Duluth Area Lakes Water Quality Assessment:

Caribou, Grand, and Pike Lakes - 1999
(MNDNR ID # 69-0489, 69-0511, 69-0490)
Pike Lake Fall Overturn Studies – 1996-1998

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TABLE OF CONTENTS

Duluth Area Lakes Water Quality Assessment :
Caribou, Grand, and Pike Lakes– 1999 and Pike Lake Fall Overturn Studies– 1996-1998

TABLES

Table 1. Average summer water quality and trophic status indicators based on 1999 epilimnion data

Table 2. Summary of nutrient data for Duluth area lakes from summer surveys, 1975-1977 (WLSSD 1979). Values represent near-surface water samples collected at offshore sites. Full details available from the Western Lake Superior Sanitary District, Duluth. MN

Table 3. Nutrient and chlorophyll concentrations at mid-lake site #102, Pike Lake, St. Louis County, MN, 1996-1998.

Table 4. Major ions and redox-controlled iron (Fe) and manganese (Mn) concentrations at mid-lake site #102, Pike Lake, St. Louis County, MN, 1996-1998.

Table 5. Whole-lake nutrient and major ion budgets pre- (i.e. stratified) and post-fall mixing. Nutrient totals are in kilograms, major ions in metric tonnes, summed over all strata from the morphometry map reported in MPCA (1994) and shown as Figure 3A.

Table 6. Semi-quantitative phytoplankton Rapid Scans for mid-lake site #102, Pike Lake, St. Louis County, MN, 1996-1998. The 1998 data represents mean cell densities from quantitative scans of seven (7) independent subsamples.

Table 7. Zooplankton densities from 0-15 m vertically integrated tows at midlake station #102 at Pike Lake, St. Louis County, MN. Values of genera are percentages of total density. A dash signifies not found in any subsamples that were counted. Total animal densities reported as mean ± standard deviation (n= # of tows).

Table 8. WLSSD data summary for 1974-1977 from the Suburban Lakes Water Quality Report (WLSSD 1979).

APPENDIX 1. 1999 Duluth Area Lakes Water Quality Data

FIGURES

Figure 20. Plots of temperature (^{o}C), DO (mg/L), pH and EC25 (microS/cm) during the period of fall mixing and thermal destratification 1996) at midlake site #102, Pike Lake, St. Louis County, MN

Figure 21. Plots for midlake site #102, Pike Lake, St. Louis County, MN in 1996 depicting stratified (9/18/96) versus non-stratified (10/25/96) condition effects on inorganic nitrogen (nitrate + ammonium), phosphorus (ortho-P and total-P), and redox-controlled dissolved iron (Fe) and sulfate (SO_4^{-2}), and non-redox controlled calcium (Ca^{+2}) and chloride (Cl^{-1}) concentrations.

Figure 22. Relationship between dissolved iron and orthophosphate for all data pairs at the midlake site #102 at Pike Lake, fall 1996-1998.

Figure 23. Site/location of sampling points on Grand Lake, numbered after Suburban Lakes Water Quality Report (WLSSD, 1979) and tabulation of water quality data from NRRI survey on July 7, 1997.

APPENDIX 2. Pike Lake Fecal Coliform Data, 1991-1999 (2 figures)

Duluth Area Lakes Water Quality Assessment:

Caribou, Grand, and Pike Lakes 1999 and Pike Lake Fall Overturn Studies 1996-1998

I. Introduction

Minnesota is divided into seven regions, referred to as ecoregions, as defined by soils, land surface form, natural vegetation and current land use. Since land use affects water quality, it has proven helpful to divide the state into regions where land use and water resources are similar. 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. Caribou, Grand, and Pike Lakes are located on the northern edge of the Duluth Metropolitan Area (Figure 1) in the Northern Lakes and Forests Ecoregion (Figure 2). Caribou Lake has an area of 569 acres (230 hectares), and a maximum depth of 21 feet (6.4 meters). The majority of the lake is less than 10 feet deep, and is dominated by emergent and submergent aquatic vegetation. Grand Lake has an area of 1742 acres (705 ha). Baby Grand Lake flows into Little Grand, which flows into Grand Lake. Similar to Caribou, much of Grand Lake (~ 95%) is less than 10 feet (3 m) deep, and vegetation dominates the shoreline and near-shore areas. Pike Lake has an area of 508 acres (206 ha), and is much deeper. The maximum depth is 60 feet (~18 m), and most of the lake is between 20-50 feet deep (6-15 m).

These lakes all have relatively developed shorelines and are likely to experience increased development pressure in the next decade. They have also experienced some degree of water quality problems in the past. Efforts are underway to improve wastewater treatment on two of these lakes. Construction of a sanitary sewer was recently (1999) begun around Pike Lake, and a constructed wetland wastewater treatment system servicing a cluster of nine (9) lakeshore homes was installed at Grand Lake in late 1995. The present study was conducted because local units of government desired additional water quality information on these Duluth area lakes for planning purposes. The Pike Lake Association also desired some follow-up work for comparison to a previous MPCA study (Bauman 1994), and to better define current lake water quality prior to the installation of a sanitary sewer in the basin. Caribou and Grand Lakes were monitored to gather current baseline water quality information since the most recent complete summer data set was from over 20 years ago when the Western Lake Superior Sanitary District published the "Suburban Lakes Water Quality Report" (WLSSD, 1979). The purpose of the project was to survey the type and condition of on-site sewage disposal systems, and relate them to lake water quality. It was concluded that none of the suburban lakes was "polluted", but that improper waste disposal was potentially contributing a high level of nutrients, thereby accelerating the lake eutrophication process (WLSSD, 1979). The Minnesota Pollution Control Agency (MPCA) conducted a water quality assessment on Pike Lake in 1993 and published a Lake Assessment Program (LAP) report (Bauman 1994). Results from that study will be discussed later in this report. Because of periodic beach closings at Pike Lake, a summary and analysis of fecal coliform surveys from Pike Lake from 1991-1999 and information regarding an outbreak of *Cryptosporidium parva* in July-August 2000 are included as appendices.

This report also presents additional data from limnological surveys conducted near fall overturn in 1996, 1997, and 1998 by the Natural Resources Research Institute as part of a graduate level course in limnology at the University of Minnesota-Duluth. Pike Lake was chosen because of (1) its proximity to the Natural Resources Research Institute (boats, field gear and laboratory facilities); (2) its limnological characteristics (e.g. relatively small and deep with summer thermal stratification and seasonal anoxia) are representative of thousands of Minnesota lakes; and (3) an initiative was in progress to sewer the residences in the basin to begin to eliminate potential nutrient discharge from onsite wastewater systems in the lake basin - and so the class data would potentially be useful in the future for evaluating the impact of this sewage treatment conversion.

One final source of data included in this report was derived from an NRRI survey of nearshore water quality in Grand Lake in July 1997 in the context of NRRI's constructed wetland demonstration project for a group of homes along the lake's shoreline.

For convenience, this report is divided into two major sections, the first being an MPCA Lake Assessment Program report based primarily on 1999 data from all three lakes and including comparisons with the 1993 MPCA Pike Lake data. The second is a presentation and analysis of limnological studies of Pike Lake from 1996-1998 that focused on the processes and changes occurring during the period of fall mixing and overturn.

II. Methodology

1. 1999 Surveys

Water quality data were collected on May 25, June 29, July 14, August 17, and September 20, 1999. Two sites were sampled in Pike Lake: site 101 near the swimming beach at the eastern end, and site 102 in the deepest hole on the western side of the lake. Samples from Caribou and Grand lakes were taken from just one site, at the deepest part of the lake. Lake surface samples for major ions, nutrients and algae (phytoplankton and chlorophyll-a) were collected with an integrated sampler, which is a PVC tube 6.6 feet (2 meters) in length with an inside diameter of 1.24 inches (3.2 centimeters). Near-bottom samples were collected with a two-liter PVC Kemmerer sampler. Sampling locations and morphometry for all three lakes are shown in Figure 3.

Standard MPCA sampling procedures were employed as used for other MPCA Lake Assessment Program reports (e.g. Heiskary and Wilson 1989). Laboratory analyses were performed by the Minnesota Department of Health using U.S. Environmental Protection Agency (EPA)-approved methods (e.g. APHA 1989, 1998). Samples were analyzed for total nitrogen, total phosphorus, color, solids, pH, alkalinity, turbidity, conductivity, chloride and chlorophyll (Table 1). Temperature and dissolved oxygen profiles, and Secchi transparency measurements were also taken. All data were stored in STORET, the EPA's national water quality data bank. Samples were also collected concurrently for analysis at the Central Analytical Laboratory of the Natural Resources Research Institute (NRRI), primarily for additional nutrient analyses (ammonium-N, nitrate/nitrite-N, and orthophosphate-P) but also for additional data quality assurance and control. For purposes of this report, certain results are reported as the average of data collected by both the MPCA and NRRI. This was the case for phosphorus, nitrogen, and chlorophyll *a*, (those parameters used to assess and model trophic status). Quality assurance and control procedures followed standardized EPA methodology involving duplicates, internal calibration spikes, and other procedures that are described in detail in APHA (1989, 1998) and Ameel et al. (1998).

2. 1996-1998 Pike Lake Surveys

Samples were collected primarily from the midlake, deepwater site designated #102 (Figure 1) in late afternoon. A second site near the middle of the eastern *basin*, designated site # 101 at about 10m depth, was sampled for temperature, pH, EC25 and dissolved oxygen on occasion but site differences were usually very small and much smaller than temporal differences (Axler, unpubl.). Discrete depth samples from typically 5-7 depths to 1-2 meters from the bottom were collected with an opaque PVC Van Dorn bottle. Temperature, DO, pH and specific electrical conductivity (EC25; temperature corrected to 25oC) were measured with a Hydrolab Surveyor II and/or YSI 85 water quality analyzer calibrated within a few hours of the field work. Water transparency was estimated with a standard 20 cm secchi disk and downwelling light attenuation with a Licor 192S PAR quantum sensor. Water samples were filtered within 2 hours of field collection and frozen in raw and filtered (GF/C) form. Water from anoxic depths was carefully drawn into polyethylene sample bottles of different sizes for specific analyses taking care to minimize oxygen diffusion from the atmosphere. Samples for iron and manganese were acidified in the field to pH<2 using Ultrex HNO3 and were then refrigerated until later atomic absorption analysis (Owen and Axler 1991; Ameel et al. 1998). Nutrient analyses were generally analyzed within 30 days; chlorophyll analyses were frozen for 2-3 months before analysis as per Axler and Owen (1994).

A limited number of Lugol's preserved phytoplankton samples were microscopically examined for algal community composition according to MPCA's Rapid Algal Assessment Technique (in Ameel et al. 1998) after sedimentation using an inverted microscope and also by examining membrane filtered samples by direct microscopy (APHA 1998). Zooplankton samples were collected using a self-closing, 13 cm x 80 micron Wisconsin net, preserved in ethanol (80% final), and enumerated to order and sometimes genus. Samples were collected from the entire water column as vertical tows.

Volumes for meter thick depth strata were estimated from the morphometry map reported in Bauman (1994) and Figure 3. Whole-lake budgets for individual ions were calculated by interpolating the morphometry curve for strata defined by the discrete depth profile for that particular date. Changes in lake levels were not determined but were probably small during the short sampling interval each year.

