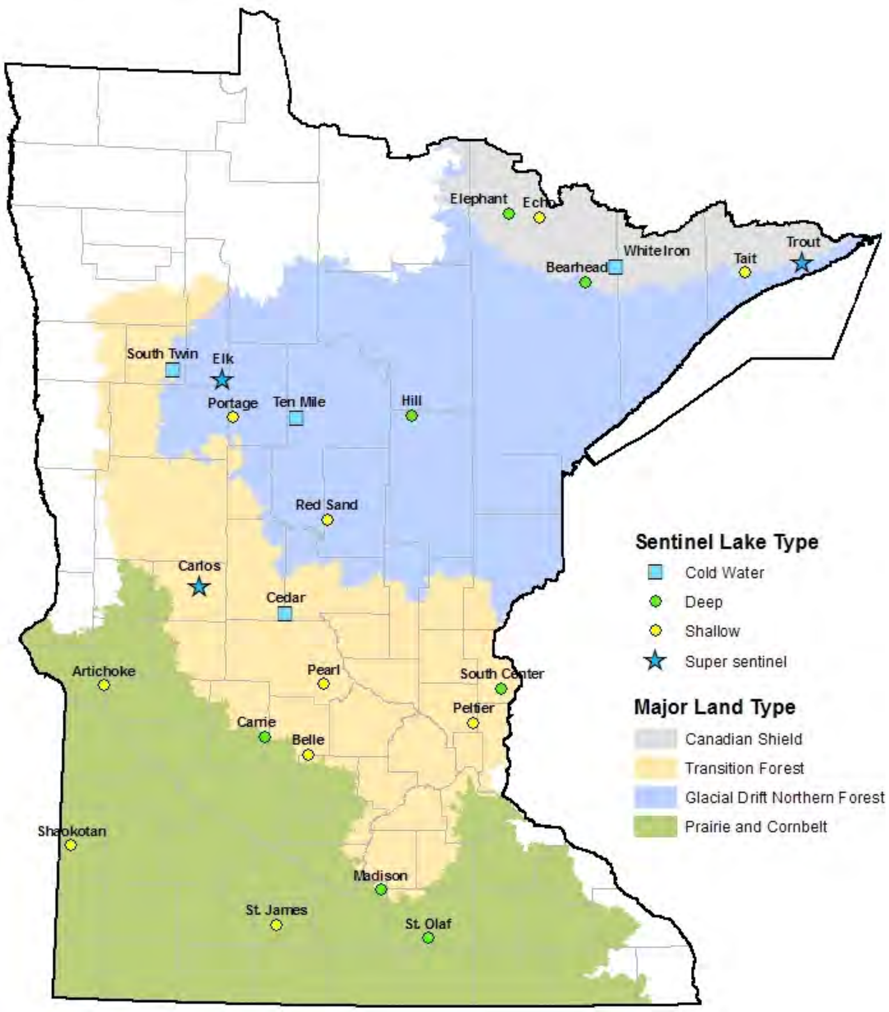
Trophic status data collected since 1986 indicates TP varied from 25 µg/L (1996) to about 45 µg/L (2009), though no long-term trend is evident. Chl-a and Secchi vary in response to changes in TP. Based on a record from 1993-2009 Secchi transparency exhibits a decline over time, with recent summer-means of one meter or less as compared to previous means in the 1.5-2.5 m range. Continued participation in CLMP is essential to determine whether this is a long-term trend or just a short-term variation in lake trophic status.

Water quality on St. Olaf Lake is much better than predicted by the MINLEAP model when WCBP ecoregion inputs are used. It has a very long water residence time, approximately ten years or more, because of its small watershed: lake area ratio and limited outflow. The model BATHTUB was used to further estimate phosphorus and water budgets for the lake. Based on standard precipitation, evaporation, runoff, and P loading values BATHTUB predicted that precipitation directly on the surface of the lake was the largest single source of water to the lake and as with MINLEAP, predicted a very long residence time. Since BATHTUB does not account for groundwater inputs, these values are estimates only. Because it has a very small watershed and its shoreline is highly developed, the relative amount of P that may reach the lake from on-site septic systems was estimated to be roughly equivalent to that from watershed runoff. This suggests that over the long term it is important to ensure that on-site systems are compliant with local ordinances to ensure that the good water quality of St. Olaf is maintained and the lake continues to meet Minnesota's lake eutrophication standards.

The fish community in St. Olaf is relatively diverse compared with other WCBP lakes and the lake is primarily managed for northern pike. A 30-in minimum size limit was put into place on the lake in 1998 to protect large fish. The regulation has been successful at increasing the size structure of the northern pike population and large fish are now common in the lake. However, given the lake's small size, limited northern pike habitat, and angling popularity, overharvest of large fish remains the primary fisheries management concern. Black and white crappie and largemouth bass are other common game fish species; however, populations are skewed towards small individuals.

Aquatic plants are relatively abundant and diverse in St. Olaf lakes compared with other lakes in Minnesota's Corn Belt. The non-native invasive curly-leaf pondweed has been present in the lake since 1954; however, the plant is typically integrated with other native aquatic plants. Significant declines in curly-leaf pondweed cover were observed in St. Olaf Lake and other sentinel lakes across the state in 2009-2011. Heavy winter snowfall and reduced under-ice light of the preceding winters is hypothesized to have played a role in these recent declines.

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 St. Olaf Lake in Waseca 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, 2009 and 2010 seasons; 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 MPCA's EQUIS water quality database. 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).

St. Olaf is located east of New Richland in Waseca County. It is small, but rather deep for a lake in this part of the state. The lake shoreline is developed with a ring of year-round and seasonal dwellings and much of the remainder of the watershed is in cultivated landuse. It is highly used and is an important resource for this part of the State.

Background

History

St. Olaf has been a part of MPCA and MDNR studies on various occasions and information compiled from those efforts is useful for describing the history of the lake and watershed. The lake was also included in a study conducted by Brigham (1992) as a part of his Master's thesis work that focused on the accumulation of mercury in select Minnesota, Wisconsin, and Alaska lakes. Some history notes were assembled as a part of that work. Brigham (1992) noted the agricultural nature of the watershed and development on the lakeshore, which in early 1990's included about 30 homes. Various historical accounts assembled as a part of that work indicated that European settlers began moving into New Richland Township in 1856 and an 1879 plat map indicated complete settlement of the St. Olaf watershed.

Following is a brief history for St. Olaf Lake and its watershed compiled based on MDNR, MPCA, and related records. This is intended as a summary of land use changes in the watershed, fish management activities, and related notes on water quality, hydrology, and overall ecology of the lake.

1879	Watershed is completely settled by Europeans during the time of the first land surveys.
1908	Initial stocking of walleye, northern pike, largemouth bass, crappies, sunfish, and perch.
1924-1957	Sporadic fish removal operations including removal of overabundant populations of common carp, bluegill, suckers, largemouth bass, and northern pike.
1938	Stop log dam, dike, and culvert inlet constructed. In 1947, water is reported to be two feet higher than before the dam was built. Today, a fixed-type concrete sill outlet structure is in place with a screen to prevent upstream movements of carp.
1941	Catch rates in July of 2.55 fish per angler hour was above the state average
1947	Shoreline is described as 70 percent hardwoods and 30 percent pasture.
1947	Submerged macrophyte growth described as "luxuriant."
1952-1990	Periodical commercial harvest of common carp
1954	Non-native invasive aquatic plant curly-leaf pondweed first documented in St. Olaf Lake.
1956	Summer creel measures 14,457 hours of angling pressure during June through August.

1985	St. Olaf was selected as an ecoregion reference lake by MPCA. This led to water quality sampling in 1986, 1996, and 2001.
1990	Sediment core collected by Mark Brigham for mercury study
1998	30-inch minimum northern pike regulation applied. The proportion of large fish in the population has increased steadily since.
2000	Yellow water lilies roped off and protected from motorboats by DNR and county.
2008	Waseca County zoning and planning drops plans to develop a second tier of properties around St. Olaf Lake from lack of public support in four years of public hearings.

Lake Morphometric and Watershed Characteristics

St. Olaf is a relatively deep lake for the WCBP ecoregion, where typical maximum depth is in the 3.0-4.5 meter (10-15 foot) range. It has a surface area of 36 ha (89 acres), of which 57 percent is considered littoral (percent of lake <15 feet). St. Olaf is a deep lake based on its maximum depth of 10 m (33 feet) and percent littoral, which is less than 80 percent of the lake. It has a very small watershed relative to its surface area (Table 1) and this means that there is limited surface runoff to the lake (in contrast to a lake with a large watershed). Lakes with small watersheds often have significant groundwater contribution, which serve to maintain lake level, since surface runoff from the watershed is often insufficient to maintain water levels.

Figure 2 Lake bathymetric map

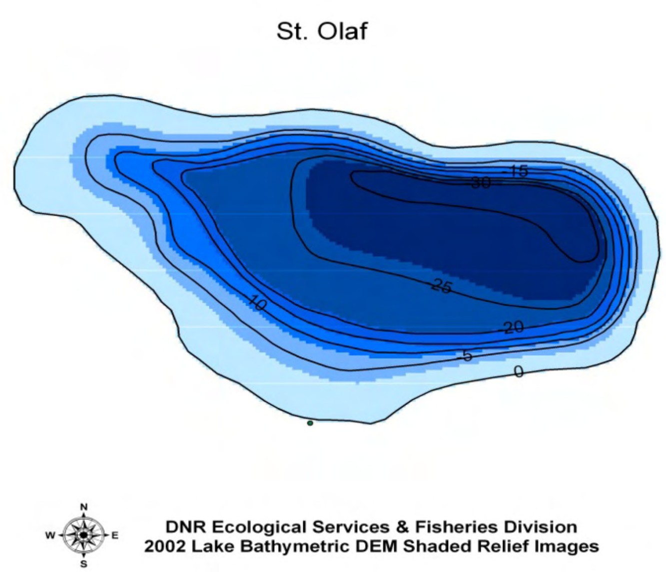


Table 1 Saint Olaf Lake and watershed morphometric characteristics.

Lake Basin hectares (acres)	Littoral Area (%)	Lake Watershed hectares (acres)	Max. Depth meters (feet)	Mean Depth meters (feet)	Watershed: Lake Ratio	Lake Volume acre-ft
36 (89)	**57 %**	**76.5 (189)**	**10 (33)**	**4.4 (14.5)**	**2.1: 1**	**1,290**

Lake Mixing and Stratification

Lake depth and mixing has a significant influence 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 the 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. In contrast, shallow lakes (maximum depths of six 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. The 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. The low oxygen environments in the hypolimnion are conducive to TP being released from the lake sediments. During stratification, dense colder hypolimnion waters are separated from the nutrient hungry algae in the epilimnion. Intermittently (weakly) stratified polymictic lakes are mixed in high winds and during spring and fall. Mixing events allow the nutrient rich sediments to be re-suspended and are available to algae.

Figure 3 Lake Stratification

Polymictic Lake: Shallow, no layers, mixes continuously

Spring, Summer & Fall

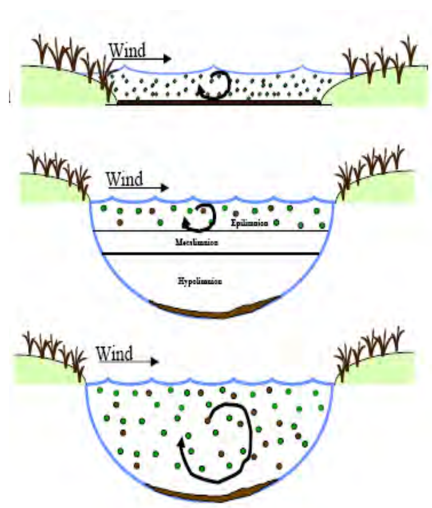
Dimictic Lake: Deep, forms layers,

mixes Spring/Fall

Intermittently Stratified:

Moderately deep, mixes during high winds

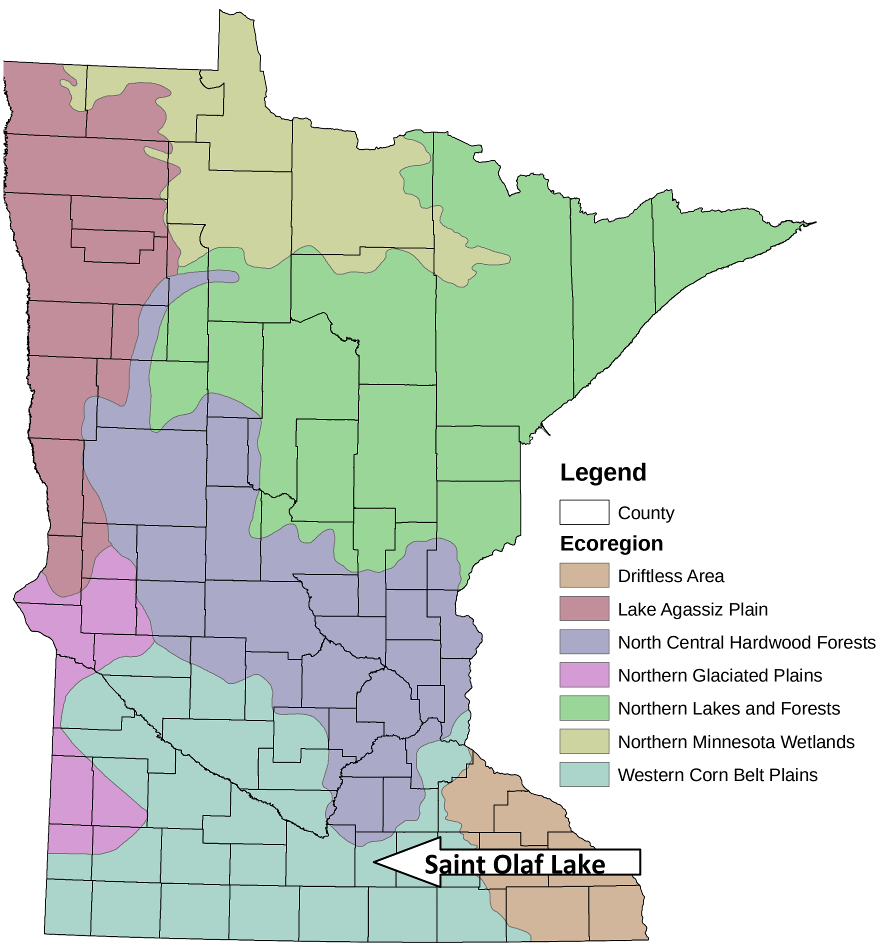
Spring, Summer, & Fall



Ecoregion and Land Use Characteristics

Minnesota is divided into seven regions, referred to as ecoregions, 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. Saint Olaf Lake lies within the Western Corn Belt Plain (WCBP; Figure 4). WCBP values will be used for land use (Table 2) and summer-mean water quality comparisons (Table 3). Additionally, the WCBP inputs will be used for MINLEAP model application.

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



Land Use

Since land use affects water quality, it has proven helpful to document the land use composition in the watershed of the lake. The Saint Olaf Lake watershed is dominated by agriculture land use (Figure 5), which is typical for a WCBP lake (Table 2). Fortunately, cultivated lands do not extend all the way to the shoreline of the lake (Figure 6) in contrast to many WCBP lakes that may be completely ringed by cultivated lands. The riparian area of St. Olaf is characterized by numerous homes, a county park, and a patchwork of woods. There is a road network around the lake; however much of the shoreline is wooded (Figure 6). A 2007 DNR lake management plan indicated near shore habitat was relatively stable based on lake surveys dating back to c1950s but there were some concerns with shoreland erosion at some locations.

Figure 5 St. Olaf watershed and land use map.

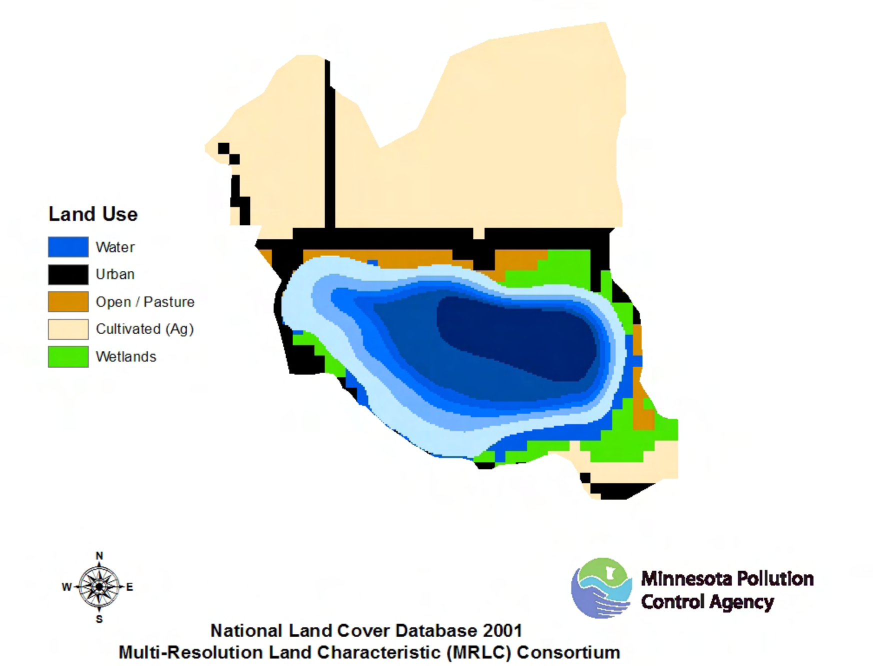


Table 2 Land use composition based on 2006 NLCD.