3. Laboratory

All analyses followed standard limnological methods used by the NRRI laboratory. The Lab has used most of these analytical procedures since 1988 and has been certified by the Minnesota Department of Health for Federal Safe Drinking Water Act and Clean Water Act parameters (Ameel et al. 1993, 1998; Axler and Owen 1994) since the inception of the program. The NRRI lab has also been certified over the past decade by the Minnesota Pollution Control Agency and the Minnesota Department of Natural Resources for low-level water quality analyses in pristine, acid-sensitive lake monitoring programs and for sediment contaminant analyses in the St. Louis River and Upper Mississippi Rivers. Water chemistry analyses followed standard methods (APHA 1998, details in Ameel et al. 1998 and Ameel et al. 1993). Chlorophyll was analyzed spectrophotometrically from 90% acetone extracts (Axler and Owen 1994; Ameel et al. 1998). QA/QC procedures were rigorous and based on a detailed field and laboratory manual (Owen and Axler 1991 and Ameel et al. 1998, revised annually) certified by the State of Minnesota for federal Safe Drinking Water and Clean Water Act procedures. Quality assurance and control procedures followed standardized EPA methodology involving duplicates, internal calibration spikes, and other procedures described in detail in APHA (1998) and Ameel et al. (1998).

III. RESULTS and DISCUSSION
A. Caribou, Grand and Pike Lakes- 1999

1. Water Quality

Oxygen and Temperature

Dissolved oxygen and temperature profiles for Caribou, Grand, and Pike Lakes are shown in Figure 4. Caribou and Grand lakes did not "permanently" thermally stratify in 1999. Both temperature and dissolved oxygen were consistent from the surface (0 meters) to the bottom (5 meters). Although shallow lakes such as these may not routinely stratify, they may do so intermittently (typically not during a scheduled monthly sampling trip), for periods of hours to days during unusually hot, calm periods in summer. Depending on the biochemical oxygen demand of the sediments and the overlying water, pronounced oxygen depletion with depth may result. If the DO is depleted below 1 mg/L, phosphorus release from the sediments into the water will usually increase, ultimately leading to increased algal (phytoplankton) and higher plant (macrophyte) growth. Excellent examples of such transient events may be found at Lake Minnetonka near Minneapolis (see http://wow.nrri.umn.edu/wow/notes/Minnetonka_animation.html) which shows the dramatic effects storms versus calm can have on DO profiles in relatively shallow lakes. Increased nutrient loads and shoreland disturbance can also magnify the effects of these natural phenomena.

Surface water oxygen concentrations at all three lakes were always above 5 mg/L - a level needed to sustain a healthy warm or cold-water fishery. Pike Lake was sufficiently deep to seasonally stratify. A thermocline (depth of greatest change in temperature with depth) was evident at approximately 4-6 meters. Dissolved oxygen concentrations ranged from 8 mg/L at the surface to near zero at the bottom (Figure 4). This pattern is typical of moderately productive (mesotrophic) to productive (eutrophic) lakes although the rate at which the hypolimnion becomes completely depleted in oxygen (anoxia) may vary from year to year. Factors that control the rate and degree of oxygen depletion in bottom waters include:

(1) the duration and extent of spring circulation -calm, hot days in spring lead to rapid thermal stratification that cuts off the hypolimnion from atmospheric O2;

(2) the date of ice-thaw and windiness in the spring – an early ice-out results in higher hypolimnion oxygen later in the season if there is an extended period of cool, windy weather that allows spring mixing to continue for several weeks. Conversely, if the lake thaws during a period of calm, warm weather, there can be a rapid stratification that does not allow the bottom waters to be completely re-aerated after winter oxygen depletion under the ice. In this case the spring overturn may be incomplete and hypolimnetic anoxia will be more severe as the summer progresses;

(3) increased inputs of organic matter, either via streams or shore land erosion or from increased algal and plant growth due to nutrient inputs, will accelerate the weather-related processes described above.

Additional graphical depictions of how these factors have controlled the oxygen dynamics on several Minnesota lakes that have been intensively monitored for 2-3 years may be found on the University of Minnesota-Duluth's *Water-on-the-We*b educational web site. Several data visualization tools provide more in-depth descriptions of how mesotrophic Ice Lake, in Grand Rapids, MN, behaves using a robotic sensor module that samples the lake water column every four hours:

http://wow.nrri.umn.edu/wow/notes/index2.html and

http://wow.nrri.umn.edu/wow/under/lakes/icedatasum.html

Total Phosphorus, Chlorophyll-*a* and Inorganic and Total Nitrogen

Total phosphorus (TP) and chlorophyll *a* (along with Secchi transparency) are commonly used to describe the trophic status of lakes. Phosphorus is the nutrient that limits algal growth in most Minnesota lakes. Chlorophyll *a* concentrations provide an estimation of algal biomass. In turn, the amount of algae in the water typically limits the transparency of the water (secchi depth is discussed further in the Water Quality Trends section). For most Minnesota lakes these three measurements are related and provide an estimate of the lake's trophic status (i.e. productivity).

An increase in chlorophyll and phosphorus concentrations throughout the summer is typical for most shallow, well-mixed lakes like Caribou Lake and Grand Lake. This is the result of warm temperatures, adequate sunlight, and abundant nutrients. A portion of their nutrient load is recycled within the lake as a result of in-lake processes and wind mixing.

Seasonal total phosphorus and chlorophyll-*a* concentrations in surface water for Caribou Lake and Grand Lake are shown in Figures 5-8. Phosphorus concentrations for Caribou Lake ranged from approximately 15- 38 µg P/L and from about 12-20 µg P/L for Grand Lake. The summer mean surface TP concentration for Caribou (24 µg P/L) and Grand (17 µg P/L) were well within the range of data for reference lakes in the NLF ecoregion (Table 1; Figures 5, 7, 9). Surface water total phosphorus and chlorophyll-*a* concentrations at Caribou Lake were quite variable throughout the season. Although TP was highest (~38 µg P/L) in May, the maximum chlorophyll-*a* was measured in August and September (10-12 ug/L), still far below concentrations found during nuisance algae blooms, when they are much greater than 20 ug/L. This differs from "textbook" descriptions of spring blooms (see below) but the monitoring frequency of one sample per month is not adequate to confidently describe the dynamics of phytoplankton communities which may "bloom" and "crash" over periods of only a few weeks. Further, Caribou Lake is relatively shallow and intermittent stratification and de-stratification can have profound effects on nutrient inputs from bottom water and sediment and, in turn, on algal growth. The pattern at Grand Lake was much less pronounced and the range of chlorophyll values was only about 15% of the mean for the five 1999 surveys. Chlorophyll-*a* concentrations for Caribou and Grand lakes were within the Northern Lakes and Forest ecoregion range (Table 1).

The concentrations of TP 1m off the bottom at Caribou and Grand Lake were very similar to the surficial samples (Figures 5 and 7). This occurred because these lakes did not stratify significantly, at least during the time of the surveys (i.e. wind mixing was able to distribute dissolved and particulate substances uniformly throughout the relatively shallow water column). High bottom water oxygen also reduces the release of phosphate from the sediments by promoting a surface layer of oxidized iron (essentially rust) on the sediment surface that effectively binds phosphorus and minimizes its diffusion up into the water column.

Although phosphorus tends to be the nutrient most deficient in regard to phytoplankton growth in most lakes, low nitrogen availability may also be very important. Ammonium (NH4+) and nitrate (NO3-) ions are the forms of nitrogen most available for algae to assimilate. Total nitrogen (TN) includes these inorganic forms in addition to particulate and dissolved organic nitrogen. The organic fraction, most of which is comprised of relatively refractory dissolved molecules (that is, they don't degrade very fast to ammonium) is usually by far the largest portion of the total-N pool. Nitrogen data for Caribou and Grand Lakes may be found in Appendix 1 and is summarized in Table 1. Briefly, both lakes have relatively low levels of available nitrogen (ammonium + nitrate) in surface water, with ammonium levels in the range of 15-38 ugN/L. Nitrate levels were very low, <3 ug N/L for most surface samples. Near-bottom concentrations were generally similar to surface water values – as expected based on the temperature and DO profiles that show complete vertical mixing. The total of ammonium plus nitrate nitrogen as a percentage of the total nitrogen concentration ranged from 3-7%. The relatively low levels of inorganic nitrogen present during summer indicate that increased N inputs as well as P may adversely affect these lakes. Algae require both N and P to grow, and growth in the summer is likely to be regulated by the low levels of each nutrient at some times.

Total phosphorus and chlorophyll *a* data from Pike Lake in 1999 are shown in Figures 9-11. Site 101 reflects data from MPCA samples, while data from site 102 is the average of samples collected by both MPCA and NRRI staff at the same time. Phosphorus concentrations were nearly an order of magnitude higher near the bottom of the lake (Figure 10), compared to surficial samples (Figure 9). It is likely that phosphorus was released from the bottom sediments due to the anoxic conditions. Earlier in the summer (May – June) phosphorus concentrations from surface water were more similar to values for near-bottom. This occurred because during spring "turn-over (or overturn)" the water column was thoroughly mixed from top to bottom. As the lake became thermally stratified later in the summer (by the June 29 survey; Figure 4), oxygen became depleted near the bottom allowing phosphorus to diffuse out of the sediments. Since the oxygen depletion worsens until fall circulation re-aerates the water column, one would expect the difference between surface and bottom water phosphorus levels to increase throughout the summer- as is observed. Figure 10 shows the inverse association between bottom water oxygen and phosphorus concentration over the course of the ice-free growing season (see also section III.B. for additional discussion of this phenomenon in fall 1996-1998). Surface water concentrations were very similar between the two sites, ranging from 9 – 22 ug/L throughout the summer. This was well within the range for other lakes in the NLF ecoregion (Table 1).

Maximum surface chlorophyll and total phosphorus concentrations in Pike Lake were observed in May, typical of Minnesota lakes (Figure 11). Springtime is characterized by high light and an influx of nutrients from snowmelt runoff and from nutrients released from the sediments under winter ice-cover. Algal biomass will often decline after this spring "bloom" due to increased grazing pressure from cladoceran zooplankton (such as the water flea *Daphnia*; Wetzel 1983; Horne and Goldman 1994). Later in the summer, a second peak in algal biomass may occur that is often associated with blue-green algae that are well adapted to warmer and more turbid water and lower nutrient conditions.

Chlorophyll *a* concentrations in Pike Lake were somewhat lower than those measured for Caribou and Grand – generally less than 10 ug/L (Figure 11). The seasonal maximum occurred in late May, values declined to $\leq$ 3 ug/L from June to August, and then increased to ~ 4.5 ug/L in September – a pattern also observed in 1993 ((Figure 11; Bauman 1994). An analysis of algae samples at that time (May 1993) indicated this was a diatom "bloom". Spring diatom blooms are quite common in lakes throughout Minnesota and in particular those lakes that thermally stratify. Spring mixing often brings abundant nutrients into the water column and the diatoms (which prosper in the cooler temperatures) are able to grow rapidly, and exhibit bloom like conditions. As the diatoms die off (often because of a shortage of silica) they will settle to the bottom, which often contributes to the noted seasonal increase of TP in the hypolimnion (Figure 10).