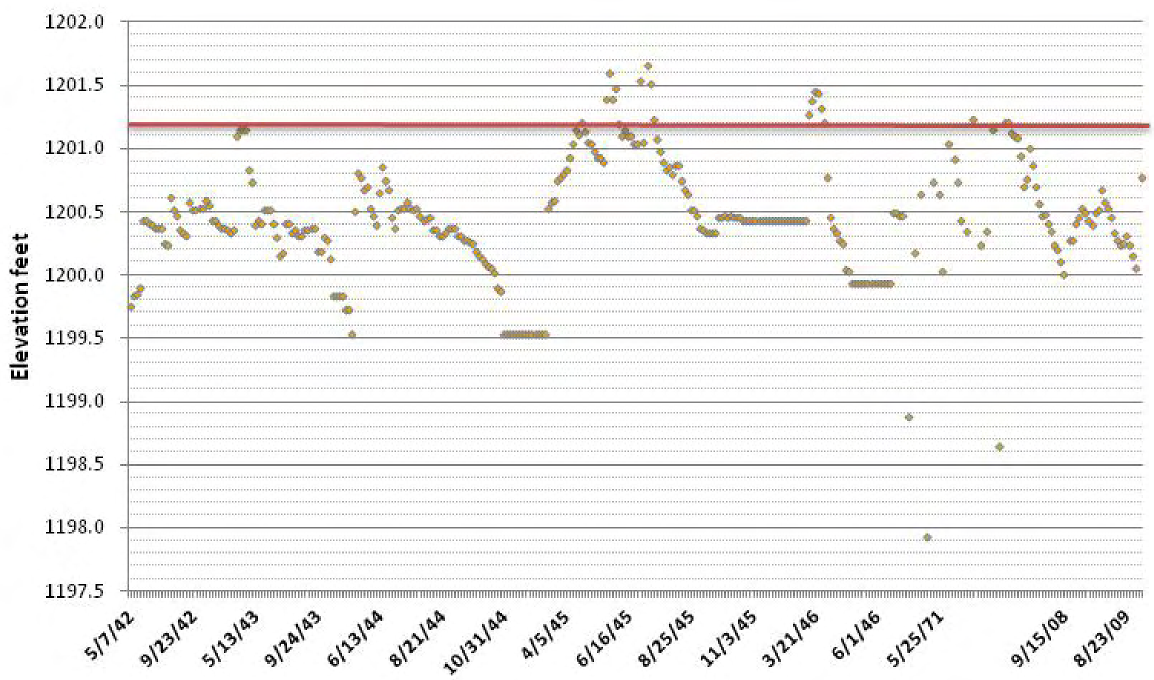
Land Use	St. Olaf Lake Land Use percent	WCBP Typical Land Use percent
Developed	16	0 – 16
Cultivated (Ag)	64	42 – 75
Pasture & Open	6	0 – 7
Forest	11	0 – 15
Water/ Wetland	3	3-26
Feedlots (#)	0	

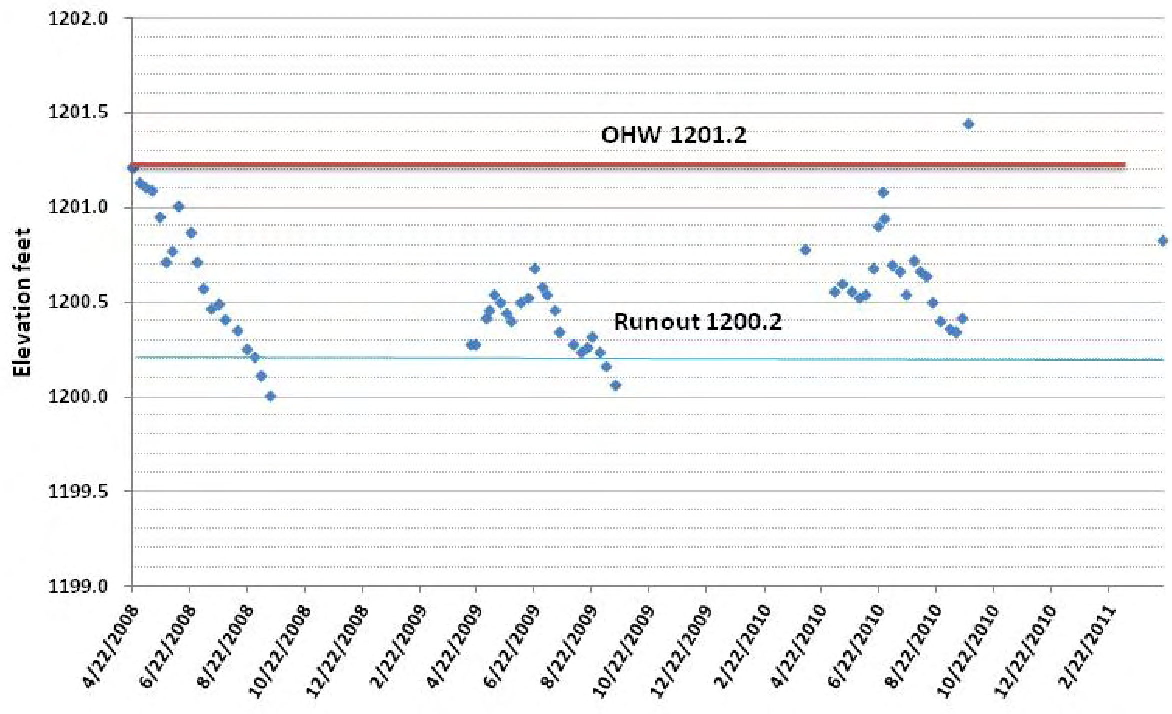
Figure 6 Aerial image and shoreline photo of St. Olaf Lake. Aerial image from USDA Farm Service September 29, 2009. Shoreline photo of western shoreline taken by Matt Lindon.

Lake Level and Ice On/Off

The MDNR Division of Waters has been measuring water levels on St. Olaf Lake since 1942. Very detailed records were acquired from 1942 – 1946 (Figure 7). Since that time, the record is rather sparse from 1947-2008. In 2008, regular measurements were instituted, as a part of the Sentinel effort. 331 measurements have been taken through April 2011. The long-term high was 1201.16 feet recorded on July 7, 1945 and the low was 1197.94 feet recorded on April 17, 1968. The Ordinary High Water (OHW) level was established at 1201.2 feet and dam run-out elevation is ~1200.2 (+/- 0.2) feet. Lake elevation has remained well below the OHW over the majority of the record (Figure 7) with the exception of September 2010, when lake level rose rapidly in response to a major precipitation event (Figure 9). For the 2008-2010 period, the lake was above run-out for much of the open water season. The recent record indicates a decline in lake level from 2008-2009 with a rebound in 2010. There is no long-term trend when the entire record is considered. The complete water level record may be obtained from the MDNR web site at: http://www.dnr.state.mn.us/lakefind/showlevel.html?id=81000300

Figure 7 Long term and recent 2008-2010 lake level measurements. Data from MDNR lake level database.





Ice on and ice off records

There has been increased interest in recording ice on and ice off dates as a part of climatological studies and the more recent interest in global climate warming. Some Minnesota lakes have very extensive records; however most do not. As a part of the Sentinel lakes effort this is something we are interested in compiling for all Sentinel lakes. Recent records for St. Olaf show the following ice on and ice off dates:

2005 – Ice on Dec. 14, 2004 and ice off April 4, 2005 (111 days of ice cover);

2008 – Ice on Nov. 29, 2007 and ice off April 16, 2008 (139 days of ice cover);

2009 – Ice on December 8, 2008 and ice off March 24, 2009 (106 days of ice cover);

2010 – Ice on December 10, 2009 and ice off March 30, 2010 (110 days of ice cover);

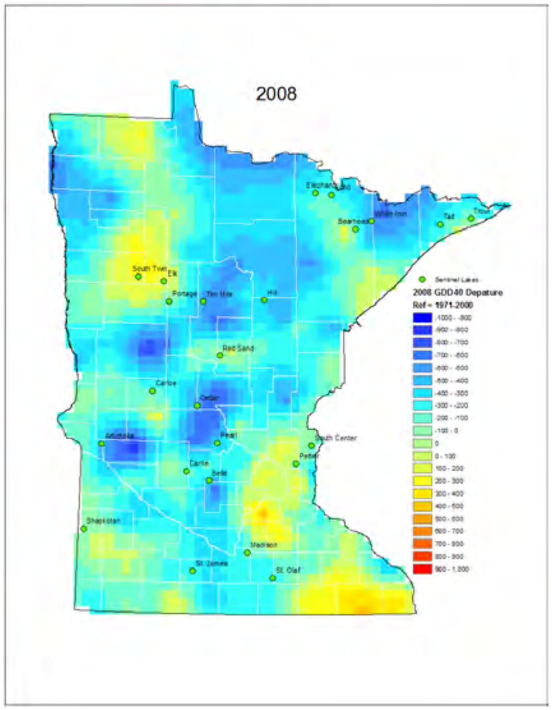
2011 – Ice on December 2, 2010 and ice off April 9 2011. (128 days of ice cover)

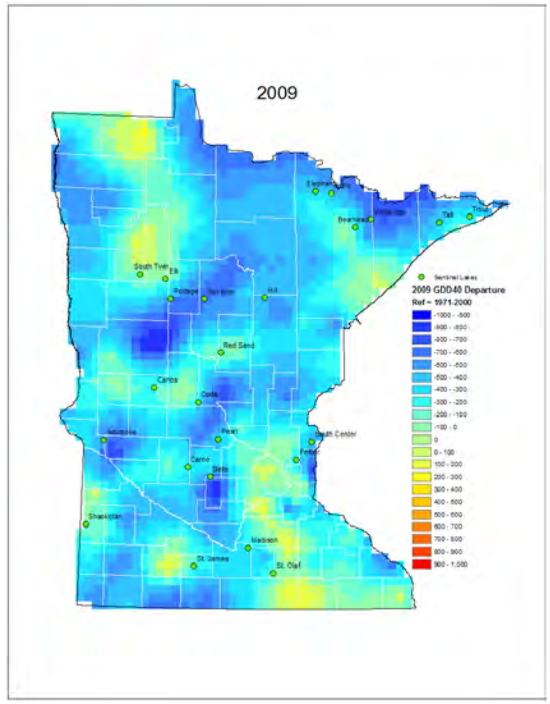
Precipitation and Climate Summary

Temperature and precipitation influence many aspects lake chemistry and biology. Large rain events often increase runoff into the lake and may influence in-lake water quality and lake levels, while periods of drought may affect lake levels and other aspects of the water quality and ecology of a lake. The National Weather Service has a station at the Waseca Experimental Station that has complete data for this area.

The summers of 2008 and 2009 were cooler than the long-term (1971-2000) norm for the area near St. Olaf Lake (Figure 8). In contrast, summer 2010 was much warmer. The differences in climate among these three years is evident in the more localized data collected at the Waseca Experimental Station. Precipitation in 2008 and 2009 was rather modest while summer 2010 had some large events (Figure 9). Snowfall and snow cover was greater in the winter of 2010 as compared to 2008 and 2009.The rapid warming in spring of 2010 was quite evident as well and contributed to the above normal degree days for 2010 (Figure 8).

Figure 8 Growing degree day departure from norm





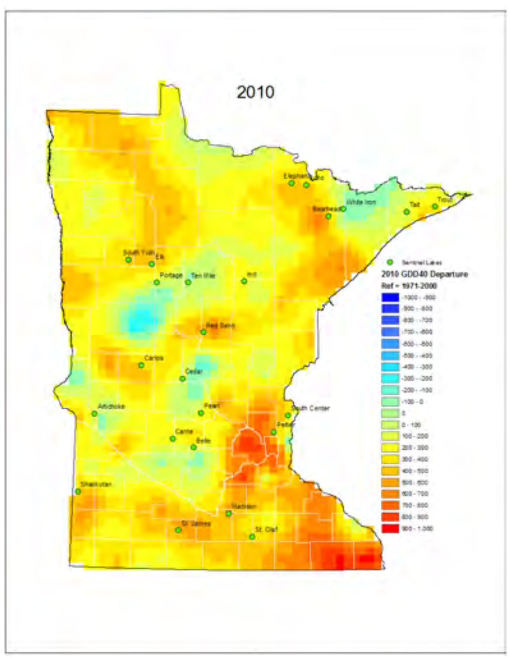
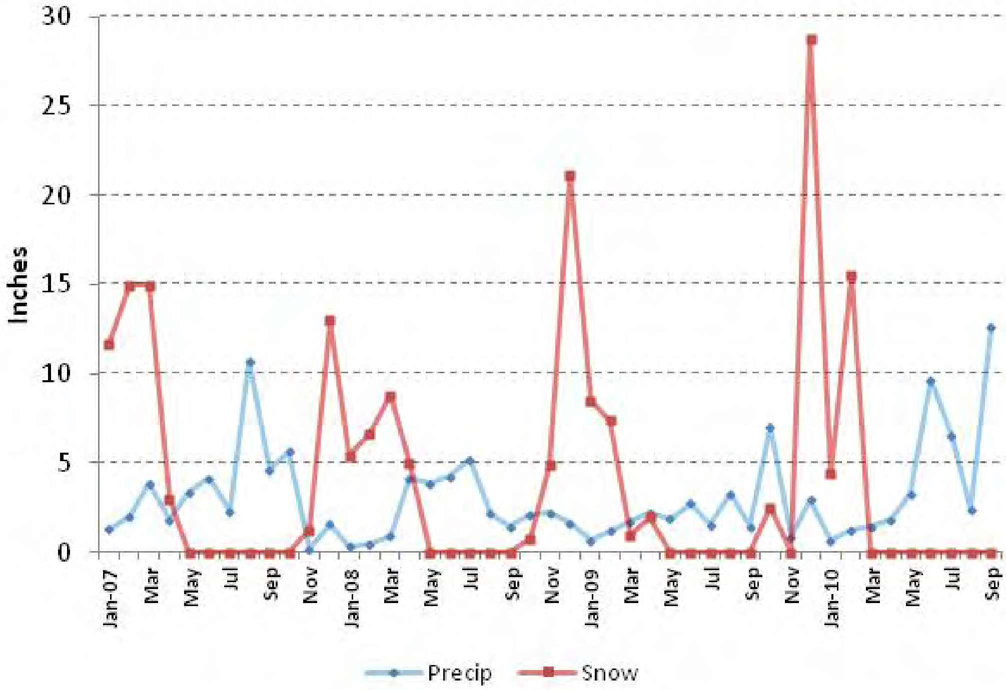
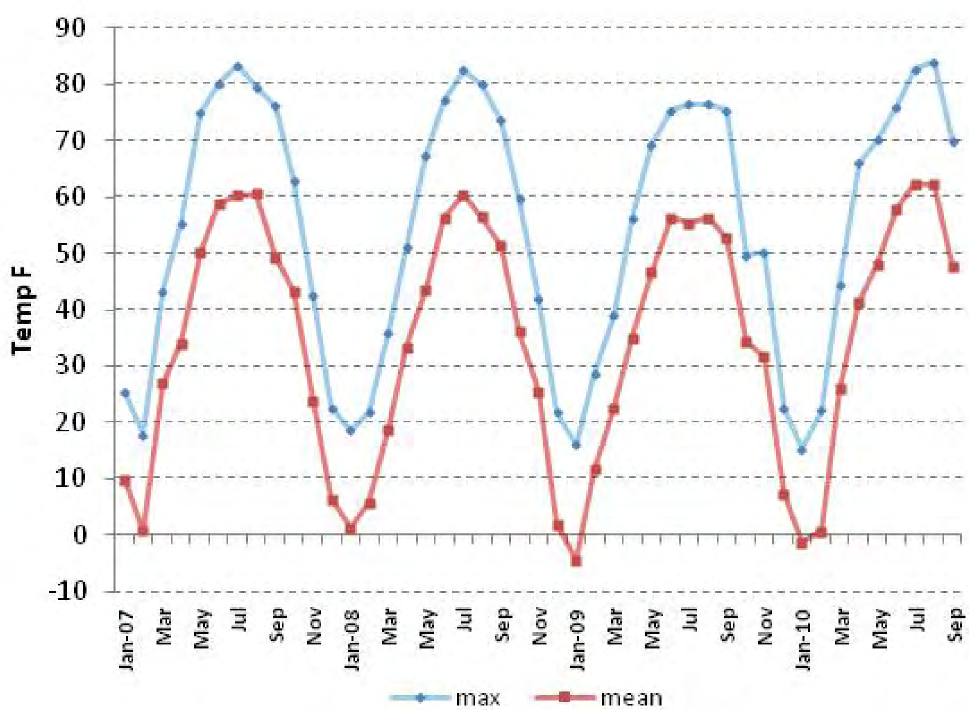


Figure 9 Monthly precipitation, snow, and temperature (maximum and mean) based on NWS data from Waseca Experimental Station for period January 2007-September 2010.





Methods

Fisheries and Aquatic Plants

Frequency of occurrence of aquatic plant species was 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 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 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

Recent sample collections were done monthly, from ice-out (April/May) through October in 2008. In 2009 and 2010, samples were collected after ice-out, July and October for a large suite of parameters. Lake surface chemistry and phytoplankton (algae)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-µm mesh Wisconsin zooplankton net. Conductivity, pH, temperature, and DO profiles along with Secchi disk transparency measurements were during each sampling event. Samples were collected at site 101. 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.

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

Zooplankton

Zooplankton samples were collected monthly from ice-out (April/May) through October in 2008 and only in April/May July and October in 2009 and 2010. 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 percent reagent alcohol. Analysis was conducted by MDNR personnel.

Each zooplankton sample was adjusted to a known volume by filtering through 80 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. The fish community in St. Olaf is relatively diverse compared with other lakes in the agricultural WCBP (Table 3). Interestingly, pugnose shiner and blackchin shiners, both rare in southern Minnesota lakes and intolerant to high nutrient levels, were identified in the 1947 and 1954 surveys respectively. However, these often-misidentified species have never been sampled again and no voucher specimens exist so it is difficult to ascertain whether these species were present in the lake. Given the low water clarity (and by extension presumed habitat conditions) when the species were supposedly sampled, it is unlikely that the species were correctly identified.

Although formal criteria have been developed for assessing the biotic integrity (IBI) of Minnesota lake fish communities (Drake and Pereira 2002, Drake and Valley 2005), St. Olaf's small size is outside of the range of conditions for which the IBI was developed. Formally, assessing integrity of St. Olaf's fish community will likely require adapted sampling or scoring criteria. Nevertheless, given the diversity of various fish guilds, qualitatively, the lake's fish community has relatively high integrity. Maintaining low nutrient levels and abundant aquatic plants will be important for maintaining high fish biotic integrity (Drake and Valley 2005)

Table 3 Fish species captured during past fisheries surveys. Thermal guilds were classified by Lyons et al. (2009) and environmental tolerances were categorized by Drake and Pereira (2002).

Common name	Species name	Trophic guild	Thermal guild	Environmental tolerance	First documented
Bluegill sunfish	Lepomis macrochirus	Insectivore	Warm	Neutral	1947
Green sunfish	Lepomis cyanellus	Insectivore	Warm	Neutral	1947
Pumpkinseed sunfish	Lepomis gibbosus	Insectivore	Warm	Neutral	1947
Orangespotted sunfish	Lepomis humilis	Insectivore	Wam	Neutral	1947
Yellow perch	Perca flavescens	Insectivore	Cool-warm	Neutral	1947
Black bullhead	Ameiurus melas	Omnivore	Warm	Tolerant	1947
Brown bullhead	Ameiurus nebulosus	Omnivore	Warm	Neutral	1954
Yellow bullhead	Ameiurus natalis	Omnivore	Warm	Neutral	1947
Tadpole madtom	Noturus gyrinus	Insectivore	Warm	Neutral	1947
White sucker	Catostomus commersonii	Omnivore	Cool-warm	Tolerant	1947
White crappie	Pomoxis annularis	Predator	Warm	Tolerant	1947
Black crappie	Pomoxis nigromaculatus	Predator	Warm	Neutral	1947
Largemouth bass	Micropterus salmoides	Predator	Warm	Neutral	1947

Northern pike	Esox lucius	Predator	Cool-warm	Neutral	1954
Walleye	Sander vitreus	Predator	Cool-warm	Neutral	1954
Sauger	Sander canadense	Predator	Cool	Neutral	1990
Common carp	Cyprinus carpio	Omnivore	Warm	Tolerant	1947
Pugnose shiner[a]	Notropis anogenus	Insectivore	Cool	Intolerant	1947
Blackchin shiner	Notropis heterodon	Insectivore	Transition	Intolerant	1954
Golden shiner	Notemigonus crysoleucas	Insectivore	Warm	Neutral	1947
Brassy minnow	Hybognathus hankinsoni	Herbivore	Cool-warm	Neutral	1947
Fathead minnow	Pimephales promelas	Omnivore	Warm	Tolerant	1947
Bluntnose minnow	Pimephales notatus	Omnivore	Warm	Neutral	1947
Spottail shiner	Notropis hudsonius	Insectivore	Warm	Neutral	1947
Bigmouth shiner	Notropis dorsalis	Insectivore	Warm	Neutral	1947
Logperch	Percina caprodes	Insectivore	Warm	Neutral	1984
Iowa darter	Etheostoma exile	Insectivore	Warm	Intolerant	1947
Johnny darter	Etheostoma nigrum	Insectivore	Warm	Neutral	1954

[a]Originally identified in the 1947 survey. On some unknown date, someone scratched out *Notropis anogenus* and inscribed *Opsopoeodus emiliae* (pugnose minnow). This specimen was not vouchered and significant doubt exists that it could be either one.

Fisheries Management

Past management activities focused on fish removal and stocking. Bluegills and crappies were removed from 1924 through 1938, 1944, 1949, and 1955. Common carp were removed in 1952, 1956, 1970, 1979, and 1990 by commercial seiners and sometimes by local sportsman groups. Suckers and largemouth bass were removed in 1955. Northern pike were removed in 1954 through 1957.

Extensive fish stocking has been ongoing up to the present date, beginning with northern pike stocking in 1908. In the early years, attempts were made to maintain populations of northern pike, largemouth bass, walleye, yellow perch, crappie, and sunfish through stocking, but most attempts were haphazard and a result of local requests and available fish. From the 1960's – the 1970's, walleye, largemouth bass, and northern pike were maintained through stocking. From the 1980's until present, fisheries management has been focused on northern pike and a regular stocking program helps maintain the population today. Today, the lake is managed primarily as a northern pike fishery and maintained through stocking. Because of cost feasibility and poor survival, walleye stocking ceased in 1982 and the lake no longer supports a walleye population.