2. Water Quality Trends

Secchi transparency provides an accurate and cost effective way to detect long-term trends in water quality. Long-term secchi data for Caribou and Pike Lake are shown in Figures 12 and 13. There is no long-term secchi data set for Grand Lake. Caribou Lake has had a statistically significant improvement in transparency over the period of record (MPCA 1999), although transparencies have been stable in the last decade, ranging from 6-8 feet (1.8-2.4 meters). The long-term mean is 6.4 feet (1.9 m). In 1999, the summer-wide average was 6.1 feet (1.8 m). Pike Lake has been enrolled in the Citizen Lake Monitoring Program (CLMP) since 1991 (Figure 14). There has not been a statistically significant change in transparency over the period of record.

The long-term mean is 14 feet (4.3 m), and in 1999 the average was 14.5 feet (4.4 m). Additional historical perspective may be gained by reviewing the data reported in WLSSD (1979). For that study, TP samples were taken from Caribou, Grand, and Pike Lakes monthly from June 1975 – October 1976. TP values ranged from 20 – 40 ug/L (WLSSD 1979 - Appendix 2). By comparison, the 1999 MPCA and NRRI data ranged from 9 – 37 ug/L (Appendix 1). Three other sources of data can be used for comparison on Pike Lake: the 1993 MPCA LAP report (Bauman 1994), the 1999 LAP conducted by the North St. Louis County Soil and Water Conservation District (SWCD), and the fall overturn studies conducted by NRRI from 1996-1998 (discussed below). Surface water phosphorus levels from these studies, as well as the 1999 MPCA/NRRI data are shown in Figure 14. There are no distinct differences in the three data sets. The CLMP data set (Secchi data in Figure 13) also indicated no trend in water quality. Although TP was not detected in the SWCD samples from May- July, their level of detection was relatively high (10 ugP/L) and their seasonal differences were well within a range of natural variability. The July peak in TP in the 1993 MPCA data may be the result of runoff from significant summer storms. Overall, there appears to be no pronounced difference between the historical data and current conditions.

3. Phytoplankton

Estimates of the relative biomass of major groups of phytoplankton in mid-lake surface water samples from June – September 1999 are presented in Figure 15. The Pike Lake phytoplankton community was dominated by blue-green algae (cyanobacteria) in all four months with this community representing 75-85% of total algal biomass. Although many blue-greens are notorious for their noxious scum-forming potential, the actual amount of algal biomass, as estimated by chlorophyll-a concentrations did not indicate a problem (Table 1 and Figure 11;

Bauman 1994). Most of the remaining biomass was due to diatoms. The 1999 data differ from the previous MPCA phytoplankton survey in 1993 in that May through July 1993 samples were dominated by diatoms (~45-80%) and chrysophytes (yellow-brown algae; 10-25%) and blue-greens did not appear until the August 1993 sampling when they comprised ~ 75% of the total biomass. The only other years for which phytoplankton data exists are 1996-1998 in September and October, straddling the period of fall overturn and mixing (see Section III.B. below for details). The September 1996-1998 data differ substantially from each other and illustrate how variable the assemblage of algae may be from year to year despite relatively similar total biomass as estimated by chlorophyll-*a*.

Grand Lake phytoplankton data for June, July and August 1999 were generally similar and were dominated by green and blue-green algae with lesser amounts of diatoms. We are unaware of any previous data for comparison. Caribou Lake surface samples from June to September were more similar to Pike Lake than to Grand Lake with blue-greens representing 45- 85% of algal biomass and diatoms representing ~ 10-40% (Figure 15). Again, we are unaware of any other source of historical data for comparison.

4. Trophic Status and Summary

One way to characterize the trophic status of a lake and to help interpret the relationship between total phosphorus, chlorophyll-*a* and Secchi transparency is to calculate Carlson's Trophic State Index (TSI, Carlson 1977). This index was developed from the interrelationships of summer Secchi transparency and the concentrations of surface water chlorophyll-*a* and total phosphorus from a variety of data sets for a wide range of North American lakes in the 1960's and 1970's. It also assumes that secchi depth is controlled by algal biomass (as opposed to silt and dissolved color), which is in turn controlled by phosphorus (i.e. P is the "*limiting*" nutrient). TSI values are calculated as follows:

Total phosphorus TSI (TSIP) = 14.42 1n (TP) + 4.15

Chlorophyll-*a* TSI (TSIC) = 9.91 1n (Chl-*a*) + 30.6

Secchi disk TSI (TSIS) = 60 - 14.41 1n (SD)

Units of TP and chlorophyll-*a* are ug/L and Secchi transparency is reported in meters. TSI values range from 0 (ultraoligotrophic) to 100 (hypereutrophic). In this index, each increase of 10 units represents a doubling of algal biomass.

Average values for the trophic variables in Caribou, Grand, and Pike Lakes and respective TSIs are presented in Figures 16-18. Based on these values, the three lakes are considered *mesotrophic* in condition. Caribou Lake borders on being eutrophic and its TSI of 51 ranks it at the 25th percentile relative to about 1075 other lakes in the Northern Lakes and Forest ecoregion. In other words, its TSI value is lower (less eutrophic) than only 25 percent of the lakes assessed in this region. Grand Lake is in the 53rd percentile, and Pike Lake is in the 65th percentile. The 1993 LAP study indicated that the overall TSI for Pike Lake was 43. In 1999, the overall TSI was 42, nearly identical. Again, it is apparent that there is no change in water quality outside of year-to-year variation.

In 1993, the lake model MINLEAP (Wilson and Walker 1989) predicted an in-lake TP concentration of 16 ug/L for Pike Lake, which was the mean summer value for 1999 (Table 1). This indicates that Pike Lake was “performing” as we would expect for a lake of its depth, volume, and watershed area in the NLF ecoregion. Further modeling estimated that water residence time was about 5-6 years, hence it may take a number of years, perhaps even a decade, before the lake assumes a new “steady state”. This assumes that septic systems were in fact a significant part of the P budget, and that the new sanitary sewer will remedy this problem.

The individual TSI values and percentiles agree fairly well for all three lakes. This implies that Secchi transparency would be a good indicator of trophic status (Figures 16-18) on average, but as noted previously, the relationship may vary from bay to bay in part because of water coloration. Secchi transparency measurements should be taken from June through September to get a good representation of “average conditions”. For Secchi transparency to be a reliable indicator of trophic status and trend analysis, a minimum of 6-10 readings per summer is needed.

III. B. Pike Lake Fall Overturn Studies 1996-1998

1. Field data (temperature, DO, pH, EC, light & clarity)

Temperature & Dissolved Oxygen

Pike Lake's limnological characteristics in the fall were typical of a north temperate, small, moderately deep lake. September field data for all three years (Figure 19) indicated strong thermal (i.e. density) stratification with an upper, warmer mixed layer (epilimnion = 16-18 oC) of about 7-10 meters depth overlaying a colder (hypolimnion = 10-12 oC). Following ice-out in the spring and depending on how warm and windy the weather is, the lake presumably stratifies and remains stratified until October or November. The thermocline is likely to range from about 4-7 meters during late spring and summer and the epilimnion temperature from about 20-25 oC.

As the mixed layer cools, the density difference between this layer and the hypolimnion decreases until the mixing energy from a breezy day is sufficient to overcome the buoyancy of the epilimnion and mix the lake completely. Temperature profiles from September 1996-1998 as well as September 1993 (Bauman 1994) and September 1999 (Figure 4) show that fall cooling had progressed enough to cool the epilimnion below 20 oC, but that an essentially two-layer system still persisted. By October 25, 1996 and October 27, 1997 the temperature profiles were essentially uniform from surface to bottom (~9-10 oC; note- the lake was not sampled after September in 1998 and 1999). Data from October 7, 1996 were collected during the transition from stratified to mixing. Temperature had decreased to a nearly uniform 12-13 oC down to about 13 meters where it dropped sharply to about 10 oC (Figure 19 and 20).

The depth pattern of oxygen during this period showed an even more striking contrast between the 2 main layers, with a nearly saturated epilimnion overlying an anoxic (essentially zero O2) hypolimnion. The transition zone in the region of the thermocline, the metalimnion, was very sharp with DO decreasing from ~8 mg/L to zero with only about a one meter decrease in depth. This oxycline regulates the metabolism of the biological organisms within these zones and leads to a number of abrupt changes in the chemistry of the lake as well. The date that the lake thaws in the spring and the weather (air temperature and wind velocity) during this period determines how rapidly stable stratification develops and the extent to which the entire water column is saturated with O2. If the lake thaws during a warm, calm period it may stratify within a few days, preventing wind mixing from circulating the entire water column enough to re-aerate it to 100% saturation. This phenomenon of incomplete spring mixing is extremely difficult to document, but was recently observed for 1998 and 1999 in another small lake of comparable depth in Grand Rapids, MN (Ice Lake). Data from a midlake robotic sensor array sampled 6 times a day immediately following ice-out (see *What's New* section at http://wow.nrri.umn.edu; Axler et al. 2000) and showed that in the three-year period 1998-2000, this lake underwent complete *mixing* only in Spring 2000.

In the fall, there is generally a period of many weeks when the water column has uniform temperature (and density) during which the water column may be come fully re-saturated with oxygen. This transition is shown clearly for 1996 in Figure 20. From a water quality perspective, the extent and duration of hypolimnetic oxygen deficiency is important because prolonged exposure to DO levels below 3 mg/L is harmful to many aquatic organisms including most game fish. Figure 19, as well as the 1999 midsummer data (Figure 4), clearly show that nearly half of the water column is unsuitable for fish habitat much of the year. Lake management has an important role to play in that excessive algal and macrophyte growth (in the sense of eutrophication) and watershed/shoreland erosion contribute excess organic matter to the lake. This increases the overall *oxygen demand* of the system and further limits the amount of oxic, or aerobic, habitat. There are additional adverse secondary impacts as well (described below).

Although algae produce oxygen by photosynthesis, they only do this during daylight, and predominantly in the mixed layer in moderately transparent lakes such as Pike Lake that have summer Secchi depth clarities of ~3-5 meters. Further, algae also consume (respire) oxygen throughout the day and night. Most of the hypolimnion is too dark to support much photosynthesis and this layer is effectively isolated from the oxygen in the atmosphere by the epilimnion. As the summer progresses, its DO concentration steadily decreases until it is recharged during fall overturn. Over the winter, there is little oxygen diffusion from the atmosphere because of ice-cover, and little DO from photosynthesis (because of insufficient sunlight), and so lake oxygen content decreases until spring mixing. Therefore, if the lake only mixes down to 12 meters in the spring, the stratum from 12-18 meters may not be re-aerated until about a full year has passed.

pH & EC25

Pike Lake pH values ranged from about 6.8 to 8.0 in the fall for all three years and were similar to data from other years. A pronounced decrease in pH occurred below the mixed layer during late summer stratification that disappeared after the lake turned over (Figure 21). The pH of a moderately productive lake that has moderate alkalinity, such as Pike Lake, would be expected to be very dynamic over time and with depth (e.g. Wetzel 1983, Horne and Goldman 1994). Algal photosynthesis in the upper sunlit zone acts to increase pH by removing CO2 from the water, while the respiration of all organisms produces CO2 that acts to decrease the pH. This pattern may be further complicated by the metabolic activities of many groups of microorganisms with respect to nitrogen and sulfur compounds, the net effect being either increased pH (the anaerobic sulfate reducing bacteria and denitrifying bacteria) or decreased pH (the aerobic groups of nitrifying bacteria and sulfide oxidizing bacteria). The increase in pH in the bottom few meters of the lake, evident in the Sep 18 and Oct 7, 1996 profiles, is real and likely caused by relatively high rates of sulfate reduction by anaerobic bacteria that are very active in this layer (see also ensuing discussion of Fe, N and S profiles).