Fish Species Assessments

Northern pike – Throughout the managed history of St. Olaf Lake, the northern pike population has been sustained through stocking and special regulations that protect large individuals. A 30-inch minimum size limit for northern pike went into effect in May 1998 and is currently still in effect. The objective of the regulation is to increase the recreational value of the northern pike population by improving the size structure. The size distribution of quality-sized fish (northern pike larger than 24 inches) has increased since the regulation went into effect. In 2011, the few fish sampled in summer gillnets were very large (Figure 10).

Despite operation of a cooperative northern pike spawning or rearing area, as well as the addition of stocked adults and fingerlings, abundance of this species has remained generally low. The standing crop of northern pike is lower than in other similar-sized lakes in this area presumably due its bowl-like morphometry and limited shallow habitats. It is believed that fish are quickly removed from the system by angling. The 1956 creel survey tallied 14,457 hours of angling pressure applied to St. Olaf's 91 acres during the summer months. During that time, 100 northern pike were removed by anglers. Modified Schnabel population estimates in 1998 and 1999 conducted by tagging northern pike and getting recaptures in ice out trap netting estimated a population of 555 individuals with a 95 percent confidence interval of 418-753, and 759 with a 95 percent confidence interval of 496-1,214 in respective years. A model in Pierce and Tomcko (2005) based on the lake morphometry and gillnet catch suggests a population estimate of 346 fish greater than 500 mm (20-in). 2010 SLICE ice-out netting mark-recapture population estimates project a spawning population of 66 fish, with a 95 percent confidence interval of 42-218 fish.

Harvest in a small lake like St. Olaf may have a profound impact on the pike population; it is difficult to generate an annual yield of more than a few pounds per acre of this predator without compromising the ability of the population to sustain itself. This places a greater reliance on stocking to "prop-up" the pike population and maintain a fishery and other ecosystem benefits provided by this top carnivore. A self-sustaining pike population with supplemental stocking is the preferred fisheries management option for St. Olaf Lake, and thus strict regulation of harvest (whether legal or voluntary) will be needed to realize this fishery management goal.

Largemouth bass – In terms of electrofishing catch rates, largemouth bass have been increasing with a more recent decrease in the population size-structure (Figure 10). Current population size may be too high to support quality-sized fish. Causes of recent increases in abundance and declines in size-structure and appropriate management options will need to be investigated.

Bluegill - Trap net sampling has been used to measure bluegill abundance in St. Olaf Lake. A research study examining sex ratios and timing of trap net sets by Minnesota DNR Fisheries is ongoing but preliminary evidence suggests that summer trapnetting may not give accurate snapshots of bluegill population status. Still, what we can glean from the long-term trends in trapnet catches is that bluegill is relatively abundant in St. Olaf and some large individuals are present in the population (Figure 10). Alternative sampling that better targets the bluegill population will be considered for future SLICE surveys.

Black and White Crappie - Black crappie recruitment appears much more variable than bluegill but overall, both species are relatively abundant and small (Figure 10). White crappie populations appear more abundant in the recent decade than in previous decades but the timing of when nets were set has changed over St. Olaf's surveyed history and this may have affected the vulnerability of white and black crappie. Like bluegill, summer trapnetting may not be adequate for characterizing black and white crappie population status and new survey techniques for evaluating black crappie trends will likely be implemented in the future.

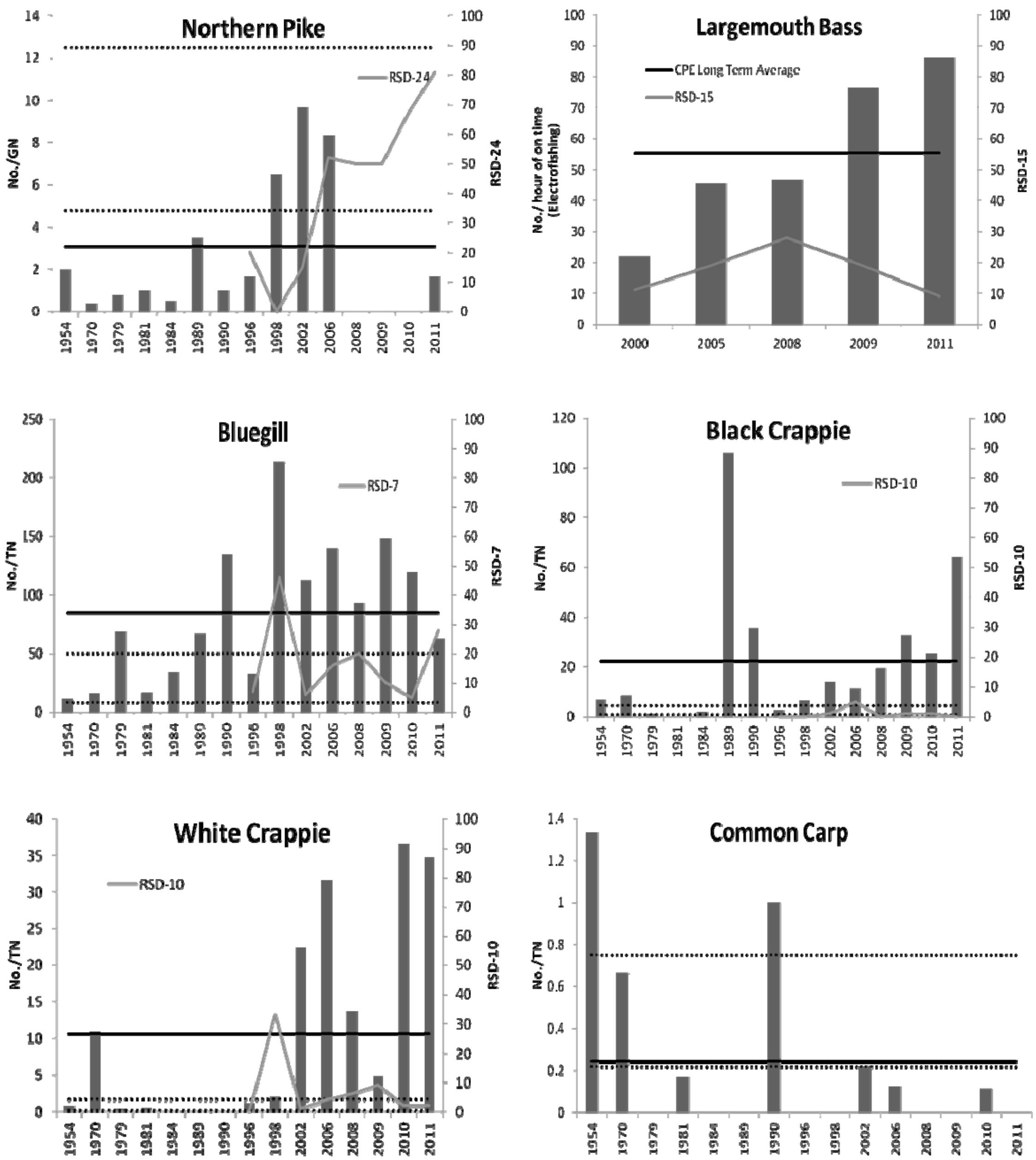
Common carp – Common carp have been rare in recent decades although commercial fishers removed as many as 10,370 lbs (2,302 individuals) of carp in 1971. Figure 10 suggests another population spike in 1990, but only two fish were caught in the two trapnets that were set during the 1990 survey. Carp likely migrate upstream from the LeSeuer River and occasionally successfully spawn in shallow, winterkill prone Reese (Mud) Lake, which is approximately 1 mi downstream from St. Olaf. A perfect combination of spawning conditions coupled with flood events may bring carp across migration barriers into St. Olaf Lake (Bajer and Sorensen 2010). Currently a fixed-type concrete sill with a screen prevents easy passage of carp from downstream. Spawning conditions within St. Olaf Lake are not likely favorable for carp spawning. Spawning conditions in Reese Lake and effectiveness of downstream fish barriers should be monitored to keep the carp population in the lake low. An outlet to Reese Lake has a fixed height concrete sill with screen that prevents fish passage. Reese lake is connected to the LeSueur River. Carp reproduction is assumed to be in lake or a product of high water years when adjacent low-lying areas get flooded and provide spawning habitat.

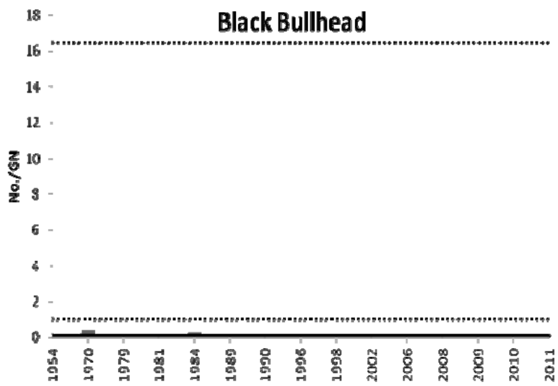
Black bullhead – Black bullhead have always been rare in St. Olaf. Given the tolerant nature of this species and widespread distribution, in lakes like St. Olaf, this is surprising. Nevertheless, predation upon black bullhead by largemouth bass and persistence of adequate winter oxygen for other predators are likely contributing factors to a low black bullhead population. A low black bullhead population is desirable from a fisheries and water quality standpoint.

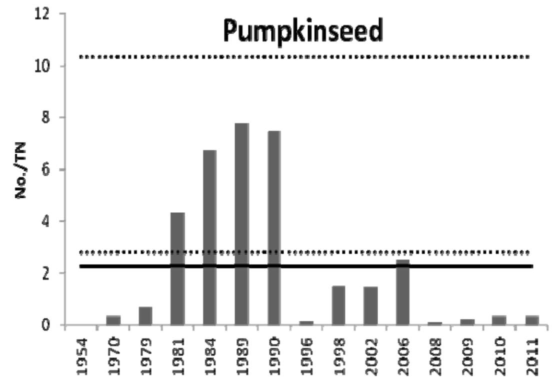
Pumpkinseed – Trap net sampling has been used to measure pumpkinseed abundance in St. Olaf Lake. Pumpkinseeds were most abundant in the 1980's, when strong year classes were documented in 1981 and 1986. Timing of sampling shifted from late July in the 1980's to mid-June starting in 1998. Four evenly distributed year classes were observed in 1990 during the last time pumpkinseeds were in relative high abundance; since that time it appears pumpkinseeds are not as well sampled in the earlier sample timing or are not as abundant recently as earlier in the catch history.

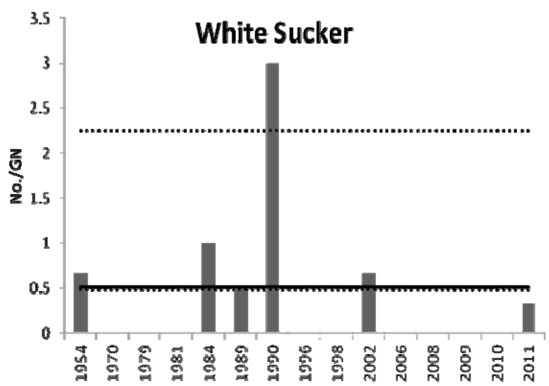
White Sucker, Yellow Bullhead, and Yellow Perch – Recruitment of these three species has been highly sporadic with an interesting simultaneous peak of populations in 1990 (Figure 10) High populations of other species are also noted in 1989-1990 (Figure 10). The cause of the apparent high fish productivity during this period is unknown but it may be related in part to the drought and flood cycles mentioned in the common carp narrative

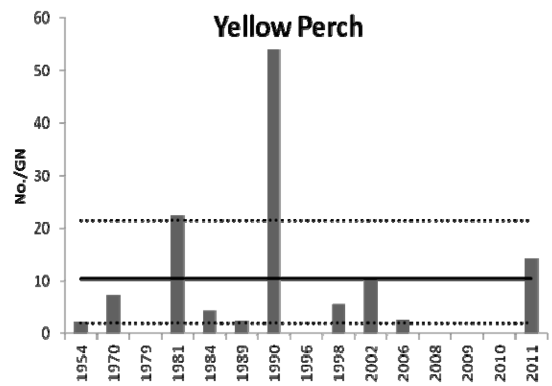
Figure 10 Historical net catches of major fish species in St. Olaf Lake, Waseca Co. Relative Stock Density of fish of sizes (in) typically regarded as desirable by anglers overlain on each figure. Dotted lines represent first and third quartiles for Lake Class 29 and solid line represents historical average catches per net for St. Olaf Lake.

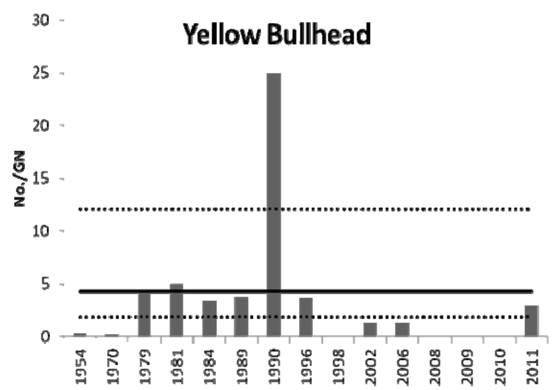



Black Bullhead
No./GN
18
16
14
12
10
8
6
4
2
0
1954
1970
1979
1981
1984
1989
1990
1996
1998
2002
2006
2008
2009
2010
2011


Pumpkinseed
No./TN
12
10
8
6
4
2
0
1954
1970
1979
1981
1984
1989
1990
1996
1998
2002
2006
2008
2009
2010
2011


White Sucker
No./GN
3.5
3
2.5
2
1.5
1
0.5
0
1954
1970
1979
1981
1984
1989
1990
1996
1998
2002
2006
2008
2009
2010
2011


Yellow Perch
No./GN
60
50
40
30
20
10
0
1954
1970
1979
1981
1984
1989
1990
1996
1998
2002
2006
2008
2009
2010
2011


Yellow Bullhead
No./GN
30
25
20
15
10
5
0
1954
1970
1979
1981
1984
1989
1990
1996
1998
2002
2006
2008
2009
2010
2011

Aquatic Plant Assessment

Presumably, because of St. Olaf's small watershed and moderate total phosphorus levels, submersed aquatic plants are relatively abundant and diverse compared with other lakes in the agricultural WCBP of Minnesota (Table 4, Table 5, Figure 11). Because past surveys up to 2008, were not quantitative or standardized, it is difficult to determine whether aquatic plant abundance or diversity has changed significantly over time.

Table 4 Aquatic plants sampled in St. Olaf Lake during historical lake surveys prior to 2008.

Year	Common Name	Species Name	Growth Form
1947	Muskgrass	*Chara sp.*	Submersed
	Stonewort	*Nitella sp.*	Submersed
	Large-leaf pondweed	*Potamogeton amplifolius*	Submersed
	Leafy pondweed	*Potamogeton foliosus*	Submersed
	Sago pondweed	*Stuckenia pectinata*	Submersed
	Flatstem pondweed	*Potamogeton zosteriformis*	Submersed
	Bushy pondweed	*Najas sp.*	Submersed
	Northern watermilfoil	*Myriophyllum sibiricum*	Submersed
	Canada waterweed	*Elodea canadensis*	Submersed
	White water buttercup	*Ranunculus longirstris*	Submersed
	Coontail	*Ceratophyllum demersum*	Submersed
	Greater duckweed	*Spirodela polyrrhiza*	Free-floating
	Lesser duckweed	*Lemna minor*	Free-floating
	White waterlily	*Nymphaea tuberosa*	Floating-leaf
	Yellow waterlily	*Nuphar variegatum*	Floating-leaf
1954	Softstem bulrush	*Scirpus validus*	Emergent
	Curly-leaf pondweed[a]	*Potamogeton crispus*	Submersed
	Claspingleaf pondweed	*Potamogeton richardsoni*	Submersed
	Large-leaf pondweed	*Potamogeton amplifolius*	Submersed
	Greater bladderwort	*Utricularia vulgaris*	Submersed
	Sago pondweed	*Stuckenia pectinata*	Submersed
	Flatstem pondweed	*Potamogeton zosteriformis*	Submersed
	Bushy pondweed	*Najas spp.*	Submersed
	Northern watermilfoil[b]	*Myriophyllum sibiricum*	Submersed
	Canada waterweed	*Elodea canadensis*	Submersed
	White water buttercup	*Ranunculus spp.*	Submersed
	Coontail	*Ceratophyllum demersum*	Submersed
	Lesser duckweed	*Lemna minor*	Free-floating
	Yellow waterlily	*Nuphar variegatum*	Floating-leaf
1970	Bulrush	*Scirpus sp.*	Emergent
	Horned pondweed	*Zannichellia palustris*	Submersed

	Curly-leaf pondweed[a]	*Potamogeton crispus*	Submersed
	Coontail	*Ceratophyllum demersum*	Submersed
	Northern watermilfoil	*Myriophyllum sibiricum*	Submersed
	Sago pondweed	*Stuckenia pectinata*	Submersed
	Bushy pondweed	*Najas spp.*	Submersed
	Claspingleaf pondweed	*Potamogeton richardsoni*	Submersed
	Greater duckweed	*Spirodela polyrrhiza*	Free-floating
	White waterlily	*Nymphaea tuberosa*	Floating-leaf
	Yellow waterlily	*Nuphar variegatum*	Floating-leaf
1984	Arrowhead	*Sagittaria sp.*	Emergent
	Common cattail	*Typha latifolia*	Emergent
	Muskgrass	*Chara sp.*	Submersed
	Narrowleaf pondweed	*Potamogeton strictifolius*[c]	Submersed
	Curly-leaf pondweed[a]	*Potamogeton crispus*	Submersed
	Large-leaf pondweed	*Potamogeton amplifolius*	Submersed
	White waterlily	*Nymphaea tuberosa*	Floating-leaf
	Yellow waterlily	*Nuphar variegatum*	Floating-leaf
1998	Muskgrass	*Chara sp.*	Submersed
	Canada waterweed	*Elodea canadensis*	Submersed
	Coontail	*Ceratophyllum demersum*	Submersed
	Northern watermilfoil	*Myriophyllum sibiricum*	Submersed
	Spiny naiad[c]	*Najas marina*	Submersed
	Large-leaf pondweed	*Potamogeton amplifolius*	Submersed
	Water celery	*Vallisneria americana*	Submersed
	Curly-leaf pondweed[a]	*Potamogeton crispus*	Submersed
	Sago pondweed	*Stuckenia pectinata*	Submersed
	Lesser duckweed	*Lemna minor*	Free-floating
	Greater duckweed	*Spirodela polyrrhiza*	Free-floating
	White waterlily	*Nymphaea tuberosa*	Floating-leaf
2002	Hardstem bulrush	*Scirpus acutus*	Emergent
	River bulrush	*Scirpus fluviatilis*	Emergent
	Three square	*Scirpus pungens*	Emergent
	Muskgrass	*Chara sp.*	Submersed
	Coontail	*Ceratophyllum demersum*	Submersed
	Canada waterweed	*Elodea canadensis*	Submersed
	Filamentous algae		
	Water stargrass	*Heteranthera dubia*	Submersed
	Northern watermilfoil	*Myriophyllum sibiricum*	Submersed

Bushy pondweed	*Najas flexilis*	Submersed
Large-leaf pondweed	*Potamogeton amplifolius*	Submersed
Curly-leaf pondweed[a]	*Potamogeton crispus*	Submersed
Illinois pondweed	*Potamogeton amplifolius*	Submersed
Clasping-leaf pondweed	*Potamogeton richardsoni*	Submersed
Narrow-leaf pondweed	*Potamogeton spp.*	Submersed
Sago pondweed	*Stuckenia pectinata*	Submersed
Water celery	*Vallisneria americana*	Submersed
White waterlily	*Nymphaea odorata*	Floating-leaf
Yellow waterlily	*Nuphar variegatum*	Floating-leaf

[a]Non-native

[b]Alternate flowered watermilfoil (*M. alterniflorum)* was entered as abundant in the survey but is rarely found, much less abundant in lakes like St. Olaf; it was likely confused with Northern watermilfoil.