Specific electrical conductivity (EC25) provides a measure of the total dissolved salts (ions) in the water. Values at Pike Lake range from about 200 – 250 uS/cm and indicate a moderate level. For comparison, values for Lake Superior are about 100uS/cm and iron ore minepit lakes near Chisholm, MN are about 400 uS/cm. The Northern Lakes and Forests ecoregion median value is 50-250 uS/cm and the MPCA 1999 summer survey of Pike Lake reported a similar average of 234 uS/cm (Table 1).

The summer stratification pattern seen at Pike Lake in September for 1996-1999 is typical of deeper, north temperate zone lakes and basically shows uniform EC throughout the epilimnion (because of wind mixing), and a gradual increase down the water column. Most of this increase in EC25 is due to the production of carbon dioxide by bacteria decomposing organic material from the steady "rain" of detritus (dead stuff, mostly algae and washed in particulate material from the watershed) down to the bottom. This material is decomposed by bacteria in the water column and after it reaches the sediments. The CO_2 rapidly dissolves in water to form carbonic acid, bicarbonate ions and carbonate ions - the relative amounts depending on the pH of the water, but mostly bicarbonate (~80%) and ~ 20% carbonic acid at Pike Lake. This "new" acid gradually decreases the pH of the water and the "new" ions increase the EC25 and the total dissolved salt (TDS) concentration.

EC25 is also a useful parameter as an indicator of large inputs of salt from road salting or wastewater leachate for many small lakes or embayments, and for estimating the risk to biological communities from salt toxicity. The average surface water chloride concentration for 1996-1998 was 23 mg/L (Sept/Oct whole-lake average) as compared to MPCA's reported surface average of 20 mg/L for 1993 (Bauman 1994) and 25.8 mg/L for 1999 (Table 1, this report). These values are all far higher than the values of 4.4 and 4.2 mg/L measured for Caribou and Grand Lake at the same time in 1999. This also far exceeds the Ecoregion average of 0.6-1.2 mg/L reported by Heiskary and Wilson (1988)(Table 1) and might indicate the result of many years of road salting within the Pike Lake watershed.

Another indication of trends in the salinity of the lake can be determined by examining the whole-lake budgets of specific ion data collected from 1996-1998 (Tables 4 and 5). The chloride content of the lake in 1996 averaged 387 metric tonnes (851,000 lbs) and it increased to 430 tonnes in 1997 and 438 tonnes in 1998, an increase of 13% over the 3-year period (Table 5). Similar percentage increases were seen for sodium, calcium and potassium. The reasons for these changes, and whether they indicate a general trend are not yet clear but provide further justification for re-surveying the lake every few years and performing a complete suite of water quality analyses for the entire water column during the summer. The observed differences may be within the range of natural year-to-year variation but the fact that the chloride levels are far higher than most lakes in the region suggests that they may be due to road salt inputs. However, the current concentrations remain far too small to be of immediate concern in terms of water quality criteria and protection of aquatic organisms.

Light & Clarity

Water clarity as estimated using the Secchi depth provides an excellent integrative measure of the environmental health of a lake, particularly when the data is collected systematically throughout the ice-free season. However trends may take a decade or more to be statistically valid because of natural variations (primarily in climate). Values for Secchi depth for the 6 NRRI surveys ranged from 2.7 to 6.2 meters, well within the range to be expected for Pike Lake (Figures 13 and 19). Complete vertical profiles of light intensity were also measured at each depth and extinction coefficients calculated for each date (Figure 19). Values for both parameters are typical of moderately productive lakes (e.g. Wetzel 1983, Horne and Goldman 1994). The light profiles (not shown) indicated that the depth of 1% light penetration, a depth often used to estimate how deep photosynthesis can occur, was 5-8 m. This shows that most of the algal production was occurring in the epilimnion; this is consistent with the sharp drop in DO that was observed at the thermocline each year prior to overturn.

2. Major ions

Major ion profiles and selected whole-lake budgets are listed in Tables 3-5. Major ion chemistry indicated that the water was of the *calcium carbonate* type:

calcium > magnesium > sodium> potassium & [carbonate + bicarbonate] > sulfate > chloride

The water has moderate hardness and alkalinity (60-80 mgCaCO3/L) and falls well within the middle range for its Ecoregion. The cations (Ca, Mg, Na, K) and the chloride ion are considered to be biologically conservative and exhibit no real pattern with depth. The alkalinity (a measure of the combined carbonate + bicarbonate ions) does show biologically induced changes as discussed above. Sulfate is also biologically controlled, and is converted to sulfide by certain bacteria in strictly anoxic water and this can be clearly seen in the stratified condition data as a decrease in sulfate at the bottom of the hypolimnion relative to the middle (Figure 21). The strong smell of hydrogen sulfide (H2S) gas was evident to the field crew in the deepest Van Dorn bottle casts and is recorded on the field data sheets. This pattern disappeared at lake turnover and the sulfide is converted back to sulfate by bacteria requiring aerobic conditions. The whole lake sulfate budgets for the 6 surveys ranged from 64 – 88 metric tonnes with no clear pattern evident (Table 5). Chloride values were discussed in more detail in the previous section in the context of electrical conductivity.

3. Nutrients

Nutrients are those elements and molecules that are essential to the nutrition of biological organisms. In the context of lake management, we are usually referring to those nutrients that are in short enough supply in the water that their concentration regulates the amount of algal and plant growth that can occur. In turn, the amount of plant growth regulates the amount of zooplankton and fish growth. Most often, phosphorus concentrations are sufficiently low to limit phytoplankton growth, but nitrogen availability during the ice-free growing season may also be very important, particularly in pristine, unproductive lakes where both N and P may be deficient and in systems overloaded with excess P from erosion or wastewater inputs.

The principal forms of nitrogen available for algal and higher plant uptake are the inorganic forms – nitrate (NO_3^-) and ammonium (NH_4^+). In more productive systems, conditions with relatively high levels of organic matter and phosphorus may deplete the pool of inorganic-N and favor the growth of certain species of blue-green algae (cyanobacteria) that can fix dissolved N_2 gas and convert it to ammonium that is then metabolically available to the cells. These organisms also are able to control their buoyancy and may cause noxious floating scums that create serious water quality problems. The principal form of phosphorus available to algae and higher plants is orthophosphate (PO_4^{-3}). Ortho-P (OP) is typically depleted to low levels in the upper sunlit zone (called the *euphotic* zone) by rapid algal and bacterial uptake and the presence of significant amounts may indicate a chronic source from agricultural drainage or domestic wastewater. OP is also readily released from decomposing detritus and is rapidly adsorbed to particles or actively assimilated, resulting in extremely rapid recycling between dissolved and particulate forms. Because of this rapid recycling, the total amount of P in the water, total-P, is generally a more useful parameter since most of the TP pool is readily and rapidly available to algae and/or bacteria. Below the euphotic zone, TP levels tend to increase with depth as particles settle out and algal growth decreases due to darkness and/or anoxia. Further, when the bottom water becomes anoxic, P –release from the sediments may greatly increase as the adsorptive surficial layer of insoluble oxidized iron (*ferric* ion) is chemically reduced to the soluble *ferrous* ion (further discussion below).

Phosphorus (total-P and orthophosphate) and nitrogen (total-N, nitrate/nitrite-N and ammonium–N) concentrations in Sep/Oct 1996-1998 mixed layer water (0-6m means) were generally similar to the late summer 0-2 m data for 1993 and 1999 although the NRRI profiles are more detailed. TP in September (still stratified) was 22 ugP/L in 1996, 18 ugP/L in 1997 and 14 ugP/L in 1998 (Table 3). Bauman (1994) reported 14 ugP/L on Sep 20, 1993 and we reported 17 ugP/L in 1999 (Figure 14; Appendix 1). TP values increased dramatically below the oxycline (DO < 1mg/L) and near bottom water (14-15 m; ~ 1m off the bottom) levels increased to 249, 153 and 232 ugP/L respectively, for the three years. The pool of total-P was comprised mostly of dissolved orthophosphate (Table 3 and Figure 21). These values are generally similar to the values of 182 and 341 ugP/L determined for Sep 1993 and 1999, respectively (Bauman 1994; Figure 14; Appendix 1).

Bottom water values increase dramatically as hypolimnetic anoxia develops primarily from diffusion of orthophosphate out of the sediments. This diffusion is minimized when surficial sediments are oxidized, as is usually the case during spring overturn, because of the formation of highly insoluble and adsorptive iron hydroxide complexes such as $Fe(OH)_3$ and others that form an orange flocculent layer of *rust* in the surface sediments. After the bottom water oxygen is consumed by microorganisms, the ferric iron is biochemically reduced to the very soluble *ferrous* ion and the adsorptive *cap* dissolves. This results in an increased rate of P release to the hypolimnion. Therefore, the timing and the magnitude of this release are controlled by climate (when does the lake thaw and how much mixing is there before stratification), but also by the rate of hypolimnetic oxygen depletion – which is controlled largely by the rate of algal growth.

Lake management to control the rate of algal growth and DO depletion by minimizing organic matter and nutrient inputs to the lake is extremely important because some of this accumulating phosphorus (and ammonium as well -see below) is mixed into the upper sunlit zone during windy storms. This new P and N then fuels increased algal growth and potentially noxious blooms. A good example of this effect was seen in late October 1996 during turnover, when despite colder water and reduced day length, chlorophyll concentrations were higher than previously measured for any summer month (17 ug/L in the 0-2 m surface layer; Table 3).

Figure 21 and the data in Table 4 show clearly how iron (Fe) is increased during stratification in September relative to after mixing (and oxygenation of the hypolimnion) in late October 1996 and 1997. Manganese behaves similarly to iron and shows a similar pattern (Table 4). Figure 22 shows the strong correlation between iron and phosphorus concentrations for 1996-1998 for all dates.