[c]Identification is questionable

Table 5 Percent frequency of occurrence of aquatic plant species at depths ≤ 15 feet sampled during point-intercept surveys on 26 August 2008, 21 August 2009, 30 July 2010, and 1 August 2011 at St. Olaf Lake, Waseca County, MN.

Season	Common Name	Species Name	Growth Form	Frequency (%) 2008	2009	2010	2011
Spring[a]	All rooted plants			65.3[b]	17.6[b]	19.2[b]	36.2[b]
	Filamentous algae			59.6	5.9	42.3	42.6
	Coontail	*Ceratophyllum demersum*	Submersed	46.2	2.0	1.9	6.4
	Curly-leaf pondweed[c]	*Potamogeton crispus*	Submersed	40.4	9.8	7.7	12.8
	Flat-stem pondweed	*Potamogeton zosteriformis*	Submersed	23.1	0	3.8	8.5
	Muskgrass	*Chara sp.*	Submersed	9.6	0	5.8	0
	Northern watermilfoil	*Myriophyllum sibiricum*	Submersed	7.7	2.0	0	6.4
	Yellow waterlily	*Nuphar sp.*	Floating-leaf	1.9	0	1.9	0
	White waterlily	*Nymphaea sp.*	Floating-leaf	0	3.9	1.9	8.5
	Sago pondweed	*Stuckenia pectinatus*	Submersed	0	0	5.8	0
	Bushy pondweed	*Najas flexilis*	Submersed	0	0	0	8.5
Summer	All rooted plants			25.5	37.5	37.2	53.1
	White waterlily	*Nymphaea sp.*	Floating-leaf	17.6	16.7	23.5	20.4
	Coontail	*Ceratophyllum demersum*	Submersed	11.8	9.6	2.0	12.2
	Filamentous algae			11.8	0	15.7	18.4
	Yellow waterlily	*Nuphar sp.*	Floating-leaf	5.9	4.2	5.9	6.1
	Clasping-leaf pondweed	*Potamogeton richardsonii*	Submersed	3.9	0	0	4.1
	Flat-stem pondweed	*Potamogeton zosteriformis*	Submersed	2	0	2.0	8.2
	Northern watermilfoil	*Myriophyllum sibiricum*	Submersed	2.0	2.1	0	12.2
	Sago pondweed	*Stuckenia pectinatus*	Submersed	2.0	12.5	3.9	10.2

Water stargrass	*Zosterella dubia*	Submersed	2.0	0	0	0
Curly-leaf pondweed[c]	*Potamogeton crispus*	Submersed	0	10.4	0	12.2
Bushy pondweed	*Najas flexilis*	Submersed	0	8.3	2.0	0
Wild celery	*Vallisneria americana*	Submersed	0	4.2	2.0	0
Muskgrass	*Chara sp.*	Submersed	0	0	2.0	6.1
Naiads	*Najas sp.*	Submersed	0	0	11.8	18.4
Curly-leaf pondweed[c]	*Potamogeton crispus*	Submersed	0	0	3.9	0
Max depth of veg growth (ft)[d]			3.8	5	3.9	6.1

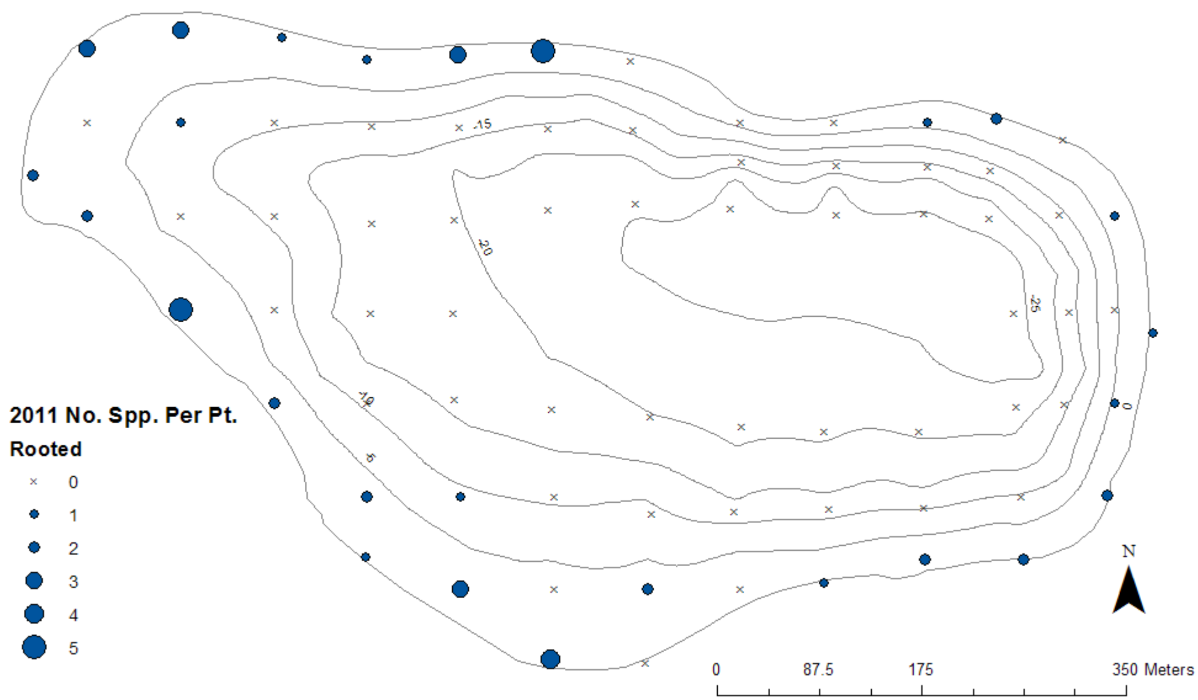
[a]Surveys targeted curly-leaf pondweed

[b]Surveyed on 12 June 2008, 19 May 2009, 25 May 2010, 1 June 2011

[c]Non-native

[d]Depth of 95 percent of all plant occurrences

Figure 11 Number of aquatic species sampled at each survey point during a survey on 1 August 2011 in St. Olaf Lake, Waseca Co.



Curly-leaf pondweed

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. The plant was first observed in St. Olaf during the 1954 lake survey. Curly-leaf pondweed grows most abundantly during early spring and senesces by mid-summer. When curly-leaf pondweed is abundant, mid-summer dieback is often followed by algae blooms, which limit light penetration that may, in turn limit growth of native aquatic plants. Consequently, aquatic plant growth during mid- to late-summer is typically sparse in lakes where curly-leaf pondweed is abundant in spring. However, that pattern does not appear consistent in St. Olaf and native plant growth remains after curly-leaf pondweed senescence.

Curly-leaf pondweed thrives in nutrient-rich conditions and at some threshold of nutrients (exact quantity unknown), is presumed to be 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 with little rooted plant growth in summer are most common in eutrophic to hypereutrophic lakes in the southern half of the state. Due to the moderate phosphorous levels in St. Olaf, it occupies a state somewhere in the middle; that is, abundant curly-leaf pondweed *and* abundant native plants that persist throughout summer. Additional nutrient loading into St. Olaf would likely greatly reduce if not eliminate summer aquatic plant growth and have negative consequences for water quality and fish habitat.

In contrast to southern eutrophic Minnesota lakes, curly-leaf pondweed is less abundant (if present at all) and typically is integrated with other aquatic plants in northern mesotrophic lakes. 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 cover was assessed with point-intercept vegetation surveys in the spring from 2008-2010 (Table 5). Interestingly, we have observed a steep decline of curly-leaf pondweed frequency of occurrence over the four years the plant was assessed (40 percent in 2008 to 10 percent in 2009 to 8 percent in 2010, back up to 13 percent in 2011; Table 5). In 2010, despite the warmer than normal spring with early ice-out conditions, we actually observed lower curly-leaf pondweed abundance in St. Olaf and several other infested lakes across the sentinel network (unpublished survey data). In contrast, the springs and summers of 2008 were slightly-to-moderately cooler than the 1971-2000 normal (Winnebago NWS station growing degree base 40 F analysis; Figure 8). The effect of climate time lags on curly-leaf pondweed growth should be evaluated.

In summary, shoreline development is relatively high on St. Olaf Lake. Thirty-nine dock structures were enumerated from aerial photos acquired from the Farm Service Administration in summer 2010 (1 dock ever 211 ft of shoreline). Lakeshore owners are allowed to remove submersed aquatic plants from a 2500 square foot area in front of their lake frontage without a permit. Therefore, lakeshore owners have the potential to remove 2.2 acres of aquatic plants. A permit from the MDNR is required for any removal beyond 2500 square feet or if chemicals are used for the treatment of aquatic plants. There has been only one permit for up to 0.46 acres of removal since 2007. Consequently, current aquatic plant removal activities probably have a relatively small impact on fish habitat in the lake. Minimal removal of aquatic plants will be required for maintaining quality fish habitat in St. Olaf Lake.

Water Quality

Standard summer-mean water quality results from 2008 and 2009 are summarized in Table 6 In addition; cations, anions, and organic carbon were analyzed on several dates and are summarized in Table 7. Individual water chemistry results are in the Appendix.

Table 6 St. Olaf Lake 2008-2009 as compared to typical range for WCBP ecoregion reference lakes

Parameter	2008-2009 summer mean	WCBP Reference Lake Inter-quartile
Number of reference lakes		**16**
Total Phosphorus (µg/L)	35	**65 – 150**
Chlorophyll mean (µg/L)	21	**30 – 80**
Secchi Disk (Meters)	1.1	**0.5-1.0**
(feet)	(3.6)	**(1.6 - 3.2)**
Total Kjeldahl Nitrogen (mg/L)	1.2	**1.3 – 2.7**
Nitrate-N (mg/L)	0.06	
Alkalinity (mg/L)	133	**125 – 165**
Color (Pt-Co U)	8	**15 – 25**
pH (SU)		**8.2 – 9.0**
Chloride (mg/L)	21	**13 – 22**
Total Suspended Solids (mg/L)	7.9	**7 – 18**
Total Suspended Inorganic Solids (mg/L)	6.1	**3 – 9**
Conductivity (µmhos/cm)	320	**300 – 650**
TN:TP ratio	34:1	**17:1 – 27:1**

Table 7 St. Olaf cation, anion, silica, iron, and organic carbon. Minnesota National Lakes Assessment interquartile results provided as a basis for comparison.

	Alk.	**Ca**	**Mg**	**Na**	**K**	**SO4**	**Cl**	**Si**	**Fe**	**TOC**	**DOC**
Date	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	ug/l	mg/l	mg/l
4/22/08	140	38.4	18.2	6.5	3.1	5.4	21.0			6.1	
7/15/08	120	36.0	18.5	6.8	2.9	6.1	20.6			7.3	
10/22/08	150	36.8	19.9	8.6	3.3	4.9	20.5			7.1	
4/29/09	150	37.4	19.1	6.5	3.1	5.1	21.2		49.2	7.5	
7/15/09	130	29.5	18.7	6.9	3.1	5.5	21.7	1.6	52.4	8.6	
10/15/09	140	32.4	18.7	6.8	3.2	4.9	22.9	2.9	24.5	7.1	
4/29/10	140	37.5	20.0	7.1	3.4	5.3	22.0		41.0	7.6	7.5
7/21/10	110	25.5				5.7	21.6	2.6		7.7	6.9
10/6/10	130	30.8	17.9		3.4	4.7	19.8	1.5		7.3	6.2
8/30/10	120	24.9	18.3	6.5	3.0	5.2	22.0		60.0		
mean	**133**	**32.9**	**18.8**	**7.0**	**3.2**	**5.3**	**21.3**	**2.1**	**45.4**	**7.4**	**6.9**
NLA 25th %		**19.1**	**6.7**	**2.2**	**0.9**	**2.2**	**1.5**			**7.3**	
NLA 75th %		**33.7**	**26.9**	**9.0**	**4.8**	**14.0**	**18.4**			**14.2**	

Dissolved Oxygen and Temperature

Profile measurements were taken regularly at one-meter intervals through the water column on each sample event. There were volunteer measurements in addition to the MPCA staff measurements and this allowed for development of isopleths (Figure 12). St. Olaf mixes soon after ice-out and remains thermally well mixed into mid April (Figure 12). Dissolved oxygen (DO) super-saturation (water holds more oxygen than anticipated based on temperature) was evident in April. This is likely because of diatom blooms combined with the very cool water that holds more oxygen. By May, thermal stratification becomes established. With the onset of thermal stratification the bottom waters quickly become hypoxic (<2.0 mg/l; (Figure 12). This hypoxic zone extends from the bottom of the lake up to a depth of four meters by mid-summer and remains this way until fall mixing that occurs near mid September in most years. Since most game fish prefer DO >5 mg/L this implies that only depths from the surface to about 3-4 meters would have been suitable for fish when the lake is stratified.

There were some differences in the DO and temperature regimes for the three summers. Summer 2010 was warmer than 2008 and 2009 and surface temperatures exceeded 26 C from mid July to mid August. In 2009, surface temperatures did not reach 26 C and in 2008, 26 C was attained for only a few days. Timing of fall mixing varied. In 2010 mixing occurred by mid September; however, in 2008 and 2009 it did not occur until late September to early October.

Phosphorus

Phosphorus is typically considered the limiting nutrient for algal growth on Minnesota lakes, and was monitored during the summers of 2008-2009 and then seasonally in 2010. Summer-mean TP is below the typical range for WCBP lakes (Table 6). TP is high in the spring following spring turnover and mixing with the nutrient-rich hypolimnetic waters (Figure 13). Spring TP in 2008 and 2009 were quite comparable; however, 2010 was much lower. By May, TP declines primarily because of diatom uptake of P and the sedimentation of diatom blooms. TP continues to decline throughout the summer because of algal growth and sedimentation; combined with minimal inputs from the watershed. A marked increase occurs in the fall with fall turnover and mixing of the lake.

A comparison of epilimnetic and hypolimnetic TP helps demonstrate the dynamics of the P cycle in the lake. Under aerobic and well-mixed conditions, epilimnetic and hypolimnetic measures are similar (Figure 14). As the lake stratifies and forms distinct layers, DO is quickly lost in the hypolimnion (Figure 12). DO is <2.0 mg/L (hypoxic) throughout the hypolimnion from late May through September in most years (Figure 12) and this promotes internal recycling of P. Hypolimnetic P varies among years (Figure 14) and this may be a function of the exact depth of sample collection, length of time of anoxic conditions and related factors. With fall mixing and re-aeration of the bottom waters hypolimnetic and epilimnetic waters mix and TP is relatively uniform in the water column. Well-mixed conditions were evident by the October sampling in all three years (Figure 12).

Figure 12 St. Olaf Lake dissolved oxygen (DO) and temperature isopleths for 2008, 2009, and 2010.

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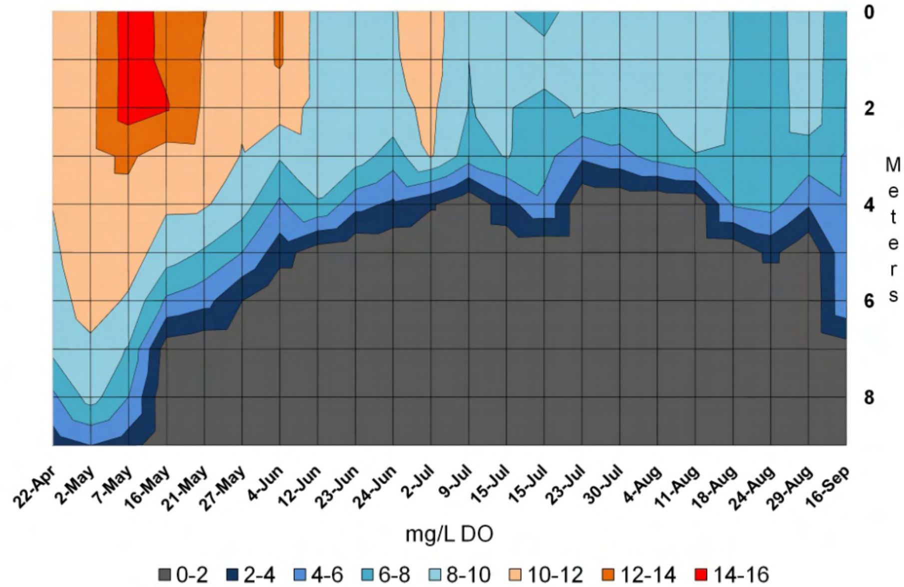

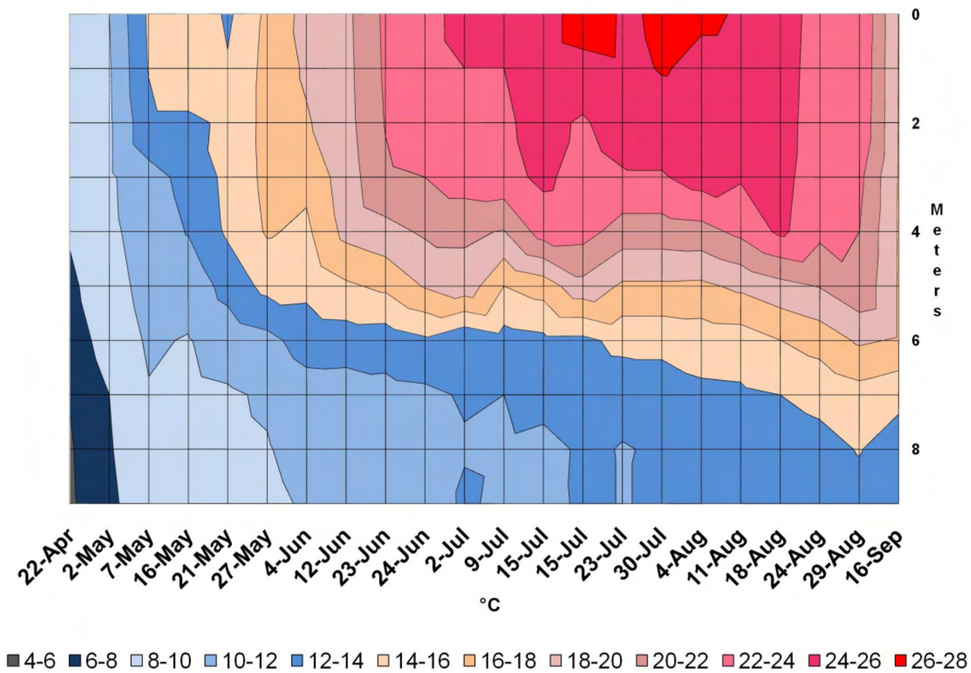

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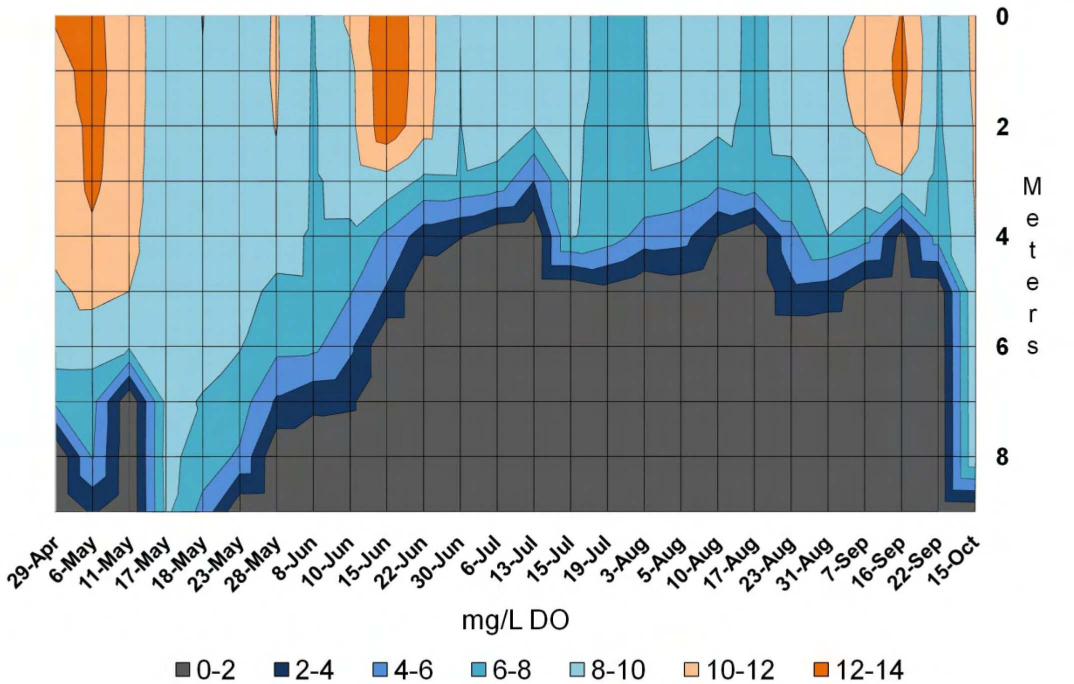

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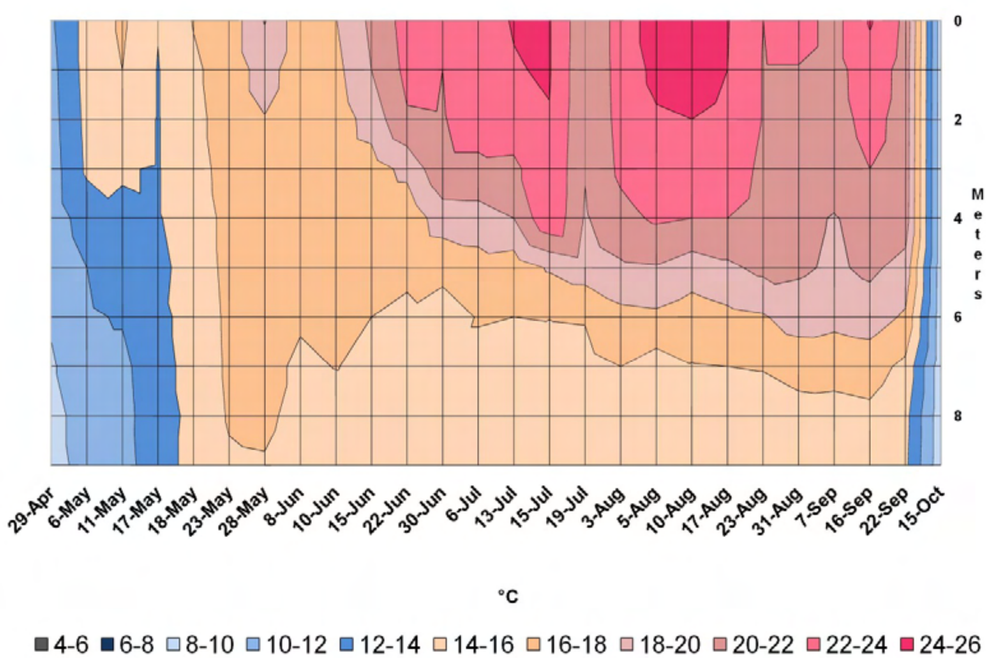

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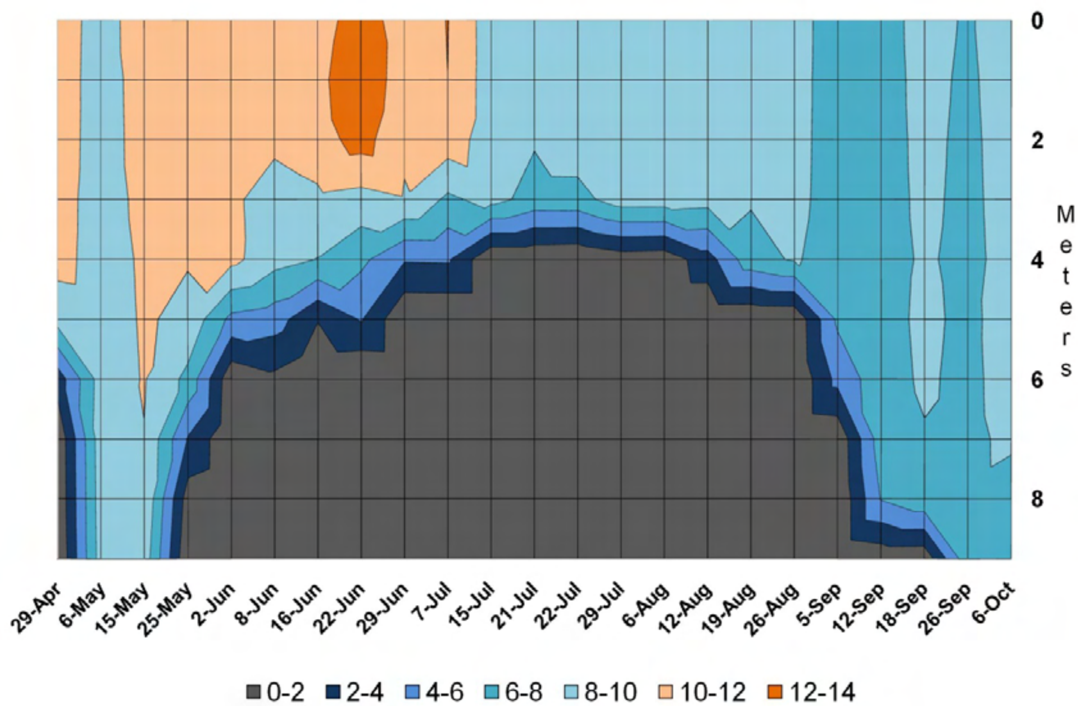
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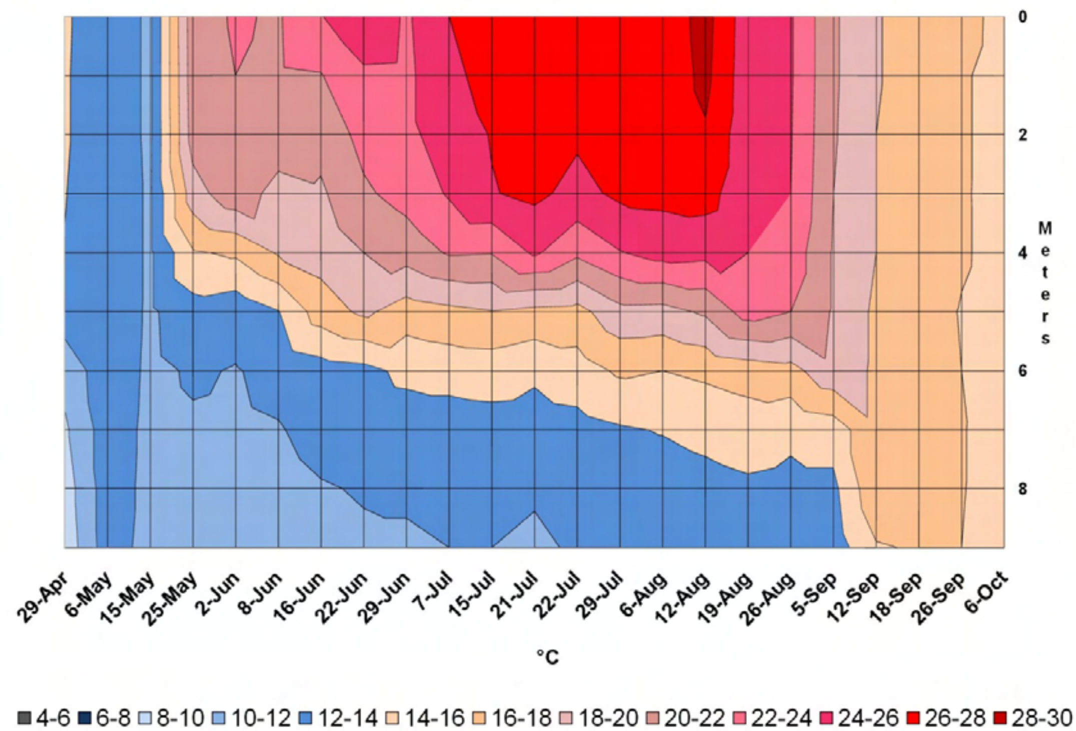
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Chlorophyll-a

Chlorophyll-a (Chl-a) is an indirect measure of the concentration of algae in lakes. Summer-mean Chl-a is on the lower end of the typical range for WCBP lakes (Table 6). Peak Chl-a in St. Olaf occurred in spring/early summer in 2008 and 2009 (Figure 13). This is a function of diatoms, which prosper in the nutrient and silica-rich waters of spring and early summer. Chl-a declines from these peaks and then increases again with fall mixing. Nuisance level (>20 µg/L) blooms did occur periodically during summer sample events.

Secchi disk transparency

Secchi measurements typically varies as a function of algal biomass (Chl-a). In St. Olaf Secchi declines in response to the major algal blooms and increases as algal biomass declines (Figure 13). Summer-mean Secchi in St. Olaf is above the typical range for WCBP lakes (Table 6).

Figure 13 Total phosphorus, Chl-a, and Secchi for 2008, 2009, and 2010.

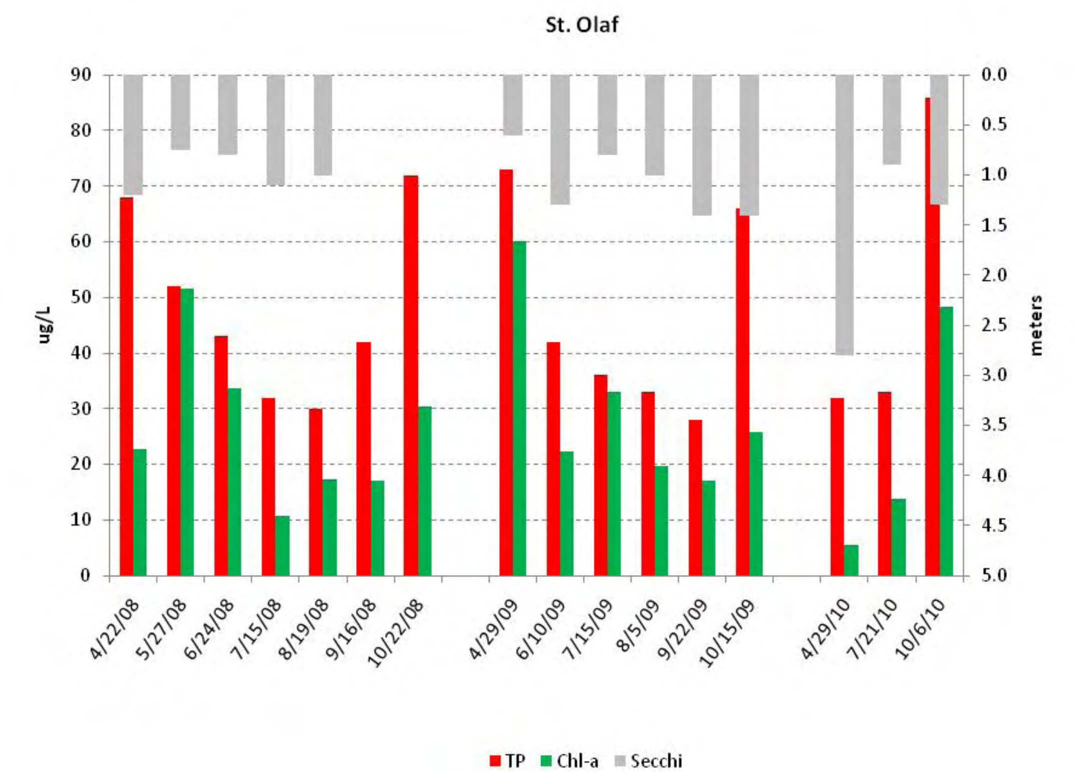
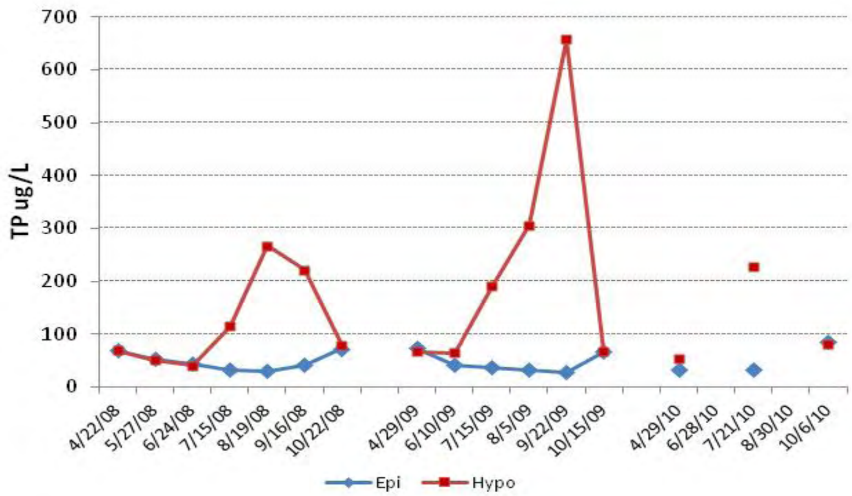


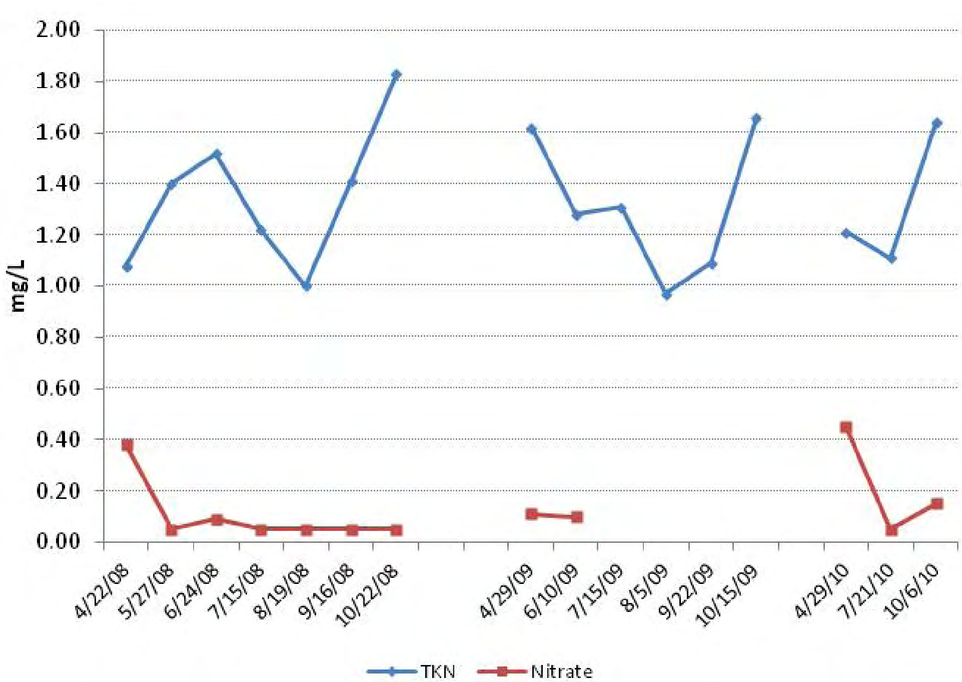
Figure 14 St. Olaf epilimnetic and hypolimnetic total phosphorus: 2008-2010



Nitrogen

Nitrogen is an essential nutrient for plant and algal growth. Total Kjeldahl nitrogen (TKN) is a measure of organic N and ammonia N. Nitrate and nitrite-N represent the oxidized inorganic N pool and most is in the nitrate form. Total nitrogen (TN) is the sum of TKN and nitrate-N. TKN for St. Olaf was at the lower end of the typical range for WCBP lakes (Table 6). Much of the TKN is in the algae so seasonal trends in TKN often mimic Chl-a (Figure 15). Nitrate-N, which is readily used by algae and rooted plants was at or below detection (0.05 mg/L) throughout most of the summer. Higher concentrations were associated with periods of higher runoff and well-mixed conditions in spring and fall (Figure 15)

Figure 15 St. Olaf TKN and nitrate-N for 2008-2010.



Dissolved minerals and organic carbon

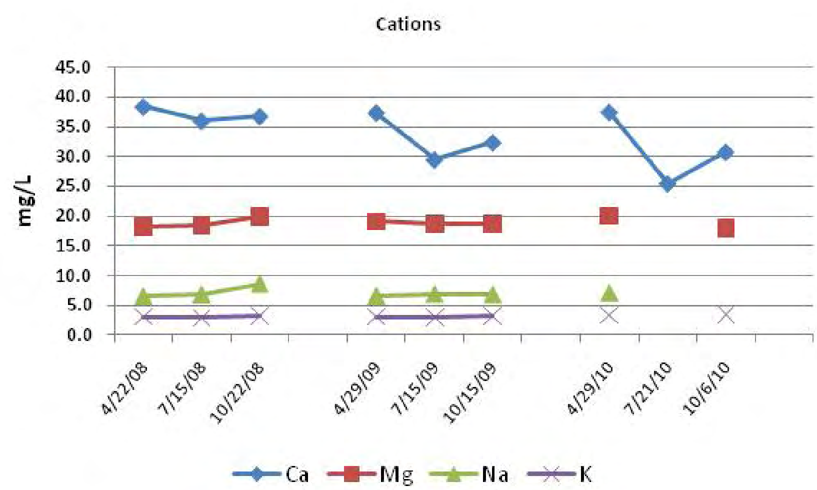
Dissolved minerals and organic carbon were measured in 2008, 2009, and 2010 as part of the long-term monitoring of St. Olaf and other Sentinel lakes. This includes some of the standard lake assessment measures of total suspended solids (TSS), alkalinity, conductivity and color (Table 6) as well as major cations, anions, silica, iron and organic carbon (Table 6). 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.

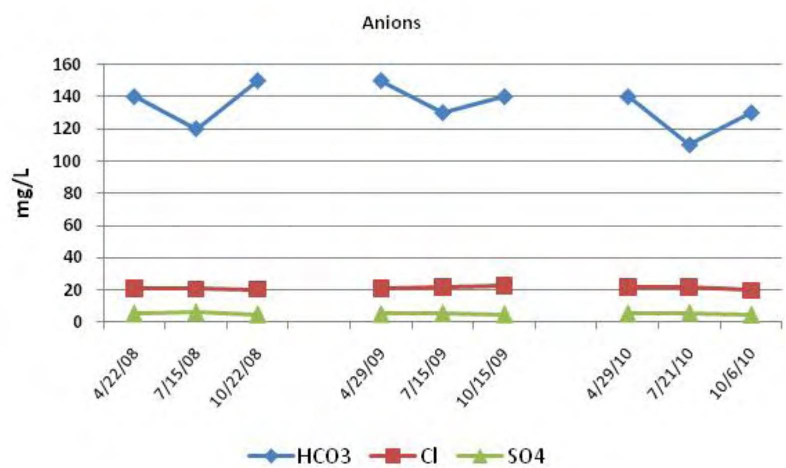
TSS is low as compared to WCBP reference lakes (Table 6) and most of the TSS can be attributed to organic SS (TSS-TSIS), i.e. suspended algae. The low color value indicates the water is clear and has minimal amount of dissolved organic carbon (DOC). As such, total organic carbon (TOC) is rather low and the majority of the TOC is in the DOC form, which is consistent with statewide data. Lakes that receive a majority of their water inputs from forest and wetland runoff often have correspondingly higher color and TOC values because of incompletely dissolved organic matter (plants, leaves, and other organic material).