In the absence of significant populations of blue-green algae than can utilize dissolved, gaseous N_2 for their metabolism, algae rely on nitrate-N (NO_3-N) and ammonium-N (NH_4-N) for their nitrogen nutrition. Nitrate was extremely low (<5 ugN/L) and near detection limits throughout the water column on all dates (1993, 1996-1998, 1999) except for May 1999, when there was 16 ugN/L in surface water and 57 ugN/L in bottom water. This early season nitrate probably was the residual nitrate inputs from spring snowmelt runoff. Ammonium levels in the mixed layer fluctuated from 18-42 ugN/L throughout summer 1999 (Appendix 1) and similarly varied from <10 to 20 ugN/L in the mixed layer during the stratified periods from 1996-1998 (Table 3 and Figure 21). During the ice-free growing season, Pike Lake algae appear to rely on recycled ammonium (animal excretion and from decomposing organic matter) to meet their nitrogen requirement and may actually be limited or co-limited with P in regard to their growth potential (in the sense described by Axler et al. 1994 for other small Minnesota lakes). Although a more in-depth study would be required to confirm this conclusion, the relatively low concentrations of available nitrogen and low DIN/TP ratios found for Pike Lake in 1999 (Table 1) make it prudent to minimize controllable sources of N to the lake from the watershed. These include wastewater leachate (presumed to be greatly reduced by the new sewer line being installed) and lawn fertilizers as well as grass clippings and soil erosion.

As anoxic conditions persisted in the hypolimnion, ammonium accumulated steadily to concentrations ranging from about 800 - 1000 ugN/L in September from 1996 to 1999 (Appendix 1; Table 3). Ammonium accumulates as algae settle and decompose as well as by diffusion from the sediments. In the absence of algal uptake (it is too dark for growth down there) and oxygen (which would allow nitrifying bacteria to oxidize it to nitrate), ammonium levels steadily increase. Under these anoxic conditions, any nitrate that might be present would be rapidly removed by anaerobic denitrifying bacteria (e.g. Horne and Goldman 1994). When the lake turned over in October 1996 and 1997 the ammonium was redistributed throughout the water column.

4. Chlorophyll-a, Phytoplankton and Zooplankton

Surface chlorophyll values were generally low (<7 ug/L) and similar to values determined in the intensive studies in 1993 and 1999. Values typically declined with depth, and were lowest at depths characterized by anoxia and low light (Table 3). As noted above, the highest values (7-17 ug/L on October 25, 1996) were observed during fall turnover in 1996. Late season *blooms* are usually associated with nutrient inputs from mixing coupled with a period of sunny weather (e.g. Horne and Goldman 1994; Wetzel 1983).

A number of qualitative scans of preserved water samples collected from various depths were made to characterize the dominant algae species (Table 6). During the stratified period in 1996 there was a diverse assemblage of blue-greens (some with heterocysts indicating N2-fixers), diatoms, and cryptophytes in the epilimnion and very low densities of predominantly small, flagellated unicells at 15m (anoxic). During intermediate mixing (October 7) densities increased, particularly colonial diatoms and flagellated cryptophytes. Heterocystous blue-greens had disappeared perhaps due to increased ammonium availability from deeper mixing. Little change occurred after complete mixing although there was an increased predominance of diatoms in surface water. The 1997 stratification data were generally similar to the 1996 epilimnion pattern for samples from 0, 3, 6 and 9 m (within the mixed layer in September 1997). Densities were greatly reduced in anoxic 12 and 15 m samples. During turnover (October 27, 1997), the algal community was a very diverse assemblage of several major groups, but the blue-greens had totally disappeared and diatoms were dominant. There were also significant amounts of green algae (chlorophytes) relative to 1996. Only one sample was collected from the surface in September 1998 and it was similar to 1996 and 1997 with dominance by blue-greens (*Anabaena sp.* with N2-fixing heterocysts).

One early-season surface sample was analyzed in May 1997 that is included in Table 6 for archival purposes since phytoplankton data is sparse. The sample was dominated by diatoms and no blue-greens were present; this is typical of north temperate lakes in spring (Horne and Goldman 1994; Wetzel 1983). This result is similar to what was found for a surface water sample collected by MPCA in May 1993 (Figure 6 in Bauman 1994) although a detailed species list was not provided. Late summer (August) phytoplankton data was also reported from 1993 and showed that the community was comprised mostly of blue-green algae although the total biomass was relatively low (chlorophyll-a ~5 ug/L). This result is generally similar to what was found in September 1998, but different (less homogeneous) than what was found in September 1996 and 1997. Surface assemblage data for 1993 and 1999 MPCA surveys are discussed above in Section III.A.

Midlake, full water column estimates of total zooplankton density and major taxonomic groups are presented in Table 7. Unfortunately not all the samples collected were enumerated but these data from a single date in each of the three years may still be useful at some future time. We have not found other zooplankton data for Pike Lake. Fall was dominated by the cladoceran zooplankton, predominantly *Daphnia sp.* and cyclopoid copepods. Densities ranged from about 4-12 animals/L integrated over a 15 m water column.

III. C. Grand Lake Nearshore survey 1997

Grand Lake, located 15 miles northeast of Duluth MN, is typical of many suburban lakes in the area as well as many throughout the state. The lakeshore was developed decades ago primarily as vacation cottages situated close to the shoreline on small lots. Outhouses (or privies), and dry wells were the typical systems used to dispose of septic wastes. For the occasional summer use these methods of disposal most likely had little impact on the lake water quality even with the high water table and poor soils associated with the small lots because the loading rate was low with intermittent rest periods between use. The potential for problems arose with the conversion of the vacation homes to year round residences without updating the septic systems. The old wastewater disposal methods were unsuited to treating the larger loads and the potential for contaminating the lake with untreated or partially treated septic waste increased. With the lot size limitations and the unacceptable soil conditions, on-site wastewater treatment options are limited and many homes have systems that do not meet current codes. Some lots/homes cannot meet current code as evidenced by at least one residence that installed a new mound system that subsided into the underlying peat within a couple of years. Where coded systems can be installed they are most likely mounds that treat to secondary standards and do not address the problems associated with nutrient discharges that may rapidly find there way into Grand Lake and cause eutrophication problems even if disinfection is adequate. Due to new regulations and the stricter county enforcement many of these homeowners are being forced to upgrade their failing systems. All home sales financed through conventional mortgage brokers are now required to have their septic systems evaluated and if they do not meet code they cannot be sold in this manner and instead sold on a contract for deed or some similar alternative financing. This provides additional incentive to upgrade the system if a sale is anticipated in the near future.

In a collaborative joint venture between St. Louis County, ten homeowners, the Natural Resources Research Institute (NRRI), and the Western Lake Superior Sanitary District (WLSSD), a small diameter clustered sewer line (collecting septic tank effluent [STE] from each home) feeding an alternative on-site wastewater treatment system was constructed in fall 1995 to serve ten homes along the Triple Lakes Road. The STE was treated using a subsurface flow constructed wetland coupled to a seepage cell for final effluent dispersal. The homeowners now have a system that treats their wastewater and disperses it in an ecologically sensitive way. The new treatment system will decrease the nutrient loading into the lake and virtually eliminate the public health risks by taking the wastewater out of the back yards of these homes, many of which had untreated or partially treated wastewater surfacing during the spring and other periods when the soil was saturated to the surface. Numerous reports have now been published about this project and are listed below.

To determine the impact (if any) that these failing systems were having on the quality of the lake a review of historical monitoring data was undertaken. The only data we found was reported by WLSSD for the years 1973-1977 as part of the Suburban Lakes Water Quality Report (WLSSD 1979). Grand Lake had the highest concentrations of phosphorus and nitrogen of the five lakes included in the study, although this may just be a reflection of the soils and swamps surrounding the lake as opposed to the anthropogenic inputs of wastewater.

Grand lake is a predominantly shallow lake (95% littoral) with a relatively small *deep*-water zone with a maximum depth of 8 meters. The WLSSD (1979) report noted “extensive fish kills” due to oxygen depletion during the winter. The shoreline is heavily developed except for the southwest corner of the lake that is too low for development. The creek from Little Grand Lake is the only inlet, and there are no outlets, although diffuse inlets and outlets probably exist through the numerous lowlands and swamps surrounding the lake. Some historical monitoring of Grand Lake has occurred but few data were found for the period between 1977 and 1997. Therefore, in order to better establish a better baseline for future assessments of Grand Lake, NRRI staff conducted a water quality survey of the lake on July 7, 1997, similar to the surveys previously conducted by WLSSD and reported in the Suburban Lakes Water Quality Report (WLSSD 1979). Although this 1997 effort consisted of only one date (it was not directly funded), it does provide a qualitative comparison of present water quality, including both nutrients and fecal coliform bacteria.

Water samples were collected at seven locations for nutrients and eight locations for fecal coliforms. Sampling site location numbers are taken from WLSSD’s Suburban Lakes Water Quality Report map #5 (Dec. 19, 1974) and shown in Figure 23. An additional location, site 33, was sampled and called the *background* site as this shoreline area has little or no development relative to the rest of the lake. Nutrient and fecal coliform analysis follow standard methods (APHA 1998, Ameel et al. 1998; see Reference list for complete citations). Nutrient samples were 0-1 meter surface composites, integrated with a sampling tube into a carboy and analyzed at NRRI. The fecal coliform samples were surface grabs collected independently of the nutrient samples directly into sterilized bottles and delivered immediately after sampling to WLSSD for analysis.

The lake temperature and D.O. were uniform from top to bottom and averaged 18.7 ^{o}C and 9 mg O_2/L - typical of midsummer values in a shallow well-mixed lake. Chlorophyll-*a* averaged 6.2 ± 1.5 ug/L (mean $\underline{+}$ standard deviation), total phosphorus averaged 20 ± 5 µgP/L, and secchi depth at mid-lake was 2.6 meters, all indicative of a mesotrophic condition. WLSSD (1979) reported TP ranging from 59 ± 41 in 1974 to 27 ± 8 in 1977. In 1997, the specific electrical conductivity (EC25) was 130 µS/cm, color was 15 Pt-Co color units, alkalinity was 59 mg $CaCO_3$/L, and pH was 8.0 - all within the range of the reported WLSSD values. Nitrate concentration was 4 ± 2 µg[NO_3/NO_2-N]/L and the ammonia was 19 ± 6 µgNH_4^+-N/L, both of which are comparable to the values in the WLSSD report and low relative to the vast majority of Minnesota lakes. Total kjeldahl nitrogen (TKN) estimated as TN minus nitrate in 1997 (NRRI measures TN to attain a lower level of detection in natural lakes and streams rather than TKN which has been traditionally used for wastewater effluents) was 553 ± 26 ug/L compared to the WLSSD (1979) values of 713 ± 16 (n=47), 495 ± 55 (n=2), and 770 ± 110 µgTKN/L (n=2) in 1975, 1976, and 1977, respectively.

Fecal coliform bacteria varied from <10 to 200 cfu/100ml, with a geometric mean value of 23 cfu/100ml. The site designated as the *background* site was comparable to the rest of the lake with respect to the nutrient and physical parameters measured. Fecal coliform levels were marginally higher at the background site (30 cfu/100ml) relative to the sites (26, 26A, 27, 27A) directly offshore from the homes along Triple Lakes Road that were connected to the new wetland treatment system (<10 cfu/100ml, range <10 to 10 cfu/100ml). The concentrations at sites at the other end of the lake (19 A,B,C) directly out from lakeshore homes in a somewhat protected bay, were greater (95 cfu/100ml, range 70 to 200 cfu/100ml) than at the background and Triple lakes Road homes. This pattern was not evident in the 4 years of WLSSD data, however these concentrations can be greatly influenced by a variety of factors not adequately represented by a one time sampling and would require an extensive sampling effort to sort out any differences between opposite ends of the lake. Note also that the federal water quality standard for bathing and swimming beaches (water contact recreation) is 200 cfu/100ml and was not exceeded. Birds and wild/domestic mammals, in addition to humans, generate fecal coliforms and so this limited data set should be used only as a general indicator of microbiological water quality.

A 7 day nutrient enrichment algal growth bioassay was performed with a control, N addition (500 ugN/L), P addition (50 ugP/L), and N + P addition (500 ugN/L and 50 ugP/L). The test was done at room temperature (similar to lake conditions at this time of the year) under a light box with twelve hours of light and twelve hours of dark and with three replicates per treatment. Algal growth was estimated by changes in chlorophyll fluorescence (as per Axler et al. 1994). The result, although only for a single surface sample from one date suggested co-limitation by both nitrogen and phosphorus. Both of these nutrients are found in wastewater at extremely high levels relative to natural inputs of water indicating the need for prudent management of the lake in the future to protect the lake’s beneficial uses.

Grand Lake would benefit from an active lake association that could take the lead in monitoring water quality on a regular basis - at the least, secchi depth as part of MPCA’s Citizen Lake Monitoring Program [CLMP]. Additional funding sources could then be sought for water quality analyses on a periodic basis (3-5 years). This would also be an avenue to further examine the failing septic system issue and provide potential solutions. The lake has the potential to be adversely affected by anthropogenic nutrient and sediment inputs which may be slowed through an active effort on the part of the homeowners.

Grand Lake Alternative Treatment System References (as of March 2001):

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V. RECOMMENDATIONS

1. Maintain the intensive CLMP data sets on Caribou and Pike Lakes, and encourage volunteer recruitment on Grand Lake. Recall that participation in CLMP is a cost-effective way to track trends in water quality. All three lakes should be continually enrolled in CLMP, as this will provide the continuous water quality record needed for trend assessment.

2. Further chemical (especially chlorophyll and nutrients) sampling by St. Louis County or lake associations should take place every 2 or 3 years as money permits, to help track trends in water quality coinciding with improvements in wastewater treatment. The minimum effort should be 4 monthly samples over the summer (8 samples per summer would be ideal).

3. Best management practices should be used when applying road deicers. Specifically, minimize the salting of roads near the lakes, and stockpile snow in upland areas away from the lakeshore. Caribou, Grand, and Pike Lake all had chloride concentrations considerably higher than the ecoregion expectations. This is most likely due to “urban” runoff. A chloride analysis of midlake surface water should be included in any monitoring effort (see above). NRRI data for the entire water column during the overturn period indicated relatively little depth or seasonal variation in chloride and so a single sample to characterize the lake for that year should suffice.

4. Although most beds of shoreline emergent aquatic vegetation on Pike Lake have likely been removed by homeowners over the years, a significant stand of bulrushes remains about midway along the southern shoreline. This is potentially important habitat for invertebrates and juvenile fish and also acts to trap washed in sediments and nutrients. Efforts to educate shoreland homeowners about the benefits of this habitat should be encouraged. A new (March 2001) website developed by the University of Minnesota’s Sea Grant College and Water Resources Center, The Minnesota Shoreland Management Guide [http://shorelandmanagement.org/], provides additional useful information on this and other issues relevant to conserving the lakes’ beneficial uses

5. Any development in the immediate watershed should be completed so that impacts to lake water quality are minimized. Setback provisions and natural buffer strips should be strictly adhered to. Soil loss can be reduced by utilizing best management practices during construction or road building. Protection of the existing vegetation along the shore will minimize erosion and preserve the aesthetic value of the lake. Use of sedimentation basins should be considered to minimize the impacts of urban development. Grass clippings should be collected properly, and not allowed to enter the lakes. Any improvements that might be realized from the sanitary sewer could be quickly masked by increases in the amount of stormwater/urban runoff.

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APPENDIX 1. 1999 Duluth Area Lakes Water Quality Data

Cond= Specific Conductivity
Secchi= Secchi Depth (meters)
TSS= Total Suspended Solids
SVS= Suspended Volatile Solids
Alk= Alkalinity as CaCO3
Color= Color in Platinum Cobalt Units

Cl= Chloride
SO4= Sulfate
TP= Total Phosphorus
TKN= Total Kjeldahl Nitrogen
Chl. a= Chlorophyll a
Phaeo= Phaephytin a

Lake	Date	Time	Site	Depth (m)	Secchi (m)	TSS (mg/L)	SVS	Color	Alk (mg/L)	Cl (mg/L)	TP (mg/L)	TKN (mg/L)	Chl a (ug/L)	Phaeo (ug/L)
Pike	5/25/99	845	101	0	3.35						0.016		8.68	1.43
Pike	5/25/99	915	102	0	3.65	3.6	2	20	60	26	0.029	0.46	9.39	1.09
Pike	5/25/99	915	102	16							0.02			
Pike	6/29/99	900	101	0	4.45						0.01		3.18	0.63
Pike	6/29/99	920	102	14							0.025			
Pike	6/29/99	920	102	0	5.8	<1	<1	20	66	27	0.02	0.38	2.39	0.34
Pike	7/14/99	930	101	0	3.4						0.013		2.53	0.43
Pike	7/14/99	1000	102	0	4.9	<1	<1	20	62	25	0.016	0.35	2.95	<.32
Pike	7/14/99	1000	102	17							0.128			
Pike	8/17/99	1030	101	0	2.8						0.016		3.62	0.57
Pike	8/17/99	1100	102	0	3.6	1.2	<1	20	62	25	0.009	0.43	3.74	<.37
Pike	8/17/99	1100	102	17							0.138			
Pike	9/20/99	930	102	0	4.15	2	1.2	20	62	26	0.022	0.44	3.88	0.83
Pike	9/20/99	930	102	16							0.343			
Pike	9/20/99	915	101	0	3.2						0.015		6.06	1.53
Caribou	5/25/99	1100	101	0	2.1	4.4	2.4	20	46	4.4	0.037	0.48	6.82	2.37
Caribou	5/25/99	1100	101	4							0.031			
Caribou	6/29/99	1115	101	5							0.018			
Caribou	6/29/99	1115	101	0	1.65	2.5	1.8	20	50	4.6	0.02	0.61	7.95	2.33
Caribou	7/14/99	1145	101	0	2.25	2	1.6	20	46	4.2	0.015	0.55	5.86	0.6
Caribou	7/14/99	1145	101	5							0.021			
Caribou	8/17/99	1230	101	6							0.027			
Caribou	8/17/99	1230	101	0	1.8	4	2.6	20	70	4.7	0.028	0.66	12.6	3.94
Caribou	9/20/99	1100	101	0	1.5	2.8	2	30	46	4	0.021	0.58	10.3	2.91
Caribou	9/20/99	1100	101	5							0.022			
Grand	5/25/99	1300	101	0	6.1 B	1.6	<1	10	66	3.7	0.017	0.54	1.05	0.31
Grand	5/25/99	1300	101	5							0.024			
Grand	6/29/99	1245	101	5							0.018			
Grand	6/29/99	1245	101	0	2.4	2	1.6	10	54	4.7	0.021	0.67	6.95	2.69
Grand	7/14/99	1330	101	0	3	1.2	1.2	20	66	4	0.02	0.56	4.23	<.32
Grand	7/14/99	1330	101	5							0.021			
Grand	8/17/99	1345	101	5							0.021			
Grand	8/17/99	1345	101	0	2.75	2.4	2	10	66	4.6	0.02	0.74	6.54	1.52
Grand	9/20/99	1230	101	0	3.1	2.8	2	10	70	3.9	0.016	0.63	5.22	1.51
Grand	9/20/99	1230	101	5							0.016			

APPENDIX 2. Pike Lake Fecal Coliform Data, 1991-1999

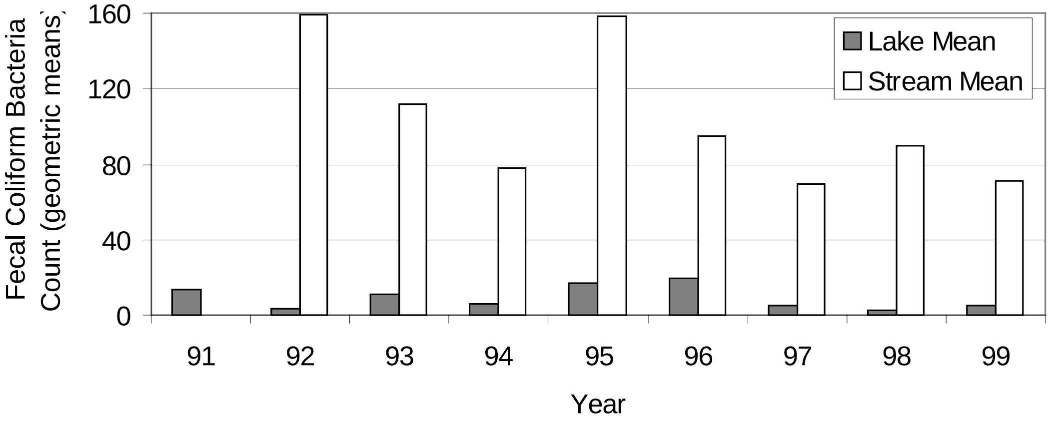
The Pike Lake Association and the St. Louis County Health Department have been routinely collecting bacteria samples on Pike Lake since 1991. Ten sites have been sampled including six near shore sites, two inlets, and one site in the main body of the lake (very near MPCA site 101; Figure 3). Samples were collected approximately one to two times per month over the summer at each site. MPCA staff analyzed the Association's data for this report.

MPCA uses fecal coliform bacteria as an indicator of swimmability in Minnesota lakes and streams. The State water quality standard is 200 colonies per 100 milliliters of water, based on the geometric mean of at least 5 samples per month. Although samples from Pike Lake were collected less frequently than required for purposes of assessing whether a water quality standard was violated, some observations can be drawn from the data. Appendix 2 Figure 1 shows the concentration of fecal coliform bacteria in the lake and at its inlets (stream sites) from 1991-99. Data are presented as the summer mean of the monthly geometric mean concentrations. The monthly geometric mean concentrations were calculated from individual samples taken at the seven sampling sites across the lake, and the three stream inlet sites.