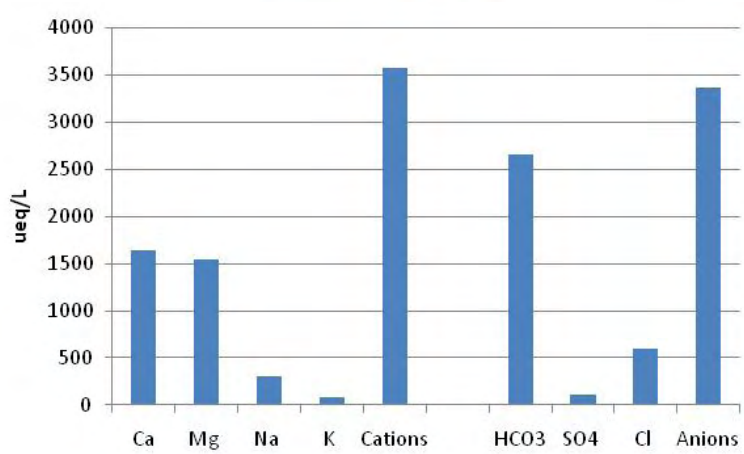
Alkalinity and conductivity are in the typical range for WCBP lakes and are indicative of hard water (Table 6). Most cation and anion concentrations were quite stable across sample events and years Table 7), which is consistent with the literature. Mg, Na, K, and Cl are noted to be relatively conservative and undergo only minor spatial and temporal change (Wetzel 2001). Mg is required by algae to produce chlorophyll-a and 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 fall may be caused by a fall diatom bloom (Figure 16).

Calcium (Ca) and magnesium (Mg) are the dominant cations and concentrations of both are within the typical range of the statewide data (Table 7). The other two major cations – sodium (Na) and potassium (K) are well within the typical range as well. Bicarbonate (alkalinity) is the dominant cation, followed by chloride (Cl) and sulfate (SO_4). Chloride is near the typical range for WCBP reference lakes (Table 6); however, it is low relative to statewide NLA data (Table 7). Elevated Cl is most often attributed to application of road salt on roads in the watershed. Sulfate is low relative to the NLA data Table 7). The average cation and anion balances (cation-anions expressed as a percentage of cations) for 2008 and 2009 were within 5 percent and 1 percent, which is well within values exhibited by the NLA lakes.

Figure 16 St. Olaf Lake cations and anions by date: 2008-2010 in mg/L and ion summary for 2008-2010 in µeq/L.







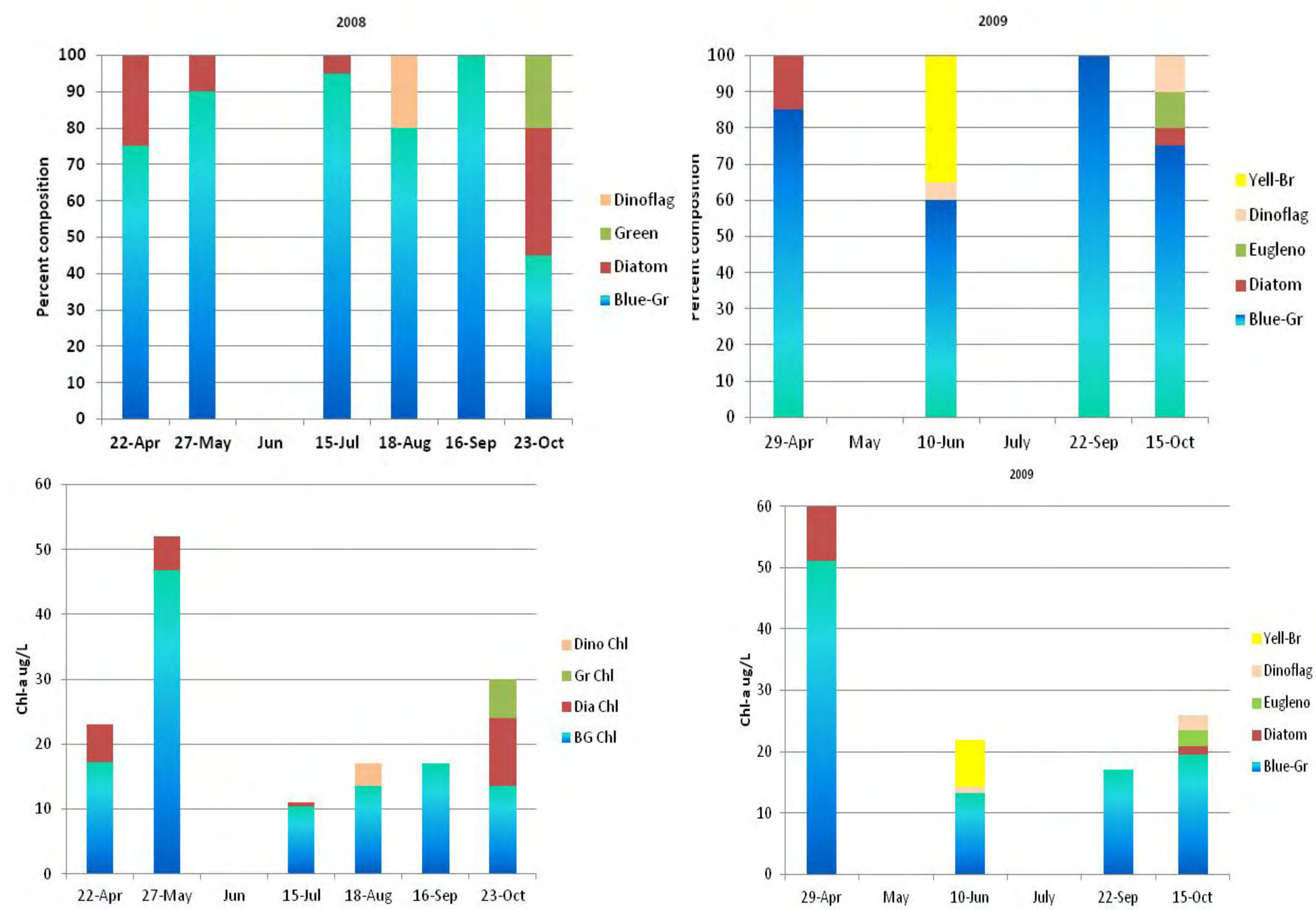
Phytoplankton (algae)

Chl-a 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 dominance of the various forms changes from spring to fall. For this purpose, algae samples were collected in St. Olaf. Blue-greens were dominant in St. Olaf samples on most dates (Figure 17). The spring dominance of blue-greens is rather surprising as diatoms are often the dominant form following spring turnover. *Microcystis* and *Aphanizomenon* were the dominant genera in May, followed by centric diatoms. In May and July, *Aphanizomenon* was the dominant blue-green. In August the dinoflagellate, *Ceratium*, was found but the blue-greens: *Aphanizomenon*, *Microcystis* and *Anabaena* were dominant. Aphanizomenon remained dominant in September. By October, centric diatoms and *Closterium* a green alga were among the dominant forms.

The percent contribution of the major algal forms can be used to estimate the relative contribution to Chl-a. If we use Chl-a > 20 as an indication of nuisance blooms – the May blue-green bloom would fall in that category (Figure 17). Though blue-greens were dominant on all sample dates the Chl-a concentrations on all other dates were relatively low and nuisance blooms may not have been evident on those dates.

The pattern of blue-green dominance was repeated in 2009 with many of the same dominant forms. Diatoms again were a rather small part of the algal community. Yellow-brown and Euglenophyte forms, which were not found in 2008, were present on two of the sample dates.

Figure 17 Major phytoplankton group composition and estimated contribution to algal biomass (Chl-a): 2008 and 2009.



Pesticide data

The Minnesota Department of Agriculture (MDA) analyzed water samples for several pesticides and their degradation products in 2009 through 2011. In St. Olaf, samples were collected on June 10, 2009, October 15, 2009, July 21, 2010, and August 12, 2011. The analyses conducted were similar to those included in the 2007 National Lakes Assessment (NLA); however, there have been some changes in analytic methodology and detection limits since that time resulting in additional analytes and lower method-reporting limits. The majority of the analytes were listed as non-detects (ND). Pesticides or their degradation products with detected concentrations are presented in Table 8.

The St. Olaf lake watershed is highly cultivated, and the associated pesticide use is likely reflected in the detection summary table. Detection frequency ranges from 25% to 100% for the various detected compounds. The detection frequency and measured concentration of pesticide degradate products tended to be higher than their associated parent pesticide for several compounds. With this said all pesticide detections in St. Olaf Lake are well below applicable water quality standards and benchmarks. The pesticide detections and concentration ranges in St. Olaf Lake are consistent with other lake sampling results of lakes located in highly cultivated areas in southern Minnesota.

Additional information about pesticide monitoring in Minnesota lakes, including the NLA report and MDA's annual monitoring reports, can be found at http://www.mda.state.mn.us/monitoring .

Table 8 Pesticides and degradation products detected in St. Olaf Lake. P = present.

Analyte	Detections	Samples	% Detection	Minimum (ng/L)	Maximum (ng/L)
2,4-D	2	2	100%	24.6	43.9
Acetochlor	3	4	75%	nd	70
Acetochlor ESA	4	4	100%	466	590
Acetochlor OXA	4	4	100%	460	780
Alachlor ESA	3	4	75%	nd	160
Alachlor OXA	2	4	50%	nd	90
Atrazine	4	4	100%	60	80
Azoxystrobin	1	2	50%	nd	33.8
Desethylatrazine	3	4	75%	nd	P (<50)
Dicamba	1	2	50%	nd	71.5
Dimethenamid ESA	2	4	50%	nd	70
Hydroxyatrazine	2	2	100%	134	155
Metolachlor	2	4	50%	nd	P (<70)
Metolachlor ESA	4	4	100%	315	610
Metolachlor OXA	4	4	100%	113	280
Propiconazole	1	4	25%	nd	P (<200)

Zooplankton

Zooplankton samples were analyzed by Jodie Hirsch at the MDNR. A summary report was prepared that included information for all the Sentinel lakes sampled in 2008 (Hirsch 2009). Results from 2009 and 2010 were charted by MPCA staff and will be included in the discussion below.

St. Olaf Lake had the highest number of taxa (15) among the WCBP ecoregion lakes in the 2008 season and intermediate mean density and biomass relative to lakes in the ecoregion (Table 8). Hirsch (2009) found that, in general, as lake productivity increased (e.g. TP or Chl-*a*) the relative abundance and biomass of zooplankton increased as well. This appears to be the case for St. Olaf and the other WCBP lakes.

Table 9. Sentinel Lake study zooplankton summary (Hirsch 2009)

Sentinel Lakes Zooplankton 2008	Mean Annual Densities (#/L)	Mean Annual Biomass (µg/L)	Total# Taxa
Western Corn Belt & Northern Glaciated Plains			
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
Madison	52.78	310.93	14
North Central Hardwood Forest			
Peltier	78.75	1098.39	12
Pearl	59.68	221.13	14
Belle	57.67	340.06	12
South Center	24.72	123.71	18
Carlos	19.66	73.49	16
Cedar	11.31	41.85	11
Northern Lakes and Forests			
Portage Lake	100.10	277.38	10
Cedar	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			

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

Zooplankton density was variable among seasons and years **(**Figure 18)**.** Typically, the zooplankton densities remain below 50 organisms per liter; however, in the spring of 2010, much higher numbers were seen. It was a very warm spring in 2010 (Figure 9) and ice off dates around St. Olaf Lake were late March/early April. Chl-*a* during the April 2010 sampling was the lowest of the three years (Figure 18) and was most likely a function of the high density of zooplankton. April 2010 zooplankton biomass was extremely high as well and Daphnia were an appreciable part of this (Figure 19). In general, though highest biomass occurs in April and May and declines over the summer. A fall resurgence (at overturn) is common in both years, though again the relative magnitude may vary. Average Daphnia size did not vary substantially among collections (Figure 18) and there was not a strong seasonal pattern for St. Olaf as is sometimes the case in other lakes. Daphnia are relatively large in St. Olaf Lake and thus may exert significant grazing pressure on algae in the lake and maintain relatively clear water.

A comparison of 2008 and 2009 biomass indicated the relative biomass of zooplankton and relative contribution of Daphnia may vary substantially among years (Figure 19).

Figure 18. St. Olaf seasonal zooplankton density for 2008, 2009 and 2010

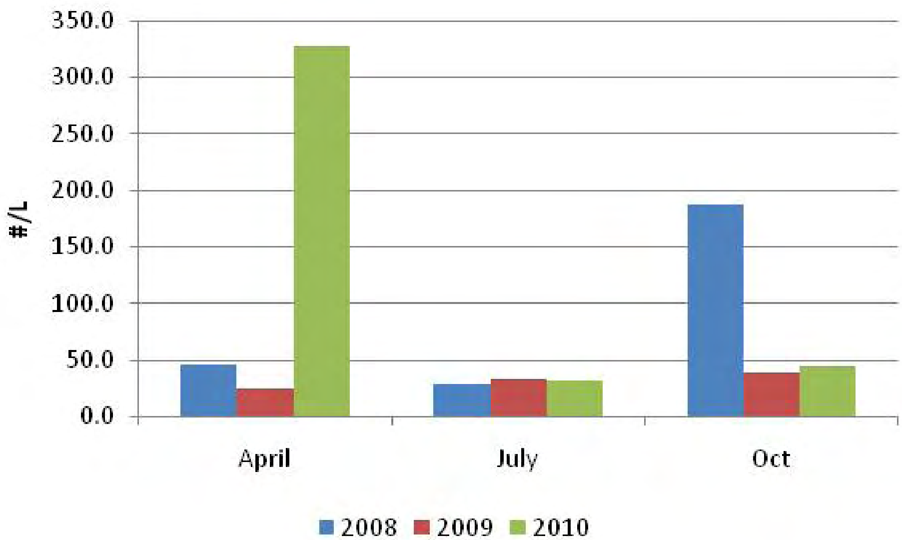
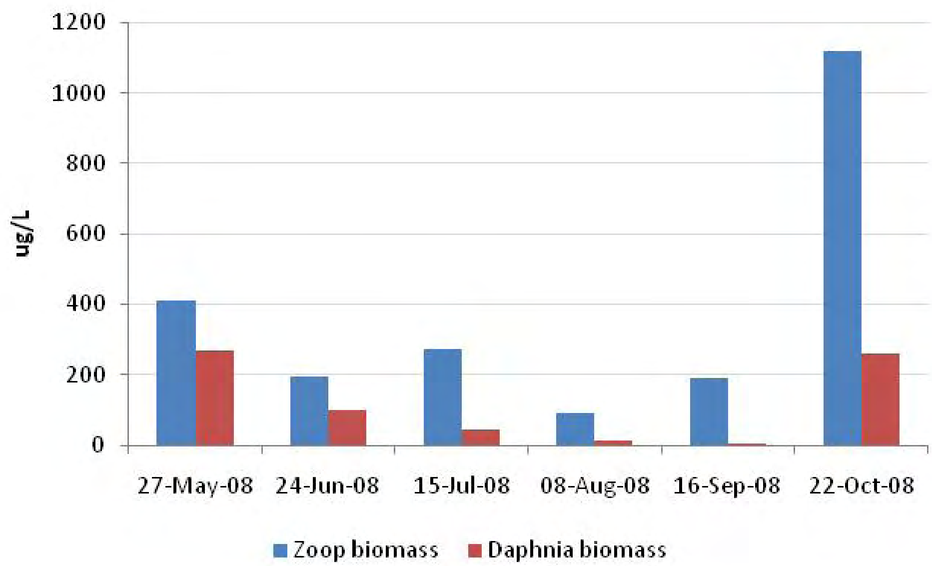


Figure 19. St. Olaf zooplankton and Daphnia biomass for 2008 and 2009



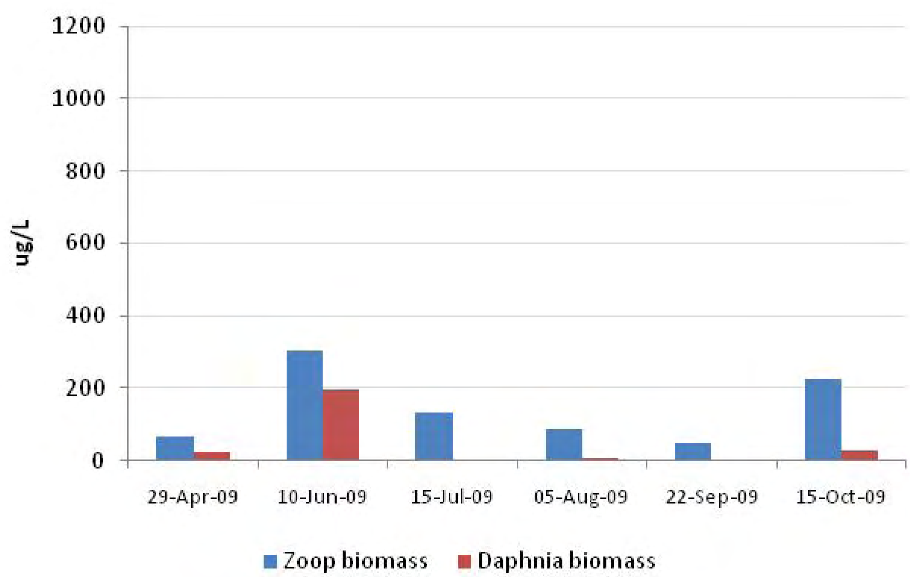
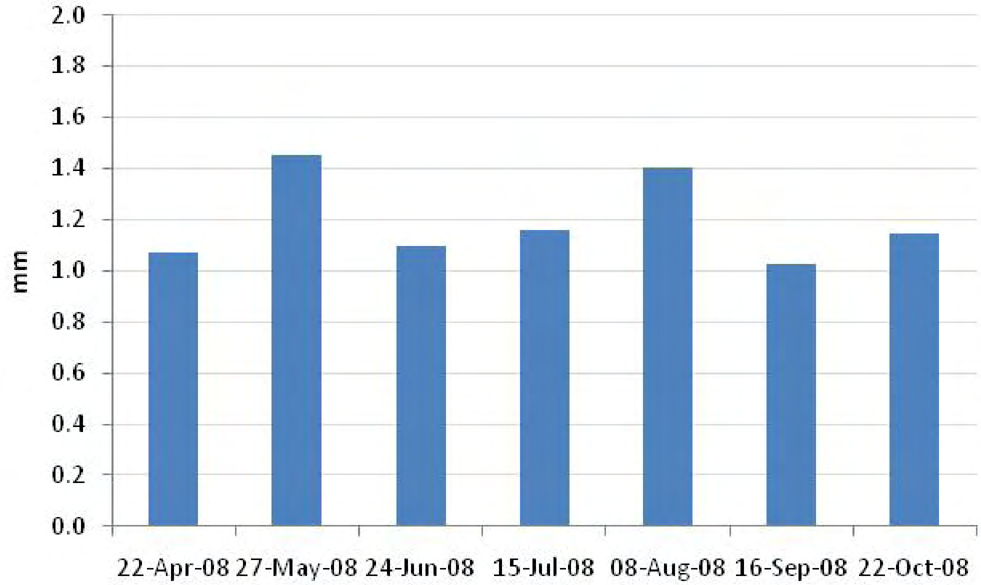
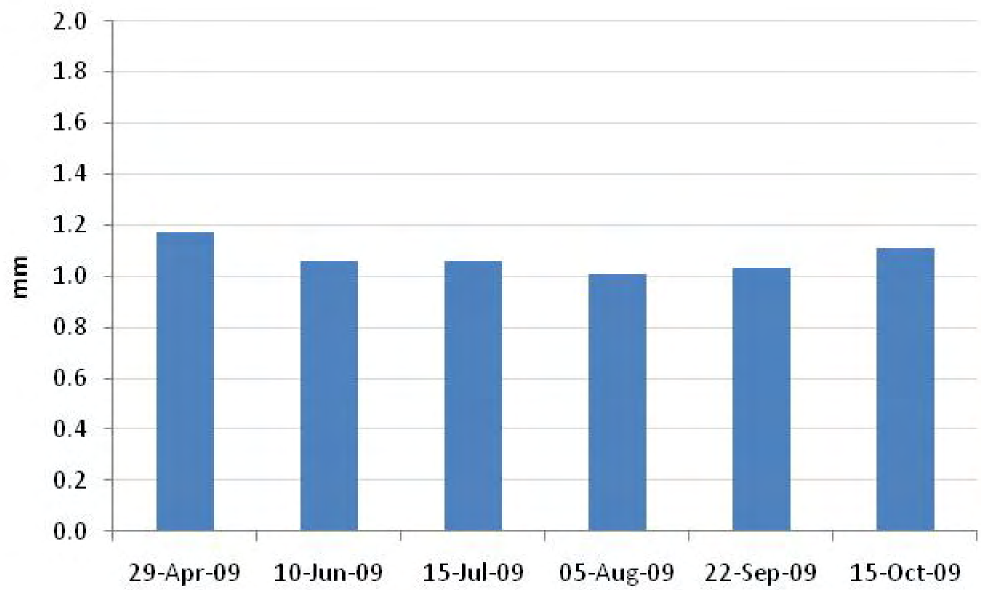


Figure 20. St. Olaf Daphnia size for 2008 and 2009





Trophic State Index and Trends

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). In this index, each increase of ten units represents a doubling of algal biomass. Comparisons of the individual TSI measures provides a basis for assessing the relationship among TP, Chl-a, and Secchi (Figure 29). In general, the TSI values are in close correspondence with each other. The average TSI values, based on summer 2008-2009 data, suggest that Chl-a and Secchi-based TSI values are slightly more eutrophic than would be anticipated based on TP (Figure 21). All three values are in the eutrophic range (Figure 21).