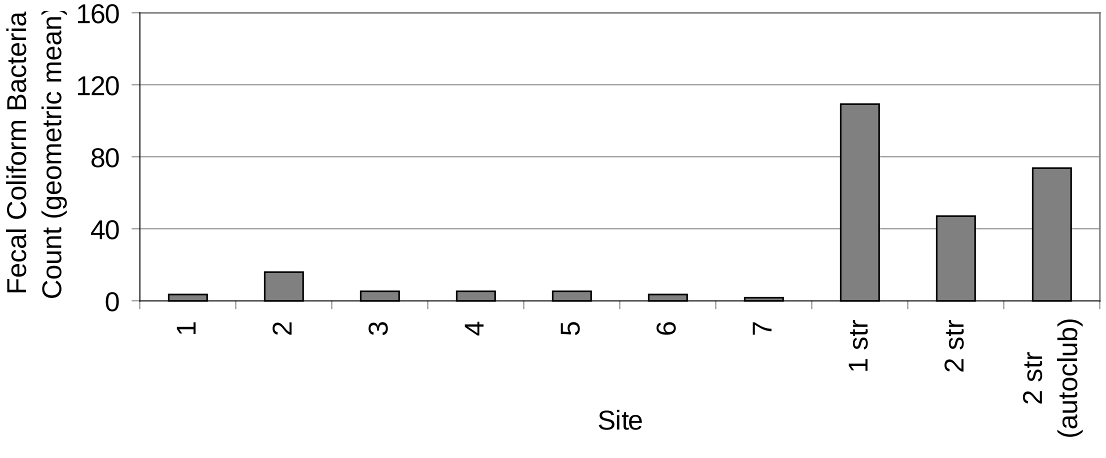
Fecal coliform concentrations were often an order of magnitude higher in the tributaries compared to the lake. This most likely occurred because of in-lake dilution effects and because the lake may provide less desirable conditions for the growth and/or survival of fecal coliform populations. Individual samples often exceeded the State standard of 200 colonies per 100 milliliters - a stream sample in June of 1995 had a count of 10,000 organisms; and the highest in-lake concentration was 1,800 colonies. The standard was only technically exceeded three times over the period of record, and this only occurred in the stream samples. Typically eight to ten years of data are needed to assess long-term water quality trends. Based on the eight to nine years of lake and stream fecal coliform data it appears that concentrations have declined in both the lake and streams over the 1990's. The installation of the new sanitary sewer should continue this improvement.

The spatial distribution of fecal coliform bacteria from Pike Lake and its tributaries is shown in Appendix 2 Figure 2. Again, the concentrations of fecal coliforms are much higher in the tributary streams than the lake. It is likely that the stream environment is more conducive to maintaining and possibly propagating fecal bacteria through activities of beaver, waterfowl, and other animals that may reside in, or use these streams. Stagnant ponds in or draining to these streams may well be sources of the bacteria. In contrast, the open waters of the lake are influenced by dilution and sunlight both of which could serve to reduce fecal bacteria concentrations. In-lake sites 1-6 are located around the perimeter of the lake (samples were collected off docks), and site number 7 is near the center of the lake. Site 7 has the lowest fecal coliform concentration, as would be expected because it is the farthest from water inflows and potential septic system impacts along the shoreline. Site 2 had the highest in-lake concentration, and was most likely influenced by the higher concentrations coming from the upstream stream sites ("2 str" and "autoclub" - Figure 2). Streams generally have higher suspended solids concentrations than lakes, because flowing water better maintains particles suspended in the water column. Concentrations of bacteria may be higher in the streams because: (1) a significant portion of the solids *are* bacteria, as opposed to soil or algae particles; (2) proximity to actual sources of fecal coliforms in the watershed; and (3) lake concentrations are reduced by both dispersion and dilution into the main body of the lake and by particles (freely suspended and also attached to silt particles) settling rapidly to the lake bottom. While we cannot state conclusively that improper treatment from nearshore septic systems was a primary source of the fecal coliform bacteria measured in the lake it is very possible it was one of the sources and as such we would hope that the installation of the new sanitary sewer should minimize any future contributions from this source.

Appendix 2-1. Fecal Coliform Bacteria Concentrations on Pike Lake and its Tributaries



Appendix 2-2. Fecal Coliform Bacteria Concentrations at Pike Lake Sites (1 -7) and Tributary Streams (str), 1991-99.



APPENDIX 3. Pike Lake Cryptosporidium Outbreak: July-August 2000

An outbreak of the parasite *Cryptosporidium parva* that was attributed to swimming at the bathing beach at Pike Lake was widely publicized in late July 2000. Because of it's importance to local citizens and officials the following summary statements from the St. Louis County Department of Environmental Health Services and the Minnesota Department of Health's Office of Acute Disease and Epidemiology.

1. *Lake Residents Survey Results* (St. Louis County Environmental Health Services, Duluth, MN 55802)

2. *Update on Pike Lake Cryptosporidium* Outbreak (dated 8/18/2000; L. Sundberg, (St. Louis County Environmental Health Services, Duluth, MN 55802)

3. *Final Report* - Minnesota Department of Health, Office of Acute Disease and Epidemiology, 717 Delaware Street SE, Minneapolis, MN 55414

PRESS RELEASE

August 18, 2000

Contact person: Larry Sundberg
(218) 725-5278

UPDATE ON PIKE LAKE CRYPTOSPORIDIUM OUTBREAK

The St. Louis County Department of Public Health and the Minnesota Department of Health are continuing the investigation of the Cryptosporidium outbreak in Pike Lake. The St. Louis County Health Department estimates the outbreak has caused over 200 cases of illness. The Health Department is still monitoring for cases of illness in people who have swum in Pike Lake during the month of August.

The investigation has not uncovered a source of the outbreak. The Health Department has searched for possible sources of fecal contamination from areas around the beach. No apparent source of fecal contamination was discovered. Investigation of illness in other parts of the lake is still underway. There are no practical or reliable methods for testing for the presence of Cryptosporidium in water. **Because no identifiable source of contamination has been found and there is no means of testing for Cryptosporidium in the water the Health Department, effective August 18, has lifted its swimming restriction for the AAA Swim Club beach and the near-by public access.** However, the public should be aware that there will always be some risk of Cryptosporidium infection, and infection by other waterborne pathogens, from swimming anywhere in Pike Lake as there is in any other natural body of water.

Individuals who have swum in Pike Lake and later developed a diarrheal illness should not swim until two weeks after their diarrhea stopped. This is due to the high number of Cryptosporidium organisms they would still be shedding in the two weeks after recovery from their symptoms.

Cryptosporidium, Giardia and other water-borne pathogens will normally be present at some level in most bodies of surface water. The public should assume there is always some risk of a infection by a water-borne pathogen when swimming in an outdoor body of water. Since it is believed most cases of these infections go undiagnosed the Health Department has no estimate of the "normal" number of Cryptosporidium infections that may occur among swimmers in Pike Lake.

To reduce the risk of getting an infection from water-borne pathogens while swimming people should observe the following practices:

1. Do not enter the water if you have diarrhea. People can spread germs in the water even without having an "accident".
2. Do not swallow the water.
3. Wash hands and the bottom thoroughly with soap and water after having a bowel movement or changing diapers.
4. Do not change diapers near the water and wash the child's bottom with soap and water before returning to any swimming area.
5. Children in diapers should always wear swim diapers or rubber cover pants over their diapers to reduce the chance of fecal matter leaking into the water. However parents must remember these items are not leakproof so they should take their children to the toilet often.

PIKE LAKE CRYPTOSPORIDIUM OUTBREAK, JULY-AUGUST 2000

LAKESHORE RESIDENTS SURVEY RESULTS.

A survey was done of Pike Lake lakeshore property residents to search for the occurrence of Cryptosporidium infections from swimming in the lake at locations other than the AAA Swim Club beach. At least two telephone call attempts were made to each lakeshore residence property on Pike Lake. Telephone contact was made with 74 residents. Seventy three of the residents agreed to be interviewed and one person declined to give an interview. Nine of the surveys were subsequently eliminated from analysis due to incomplete data.. This left 64 completed surveys.

The initial survey instrument asked "Between July 28 and today (usually 8/10 or 8/11) have you been in Pike Lake where you got your face or head wet." Later the instrument was changed to expand the time frame to July 20 to the time of the interview. Most of the interviews were completed using the July 28 to interview date time frame. While the water exposure question was directed specifically to the person giving the interview some of the respondents also provided water exposure and illness history data on children staying in the residence.

No one was reported to have swam at 31 of the residences surveyed. Someone in the household was reported to have swam at 33 of the residencies. For two of these households the individuals had only swam at the AAA Swim Club beach. One person had swam both in front of the home and at the AAA Swim Club beach on July 30. One person reported swimming almost daily from a boat anchored in the middle of the lake. At the remaining 29 residencies people reported they swam in the lake only in front of their house. Many of these 29 respondents reported swimming in the lake every day or nearly every day.

Ten of the people who swam in the lake reported having a history of gastrointestinal illness. Only two of these illnesses met the case definition for this investigation. One of these case was the person who had swam both in front of the home and at the AAA Swim Club beach on July 30. The other person had swam only in front of the home. This person's house is located on the East end of the lake about ½ mile from the AAA Swim Club beach.

One person, who swam only in front of his home, was in his second day of illness when interviewed. The individual had diarrhea and a headache but no vomiting, abdominal pains or fever. This person was not called back at a later date to see if his diarrhea lasted long enough for him to be classified as a case. This person's home is on the north shore of the lake about 2/3 of the way to the opposite end of the lake from the AAA Swim Club beach.

The resident survey data is interpreted as not showing an elevated risk for cryptosporidium infection in areas away from the vicinity of the AAA Swim Club beach. Water currents away from the AAA Swim Club beach are likely to move in a northwesterly or northerly direction because of prevailing wind patterns and sheltering around the lake.

Outbreak of Cryptosporidiosis Associated with a Swimming Beach
St. Louis County, MN
July and August, 2000

Background:

On August 10, 2000 the Minnesota Department of Health (MDH) received a call from the St. Louis County Department of Public Health and Long Term Medical Health (St. Louis County) about a possible outbreak of cryptosporidiosis associated with a swimming beach operated by the AAA on Pike Lake. The county had received a report on August 8 from a day care provider that had taken children to the beach on July 31, and all the children had subsequently become ill with gastrointestinal symptoms. On August 10, stool samples from at least one of those children yielded *Cryptosporidium parvum.* The county issued a press release asking sick people who had used the swimming beach to call St. Louis County. St. Louis County closed the swimming beach for public use on August 10.

Methods:

People calling in to report illness were interviewed by either St. Louis County or epidemiologists from the MDH. People who used the swimming beach without clinical illness were also interviewed as controls. The interview included questions regarding swimming exposures and food consumed at the swimming beach. A case was defined as anyone who had swum at Pike Lake and subsequently developed vomiting or diarrhea of 3 or more days duration. Diarrhea was defined as 3 or more loose stools in a 24-hour period.

Homeowners around the lake were called by St. Louis County and questioned about any gastrointestinal illness and swimming history.

Several hundred people swam at the beach on August 6 as part of a triathalon. A list of participants was obtained from the event organizer. Twenty randomly selected participants were contacted and asked about illness history.

St. Louis County inspected the plumbing in the club house at the swimming beach to determine if there were any plumbing deficiencies that could allow human sewage to contaminate the swimming area. The club house contains shower rooms, restroom facilities, concession stand, and a golf pro shop. City sewer lines were being extended to the lakeshore residents, and septic tanks in areas around the lake were being abandoned. Inquiries were made to the contractors installing the city sewer lines to determine if there was any possibility that a sewage spill could have occurred during this construction. Air surveillance was conducted of areas upstream from the lake to determine if there was a chance for animal effluent entering the swimming area.

Cryptosporidium parvum isolates received at the MDH Laboratory were analyzed by PCR to determine if they were Type 1 (human-associated) or Type 2 (animal- associated) genotypes.