Charting summer-mean values (Figure 22) and corresponding TSIs provides further insight into trends and variability for St. Olaf Lake. Based on available data, summer-mean TP ranged from about 25–45 µg/L in St. Olaf (Figure 22) with a long-term average of 35 µg/L. Based on the five summers of data, over the 24-year period no trend is evident for TP. Summer-mean Chl-a ranged from 12-24 µg/L and averaged 19 µg/L over this same timeframe and no long-term trend was evident. The Secchi record is more complete and summer-mean Secchi has ranged from 1.8 – 2.6 m with a long-term mean of 1.5 m. Year-to-year variability in Secchi is evident, with measures cycling from deeper to shallower over a series of years; however based on the entire record there is evidence of a slight decline over time. A review of Secchi measures from past DNR fishery surveys from 1947, 1954 and 1984 revealed measurements of 0.6 m, 1.0 m, and 2.0 m, respectively, which suggests that measures in the modern-day record (Figure 22) are in the same range as those observed in earlier decades. Continued Secchi measurement through the CLMP will be essential to tracking trends over time in St. Olaf.

Charting TSI values provides another basis for trend analysis as well as helping to characterize the relationship among TP, Chl-a and Secchi TSIs (Figure 22). Agreement among the three variable is reasonable and generally within ±5 TSI units, though there is a tendency for the Chl-a TSI to indicate slightly more eutrophic conditions than anticipated based on TP or Secchi. Catching significant blooms in the monitoring events could in part explain this. Maximum Chl-a values in the 33-37 µg/L range in 1986, 2008 and 2009 may have served to elevate the means in those years. The trend of increasing trophic state based on Secchi is evident in these data as well.

Figure 21. Carlson Trophic State Index. Values for St. Olaf noted based on 2008-2010 data.

TSI < 30 Classical Oligotrophy: Clear water, oxygen throughout the year in the hypolimnion, salmonid fisheries in deep lakes.

TSI 30 - 40 Deeper lakes still exhibit classical oligotrophy, but some shallower lakes will become anoxic in the hypolimnion during the summer.

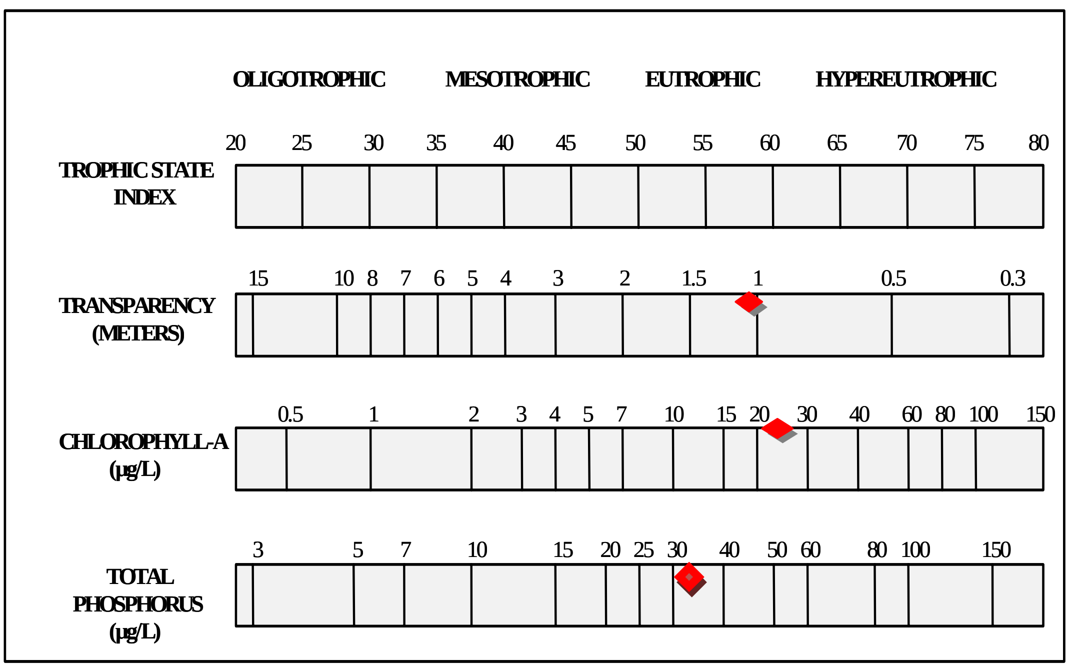
TSI 40 - 50 Water moderately clear, but increasing probability of anoxia in hypolimnion during summer.

TSI 50 - 60 Lower boundary of classical eutrophy: Decreased transparency, anoxic hypolimnia during the summer, macrophyte problems evident, warm-water fisheries only.

TSI 60 - 70 Dominance of blue-green algae, algal scums probable, extensive macrophyte problems.

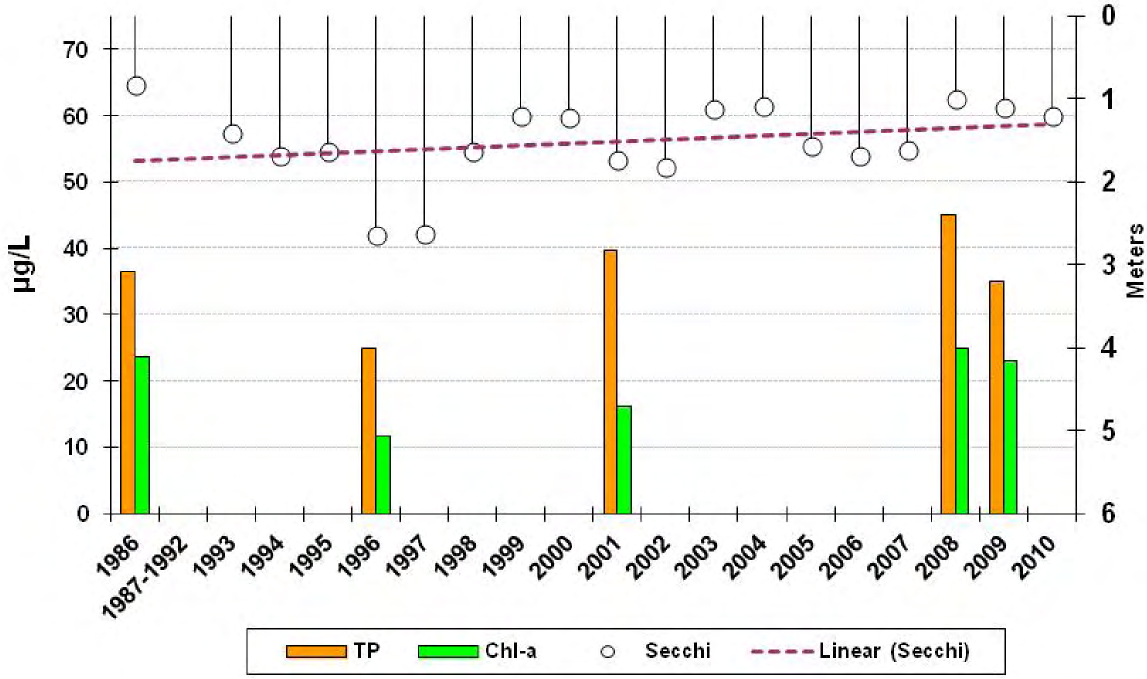
TSI 70 - 80 Heavy algal blooms possible throughout the summer, dense macrophyte beds, but extent limited by light penetration. Often would be classified as hypereutrophic.

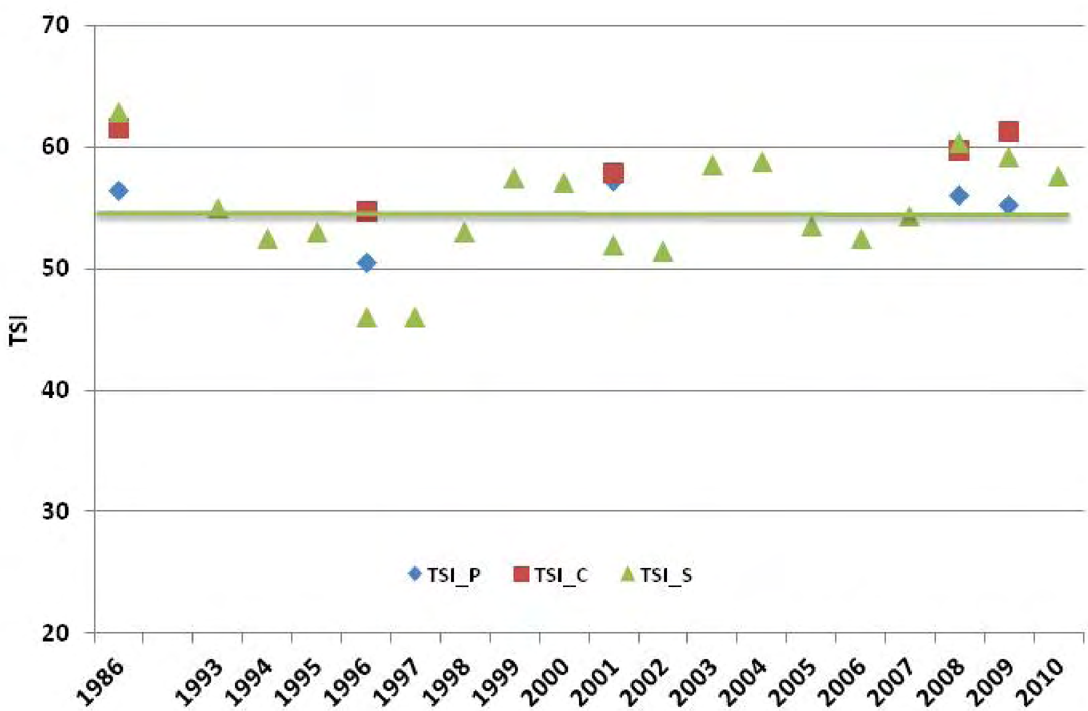
TSI > 80 Algal scums, summer fish kills, few macrophytes, dominance of rough fish.



After Moore, l. and K. Thornton, [Ed.]1988. Lake and Reservoir Restoration Guidance Manual. USEPA>EPA 440/5-88-002.

Figure 22. St. Olaf TP, Chl-a and Secchi and TSI summer-means. Simple linear regression for Secchi in upper chart and long-term mean Secchi TSI on lower chart.

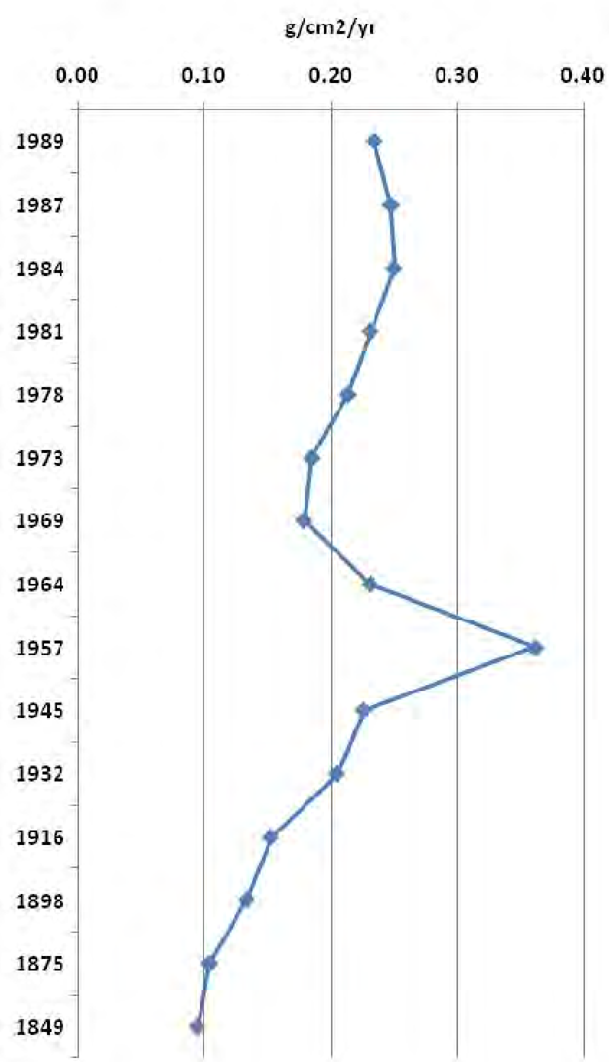




Sediment core study

St. Olaf was included in a study by Brigham (1992) that was designed to assess mercury and sediment accumulation rates in several Minnesota, Wisconsin, and Alaska lakes. For the Sentinel lakes, determining sediment accumulation rates is of particular interest. Brigham noted very high sediment accumulation rates in St. Olaf, as compared to the other lakes in the study. The core was about 130 cm and the deepest stratum in the core that he could reliably date was 140 years before present (1990), which corresponded to about 1840. Land clearing for agricultural uses was initiated in c1850. Sediment accumulation rates increased steadily from about 1850 through 1945 (Figure 23). From ~1945-1960 the rate of sediment accumulation peaked and then decreased, until the mid 1970s when rates increased but at a much lower rate than the 1945-1960 period. Brigham found unusually high Hg concentrations in the lower portion of the core, which was unanticipated since if the core reached pre-industrial sediments, Hg concentrations should attain relatively steady background levels (Brigham 1992). Hg concentrations increased further toward the top of the core. He attributes the elevated Hg in the sediment of St. Olaf Lake to excessive sedimentation rates that is most likely related to watershed disturbance, related to agricultural land use.

Figure 23. St. Olaf sediment accumulation rates (g/cm2/yr). Graphic modified from Brigham 1992.



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 predicted water quality as compared to the St. Olaf Lake, the Minnesota Lake Eutrophication Analysis Procedures (MINLEAP) model (Wilson and Walker, 1989) was used. The US Army Corps of Engineers model BATHTUB (Walker 1996) was also used to provide additional perspective and as a basis for estimating relative contributions from watershed, nearshore (e.g., on-site systems) and atmospheric sources.

MINLEAP was developed by MPCA staff based on an analysis of data collected from the ecoregion reference lakes. It is used as a screening tool for estimating lake conditions with minimal input data and is described in 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 St. Olaf Lake, MINLEAP was applied as a basis for comparing the observed TP, Chl-a, and Secchi values with those predicted by the model based on the lake size and depth and the area of the watershed.

Using MINLEAP, three model runs were conducted: a. WCBP inputs (ecoregion lake is in); b. calibrated WCBP inputs (stream inflow P reduced until modeled P = observed P), and c. NCHF inputs (adjacent ecoregion) to help bracket lake response (Table 9). Observed TP is slightly lower but not significantly different from the un-calibrated WCBP prediction. However observed Chl-a is slightly higher and Secchi is slightly lower than model-predicted. Based on the WCBP inputs the predicted P loading rate is about 167 kg/yr and the lake retains about 92 percent of the P that enters the lake. St. Olaf is also predicted to have a long water residence time, which is a result of the lake's very small watershed and the minimal outflow from the lake. Since these calculations do not directly consider groundwater input and output, they are estimates only.

A second model run was conducted whereby stream P input was reduced so that observed in-lake P was equal to predicted. This average stream inflow P concentration (377 µg/L) is likely a more reasonable estimate given that the WCBP un-calibrated stream P takes into account summer internal P recycling and incomplete sedimentation, which is common in shallow WCBP lakes. Given that St. Olaf is stratified in the summer months internal, recycling is likely a small input in the summer months. This model run estimated the P loading rate at 113 kg/yr.

A third model run was conducted with NCHF inputs since St. Olaf is near the transition of the WCBP and NCHF ecoregions. Those inputs, which include a lower stream TP, higher runoff and lower evaporation result in a much lower predicted P loading rate (63 kg/yr) an in-lake P.

One additional sub-routine in the MINLEAP model, referred to as Vighi and Chiaudani, provides an estimate of in-lake P that might be attributed to background P loading. This estimate is based on work described in Vighi and Chiaudani (1985) and could "loosely" be considered as an estimate of in-lake P prior to pre-European land settlement. For St. Olaf their equation predicts a background P of 23 µg/L, which is measurably lower than the observed P of 35 µg/L. This suggests that land use changes and related factors over time have increased the P loading to St. Olaf Lake, which is consistent with the sedimentation record for the lake (Figure 23).

Table 10. MINLEAP model predictions for St. Olaf Lake. WCBP & NCHF ecoregion inputs used. Standard error of model-predicted values noted.

Parameter	2008-2009 St. Olaf Lake Obs.	a. MINLEAP Pred. WCBP	b. MINLEAP Pred. WCBP (calibrated)	c. MINLEAP Pred. NCHF
TP (µg/L)	35 ± 3	44 ±19	36 ±15	25 ±10
Chl-a (µg/L)	21 ± 4	16.3 ±11.8	12.3 ±8.8	7.2 ±5.1
Secchi (m)	1.1 ± 0.1	1.5 ±0.7	1.8 ±0.8	2.4 ±1.1
P loading rate (kg/yr)		68	48	63
P retention (%)		92%	91%	89%
P inflow conc. (µg/L)		558	377	224
Water Load (m/yr)		0.34		0.32
Outflow volume (hm^3/yr)		0.30		0.28
Residence time (yrs)		~13		~14
Vighi & Chiaudani		23		23

BATHTUB inputs were similar to many of those used in MNLEAP but also employed watershed land use composition, estimated P export and runoff for each land use category uses, number of residences (cabins and homes) as a basis for estimating on-site system inputs to the lake, and estimated atmospheric P deposition on the lake. Standard long-term values were used for precipitation, evaporation and runoff. On-site P loading was estimated based on a count of 39 homes around the lake, using standard per capita P loads and a soil retention of 80 percent (based on techniques in Reckhow and Simpson 1980). The 80 percent retention assumes systems are generally up to code and the system and soils retain 80 percent of the P that enters the system. This is a best estimate based on previous application of this sub-routine and actual values (loads) may be higher or lower depending on age and maintenance of on-sites systems, soils, and related factors. The actual data inputs and sub-routines used in this BATHTUB model run are included in the Appendix.

Based on the above noted inputs predicted and observed TP are in good agreement and are not considered significantly different (Table 11). Similar to MINLEAP the model predicts a lower Chl-a and higher Secchi for St. Olaf, which suggests that St. Olaf produces more Chl-a per unit TP than expected based on typical empirical models.

Table 11. BATHTUB model summary results for St. Olaf Lake

BATHTUB	Predicted	Observed
TP µg/L	39	35
Chl-a µg/L	18	21
Secchi m	1.5	1.1
P loading rate (kg P/yr)	53	
P retention	97%	
Residence time (years)	~17	

BATHTUB also provides an opportunity to estimate relative contributions to the water and P loading to the lake from the three primary source categories considered watershed runoff, on-site system seepage to the lake and precipitation on the surface of the lake. Water loading to the lake was estimated based simply on watershed runoff, precipitation and evaporation. Based on these estimates precipitation directly on the lake accounts for about 70 percent while watershed runoff accounts for about 30 percent of the water load to the lake. It is important to note that the model does not account for groundwater inflow, which can be quite significant (on a relative basis) for lakes with small watersheds.

In terms of P loading, watershed runoff and seepage from shoreland on-sites systems potentially contribute a similar proportion of the overall estimated P load (Figure 24). A simple sensitivity analysis allows us to estimate the relative impact of increasing or decreasing P loading from any of these source categories on the in-lake P. As demonstrated in Figure 25, a doubling of the P loading from on-sites could potentially increase in-lake P to ~48 µg/L, whereas halving it would yield an in-lake P of ~33 µg/L. While these are only estimates, they are useful for demonstrating the relative importance of sources of water and phosphorus that enter the lake and provide a basis for estimating in-lake response to changes in any of the inputs.

Figure 24. Relative contribution to St. Olaf Lake P load

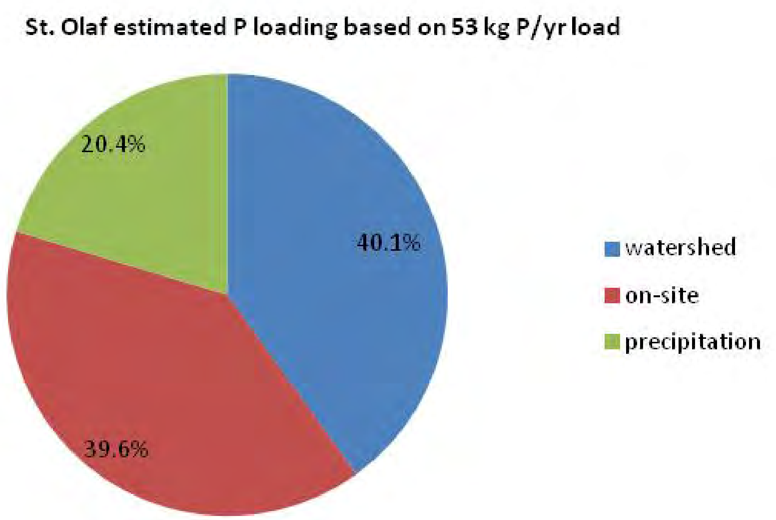
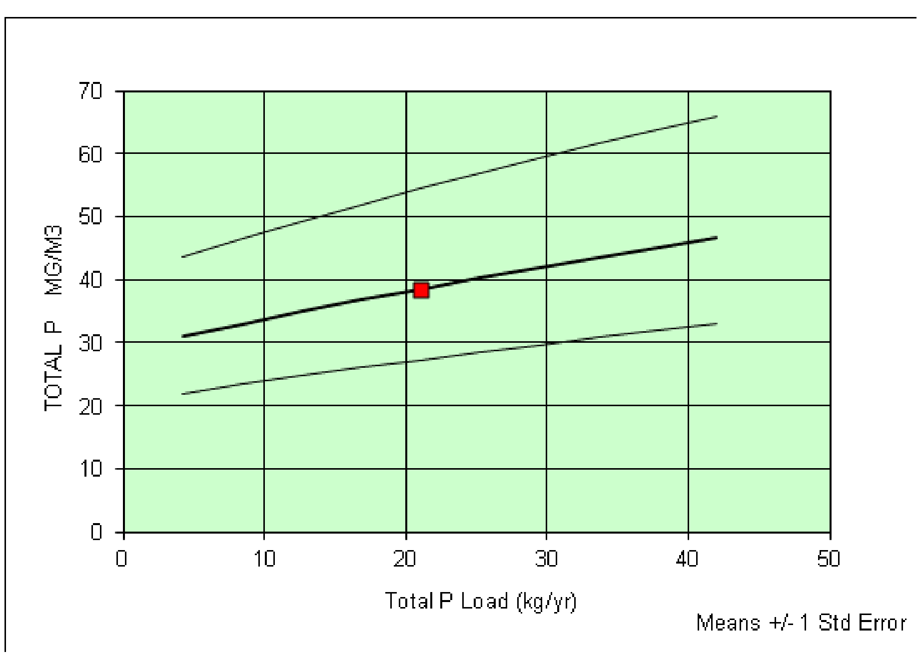


Figure 25. St. Olaf Lake predicted in-lake P as a function of varying on-site P input



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. We assess Minnesota’s water resources for numerous other water quality standards. An example is mercury found in fish tissue. If a water body is listed, an investigative 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. In Minnesota, the MPCA is responsible for performing assessment activities, listing impaired waters, and ensuring that TMDL studies are carried out.

Based on observed summer data from 2008-2010 St. Olaf meets the water quality standards for a deep WCBP lake (Table 11). While in-lake P is sufficiently below the standard Chl-a is rather close to the standard and this could be a reason for concern if concentrations were to increase further. It will be important that P loading to St. Olaf be reduced wherever possible to ensure that the lake continues to meet water quality standards and that algal concentrations (Chl-a) do not become excessive and impair uses on this small but important lake. The data in this report and the BATHTUB model framework will prove useful to any efforts to protect and improve the quality of St. Olaf Lake.

Table 12 Eutrophication standards and long-term summer-mean values.

Ecoregion	TP	Chl-*a*	Secchi
	µg/L	µg/L	meters
WCBP & NGP – Aquatic Rec. Use (Class 2B)	**< 65**	**< 22**	**> 0.9**
WCBP & NGP – Aquatic Rec. Use (Class 2b) Shallow lakes	**< 90**	**< 30**	**> 0.7**
Saint Olaf Lake 2008 – 2010 (June – September)	**35**	**21**	**1.1**

References

Bajer, P.B., and P.W. Sorensen. 2010. Recruitment and abundance of an invasive fish, the common carp, is driven by its propensity to invade and reproduce in basins that experience wintertime hypoxia in interconnected lakes. Biological Invasions 12: 1101-1112.

Brigham, M. 1992. Accumulation of mercury in Minnesota, Alaska, and Wisconsin lakes. A thesis submitted to the Graduate School of the University of Minnesota. In partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

Carlson, R.E. 1977. A trophic state index for lakes. Limnology and Oceanography. 22:361-369.

Carlson, R.E, and K.E. Havens. 2005. Graphical methods for the interpretation of relationships between trophic sate variables. Lake and Reserv. Manage. 21(1):107-118

Charpentier, F. and B.H. Jamnick. 1994. ZCOUNT-A zoological counting program. Version 2.4 Voila Data Inc., Gloucester, Ontario.

'Closest Station' Climate Data Retrieval, October 2007 – September 2008. State Climatology Office, Minnesota Department of Natural Resources. 2009.

Drake, M. T., and D. L. Pereira. 2002. Development of a fish-based index of biotic integrity for small inland lakes in central Minnesota. North American Journal of Fisheries Management 22:1105-1123.

Drake, M. T., and R. D. Valley. 2005. Validation and application of a fish-based index of biotic integrity for small central Minnesota lakes. North American Journal of Fisheries Management 25:1095-1111.

Madsen, J. D. 1999. Point intercept and line intercept methods for aquatic plant management. Army Corps of Engineers Waterways Experiment Station, MI-02, Vicksburg, MS.

Pierce, R.B. and Tomcko, C.M. (2005) Density and Biomass of Native Northern Pike Populations in Relation to Basin-Scale Characteristics of North-Central Minnesota Lakes. Transactions of the American Fisheries Society 134(1): 231-241.

Reckhow, K., and J. Simpson. 1980. A procedure using modeling and error analysis for the prediction of lake phosphorus concentration from landuse information. Can.J. Fish. Aquat. Sci. 37: 1439-1448.

Schupp, D. and B. Wilson 1993. Developing lake goals for water quality and fisheries. LakeLine. December 1993:18-21.

Scott, W.B. and E.J. Crossman. 1973. Freshwater fishes of Canada. Bull. Fish. Res. Board Can. 184:1-966.

Valley, R.D. 2010. Sustaining Lakes in a Changing Environment – SLICE: A working operational research and management plan for conserving Minnesota lake resources while confronting major ecological drivers of change: Phase 1 – 2008-2011.
http://files.dnr.state.mn.us/fish_wildlife/fisheries/slice/rm.pdf

Vighi, M. and G. Chiaudani. 1985. A simple method to estimate lake phosphorus concentrations resulting from background loading. Water Res. 19:987-991.

Walker, W.W. Jr. 1996. Simplified procedures for eutrophication assessment and prediction: Users Manual. Prepared for USACE Waterways Experiment Station Vicksburg MI. Report W-96-2.

Water Year Precipitation data State Climatology Office, Minnesota Department of Natural Resources. 2010.

Wetzel, R. 2001. Limnology. W.B. Saunders Co. Philadelphia. 3rd Ed.

Wilson, C. and W.W.Walker, Jr. 1989. Development of lake assessment methods based upon the aquatic ecoregion concept. Lake and Reserv. Manage. 5(2): 11-22.

Appendix: Recent water quality records & BATHTUB input/output

Nutrients, chlorophyll-a, and standard analytes: 2008-2010

	TP	Chl-a	Pheo	Secchi	TKN	NO3-N	NH4-N	Color	Cond	Temp	TSS	TSV
	mg/L	ug/L	ug/L	m	mg/L	mg/L	mg/L	PCU	umhos	C	mg/L	mg/L
4/22/08	0.068	22.7	2.3	1.2	1.080	0.380		10		9.5	6.8	4.0
5/27/08	0.052	51.5	5.1	0.8	1.400	0.050				16.4		
6/24/08	0.043	33.7		0.8	1.520	0.090			299	23.3		
7/15/08	0.032	10.7	15.8		1.220	0.050		5	328	24.5	4.8	3.2
8/19/08	0.030	17.2			1.000	0.050						
9/16/08	0.042	17.1	3.0		1.410	0.050						
10/22/08	0.072	30.4	3.7		1.830	0.050		10			8.4	4.0
4/29/09	0.073	60.2	8.1	0.6	1.620	0.110		5	320	11.7	17.0	12.0
6/10/09	0.042	22.4	1.8	1.3	1.280	0.100			357	17.9		
7/15/09	0.036	33.0	6.1		1.310			10			11.0	8.2
8/5/09	0.033	19.6		1.0	0.970				340	25.1		
9/22/09	0.028	17.1	0.5	1.4	1.090				310	21.5		
10/15/09	0.066	25.9	2.1	1.4	1.660		0.620	10	312	8.8	6.0	4.0
4/29/10	0.032	5.6	2.5	2.8	1.210	0.450	0.170	10	334	14.1	4.4	1.6
7/21/10	0.033	13.7	0.9	0.9	1.110	0.050	0.050	10	290	26.9	8.0	6.8
10/6/10	0.086	48.3	5.0	1.3	1.640	0.150	0.419	10	276	15.4	9.2	5.6

Cations and anions: 2008-2010

	Alk. Total	Calcium	Magnesium	Sodium	Potassium	Sulfate	Chloride	Silica	Iron Total	Iron Diss.
Date	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	ug/l	ug/l
4/22/08	140	38.4	18.2	6.5	3.1	5.4	21.0			
5/27/08										
6/24/08										
7/15/08	120	36.0	18.5	6.8	2.9	6.1	20.6			
8/19/08										
9/16/08										
10/22/08	150	36.8	19.9	8.6	3.3	4.9	20.5			
4/29/09	150	37.4	19.1	6.5	3.1	5.1	21.2		49.2	
6/10/09										
7/15/09	130	29.5	18.7	6.9	3.1	5.5	21.7	1.6	52.4	
8/5/09										
9/22/09										
10/15/09	140	32.4	18.7	6.8	3.2	4.9	22.9	2.9	24.5	
4/29/10	140	37.5	20.0	7.1	3.4	5.3	22.0		41.0	
7/21/10	110	25.5				5.7	21.6	2.6		17.2
10/6/10	130	30.8	17.9		3.4	4.7	19.8	1.5		19.9
8/30/10	120	24.9	18.3	6.5	3.0	5.2	22.0		60.0	

BATHTUB Model input and output

Global Variables	Mean	CV
Averaging Period (yrs)	1	0.0
Precipitation (m)	0.8	0.0
Evaporation (m)	0.9	0.0
Storage Increase (m)	0	0.0

Atmos. Loads (kg/km^2-yr	Mean	CV
Conserv. Substance	0	0.00
Total P	30	0.50
Total N	1000	0.50
Ortho P	15	0.50
Inorganic N	500	0.50

Model Options	Code	Description
Conservative Substance	0	NOT COMPUTED
Phosphorus Balance	8	CANF & BACH, LAKES
Nitrogen Balance	0	NOT COMPUTED
Chlorophyll-a	5	P, JONES & BACHMA
Secchi Depth	1	VS. CHLA & TURBIDIT
Dispersion	0	NONE
Phosphorus Calibration	1	DECAY RATES
Nitrogen Calibration	1	DECAY RATES
Error Analysis	1	MODEL & DATA
Availability Factors	0	IGNORE
Mass-Balance Tables	1	USE ESTIMATED CON
Output Destination	2	EXCEL WORKSHEET

Segment Morphometry

		Outflow		Area	Depth	Length	Mixed Depth (m)		Hypol Depth	
Seg	Name	Segment	Group	km^2	m	km	Mean	CV	Mean	CV
1	Lake	0	1	0.36	4.4	1	4.2	0	3	0

Segment Observed Water Quality

	Conserv		Total P (ppb)		Total N (ppb)		Chl-a (ppb)		Secchi (m)		Organic N
Seg	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean
1	0	0	35	0.1	1.2	0.2	21	0.2	1	0	0

Segment Calibration Factors

	Dispersion Rate		Total P (ppb)		Total N (ppb)		Chl-a (ppb)		Secchi (m)		Organic N
Seg	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean
1	1	0	1	0	1	0	1	0	1	0	1

Tributary Data

				Dr Area	Flow (hm^3/yr)		Conserv.		Total P (ppb)	
Trib	Trib Name	Segment	Type	km^2	Mean	CV	Mean	CV	Mean	CV
1	Watershed	1	2	0.77	0	0	0	0	0	0
2	On-site	1	3	0	0.01	0	0	0	2100	0

Tributary Non-Point Source Drainage Areas (km^2)

		Land Use Category--->							
Trib	Trib Name	1	2	3	4	5	6	7	8
1	Watershed	0.08	0.02	0.5	0.05	0.12	0	0	0
2	On-site	0	0	0	0	0	0	0	0

Non-Point Source Export Coefficients

		Runoff (m/yr)		Conserv. Subs.		Total P (ppb)		Total N (ppb)		Ortho P (p
Categ	Land Use Name	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean
1	forest	0.15	0	0	0	50	0	0	0	0
2	wetland	0.1	0	0	0	50	0	0	0	0
3	cultivated	0.15	0	0	0	200	0	0	0	0
4	pasture	0.15	0	0	0	100	0	0	0	0
5	urban	0.2	0	0	0	200	0	0	0	0
6		0	0	0	0	0	0	0	0	0
7		0	0	0	0	0	0	0	0	0
8		0	0	0	0	0	0	0	0	0

Model Coefficients	Mean	CV
Dispersion Rate	1.000	0.70
Total Phosphorus	1.000	0.45
Total Nitrogen	1.000	0.55
Chl-a Model	1.000	0.26
Secchi Model	1.000	0.10
Organic N Model	1.000	0.12
TP-OP Model	1.000	0.15
HODv Model	1.000	0.15
MODv Model	1.000	0.22
Secchi/Chla Slope (m^2/mg)	0.015	0.00
Minimum Qs (m/yr)	0.100	0.00
Chl-a Flushing Term	1.000	0.00
Chl-a Temporal CV	0.620	0
Avail. Factor - Total P	0.330	0
Avail. Factor - Ortho P	1.930	0
Avail. Factor - Total N	0.590	0
Avail. Factor - Inorganic N	0.790	0

Predicted & Observed Values Ranked Against CE Model Development Dataset

Segment: **1** **Lake**

Variable	Predicted Values---> Mean	CV	Rank	Observed Values---> Mean	CV	Rank
TOTAL P MG/M3	38.6	0.41	40.5%	35.0	0.10	36.4%
TOTAL N MG/M3	1.2	0.20	0.0%	1.2	0.20	0.0%
C.NUTRIENT MG/M3	0.8	0.00	0.0%	0.8	0.20	0.0%
CHL-A MG/M3	16.8	0.65	77.4%	21.0	0.20	85.2%
SECCHI M	1.6	0.28	69.3%	1.0		46.0%
ORGANIC N MG/M3	567.7	0.45	63.8%			
TP-ORTHO-P MG/M3	34.7	0.58	56.1%			
HOD-V MG/M3-DAY	327.5	0.36	97.4%			
MOD-V MG/M3-DAY	198.9	0.42	93.5%			
ANTILOG PC-1	33.6	0.64	6.5%	535.6	0.19	72.5%
ANTILOG PC-2	27.6	0.36	99.7%	10.6	0.13	82.7%
(N - 150) / P	0.3	0.42	0.0%	0.3	0.10	0.0%
INORGANIC N / P	0.3	3.28	0.0%			
TURBIDITY 1/M	0.4		29.6%	0.4		29.6%
ZMIX * TURBIDITY	1.6		19.0%	1.6		19.0%
ZMIX / SECCHI	2.7	0.28	15.7%	4.2		41.3%
CHL-A * SECCHI	26.5	0.41	91.2%	21.0	0.20	84.6%
CHL-A / TOTAL P	0.4	0.32	89.5%	0.6	0.22	96.1%
FREQ(CHL-a>10) %	69.9	0.54	77.4%	81.2	0.10	85.2%
FREQ(CHL-a>20) %	27.6	1.27	77.4%	40.8	0.30	85.2%
FREQ(CHL-a>30) %	10.6	1.79	77.4%	18.8	0.47	85.2%
FREQ(CHL-a>40) %	4.3	2.18	77.4%	8.9	0.59	85.2%
FREQ(CHL-a>50) %	1.9	2.48	77.4%	4.4	0.70	85.2%
FREQ(CHL-a>60) %	0.9	2.73	77.4%	2.3	0.79	85.2%
CARLSON TSI-P	56.8	0.11	40.5%	55.4	0.03	36.4%
CARLSON TSI-CHLA	58.3	0.11	77.4%	60.5	0.03	85.2%
CARLSON TSI-SEC	53.4	0.08	30.7%	60.0		54.0%

Segment Mass Balance Based Upon Predicted Concentrations

Component:		TOTAL P	Segment:	1	Lake		
			Flow	Flow	Load	Load	Conc
Trib	Type	Location	hm^3/yr	%Total	kg/yr	%Total	mg/m^3
1	2	Watershed	0.1	28.8%	21.3	40.1%	176
2	3	On-site	0.0	2.4%	21.0	39.6%	2100
PRECIPITATION			0.3	68.8%	10.8	20.4%	38
NONPOINT INFLOW			0.1	28.8%	21.3	40.1%	176
POINT-SOURCE INFLOW			0.0	2.4%	21.0	39.6%	2100
***TOTAL INFLOW			0.4	100.0%	53.0	100.0%	127
ADVECTIVE OUTFLOW			0.1	22.6%	3.6	6.9%	39
***TOTAL OUTFLOW			0.1	22.6%	3.6	6.9%	39
***EVAPORATION			0.3	77.4%	0.0	0.0%	
***RETENTION			0.0	0.0%	49.4	93.1%	

Hyd. Residence Time = 16.7619 yrs

Overflow Rate = 0.3 m/yr

Mean Depth = 4.4 m