Results:

Three hundred twenty-six people were interviewed as part of the call-in survey. Eighteen cases of *Cryptosporidium parvum* infection were confirmed; one of these cases also had *Giardia*. Another case of *Giardia* infection was also confirmed. Both *Giardia* cases were members of one family. Another member of that family was diagnosed with only a *Cryptosporidium* infection. An additional 202 people met the outbreak case definition. Dates of exposure at the beach ranged from July 20 through August 7 (Figure 1). Onset of illness ranged from July 24 through August 18.

One of twenty triatheletes interviewed met the case definition; this case was not laboratory confirmed. The only time that person swam at the beach was during the triathalon on August 6. Onset of illness for this case was August 7.

Two people among 33 households of lakeshore homeowners that were interviewed met the case definition. One of these people had swum at the AAA beach as well as in front of their home.

Risk factors associated with clinical illness on univariate analysis included; getting the head wet while swimming (odds ratio [OR] = 17.9; 95% confidence interval [CI], 7.4, 41.5; $p<0.0001$) and eating food brought from home (OR = 3.2; 95% CI, 1.1, 11.2; $p = 0.025$). Upon multivariate analysis the only risk factor independently associated with illness was getting the head wet while swimming (OR = 21.4; 95% CI, 8.1, 56.7; $p<0.001$).

Of eight *Cryptosporidium parvum* isolates analyzed by PCR, seven were genotype 1 (human- associated). The genotype of the genotype 2 isolate could not be confirmed on retesting.

No plumbing irregularities were identified at the swimming beach facilities. No animal reservoirs were identified upstream from the beach. Contractors working on the sewer line project denied any incidents that would cause a sewage spill into the lake. There were numerous reports of people changing babies' diapers on the beach, and even washing off babies in the lake while changing diapers.

Interventions were suggested to the AAA including adding diaper changing stations in the restrooms, restricting diaper changes on the beach, and requiring diaper-aged children to wear special swimming diapers. The beach was allowed to reopen on August 19.

Conclusion:

This is an outbreak of cryptosporidiosis and associated with a swimming beach. The magnitude of the role of *Giardia* in this outbreak was not clearly established. No definitive source of contamination was identified, but contamination from diaper-aged children was the most plausible source.

Figure 1. Cases of Cryptosporidiosis,
Pike Lake, Minnesota,July-August 2000, by date of exposure

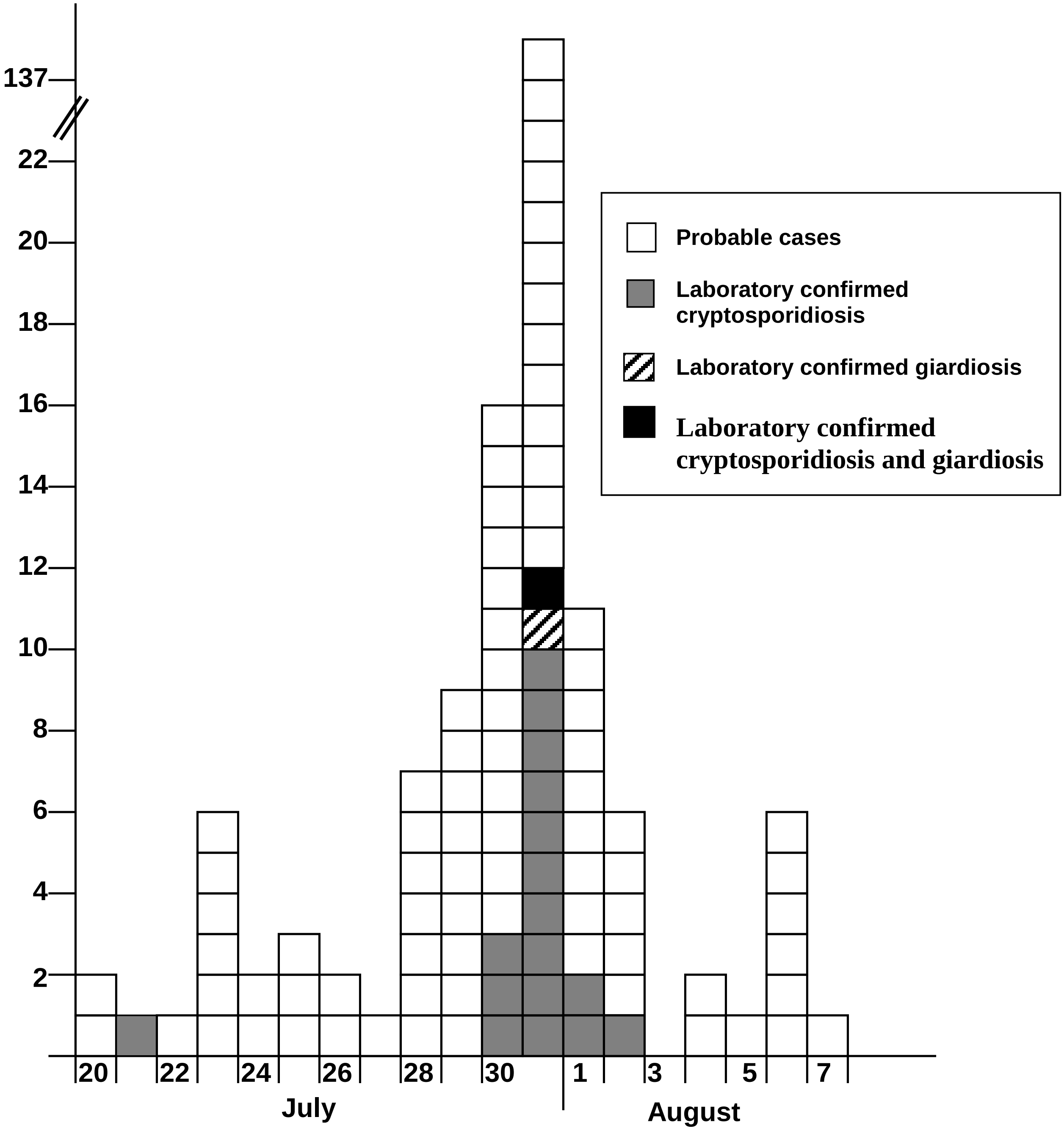


Table 1. Average summer water quality and trophic status indicators from 1999 epilimnion data

Parameter [1]	Caribou	Grand	Pike [2]	Typical Range: NLF Ecoregion [3]
Total Phosphorus (µg/L)	24	17	16	14-27
Chlorophyll *a* (µg/L) [4]				
- Mean	8.3	4.4	3.6	<10
- Maximum	12.6	6.95	7.6	<15
Secchi disk (feet) [meters]	6.1 [1.8]	11.1 [3.4]	14.5 [4.4]	8 – 15 [2.4 – 4.6]
Total Nitrogen (mg/L)	0.57	0.64	0.40	<0.75
Alkalinity (mg/L)	52	64	62	40 - 140
Color (Pt-Co Units)	22	12	20	10-35
pH (SU)	7.8	8.5	7.4	7.2 – 8.3
Chloride (mg/L)	4.38	4.18	25.8	<2
Total Suspended Solids (mg/L)	3.1	2.0	2.3	<1 – 2
Total Suspended Inorganic Solids	2.1	1.7	1.6	<1 – 2
Conductivity (µmhos/cm)	104	137	234	50 – 250
TN:TP Ratio	24:1	38:1	25:1	25:1 – 35:1
DIN:TP Ratio	1.3:1 (n=2)	1.9:1	2.6:1	See note 5

[1] TP, TN, and Chl. *a* data are averages of samples collected from MPCA and NRRI
[2] Data from site 102 only
[3] Derived from Heiskary and Wilson (1989)
[4] Chlorophyll *a* measurements have been corrected for phaeophytin
[5] see Axler et al. 1994 for discussion of TN:TP and DIN:TP ratios in regard to phytoplankton nutrient deficiency

Table 2. Summary of nutrient data for Duluth area lakes from summer surveys, 1975-1977 (WLSSD 1979). Values represent near-surface water samples collected at offshore sites. Full details available from the Western Lake Superior Sanitary District, Duluth. MN.

Lake	Total Phosphorus (mgP/L)	Total Nitrogen (mgN/L)
Grand Lake	**0.035**	**0.88**
Caribou Lake	**0.023**	**0.77**
Chub Lake	0.021	0.60
Pike Lake	**0.018**	**0.54**
Little Grand Lake	0.014	0.65

Table 3. Nutrient and chlorophyll concentrations at mid-lake site #102, Pike Lake, St. Louis County, MN, 1996-1998.

1996 NRRI NUTRIENT & CHLOROPHYLL DATA

DATE	LAKE	STATION	Depth (m)	OP (ug/L)	TP (ug/L)	NH3-N (ug/L)	NO3-N (ug/L)	TN (ug/L)	CHL-A (ug/L)
9/18/96	PIKE LK	102	0	13	25	<10	<5	399	4.0
9/18/96	PIKE LK	102	3	<5	22	19	<5	444	2.0
9/18/96	PIKE LK	102	6	<5	18	<10	<5	379	2.7
9/18/96	PIKE LK	102	9	64	20	358	<5	421	4.2
9/18/96	PIKE LK	102	12	90	107	785	<5	697	0.4
9/18/96	PIKE LK	102	15	192	249	795	<5	1084	0.1
10/7/96	PIKE LK	102	0	<5	21	12	<5	437	5.3
10/7/96	PIKE LK	102	5	<5	18	33	<5	400	5.7
10/7/96	PIKE LK	102	10	<5	16	<10	<5	370	3.7
10/7/96	PIKE LK	102	14	89	91	661	<5	899	0.5
10/25/96	PIKE LK	102	0	<5	24	43	<5	460	17.4
10/25/96	PIKE LK	102	5	<5	26	17	<5	428	--
10/25/96	PIKE LK	102	10	<5	23	41	<5	416	11.2
10/25/96	PIKE LK	102	14	<5	26	<10	<5	452	6.9

1997 NRRI NUTRIENT & CHLOROPHYLL DATA

DATE	LAKE	STATION	Depth (m)	OP (ug/L)	TP (ug/L)	NH3-N (ug/L)	NO3-N (ug/L)	TN (ug/L)	CHL-A (ug/L)
9/24/97	PIKE LK	102	0	1	18	20	<5	348	2.6
9/24/97	PIKE LK	102	3	3	18	16	<5	386	2.5
9/24/97	PIKE LK	102	6	3	19	19	<5	306	1.0
9/24/97	PIKE LK	102	9	2	17	16	<5	357	2.2
9/24/97	PIKE LK	102	12	4	28	224	<5	560	0.9
9/24/97	PIKE LK	102	15	153	153	638	<5	961	0.3
10/22/97	PIKE LK	102	0	8	25	90	<5	459	1.7
10/22/97	PIKE LK	102	3	5	26	100	<5	468	1.2
10/22/97	PIKE LK	102	6	5	25	100	<5	452	0.6
10/22/97	PIKE LK	102	9	6	26	100	<5	455	1.5
10/22/97	PIKE LK	102	12	4	26	104	<5	436	1.6
10/22/97	PIKE LK	102	15	4	24	98	<5	454	1.6

1998 NRRI NUTRIENT & CHLOROPHYLL DATA

DATE	LAKE	STATION	Depth (m)	OP (ug/L)	TP (ug/L)	NH3-N (ug/L)	NO3-N (ug/L)	TN (ug/L)	CHL-A (ug/L)
9/21/98	PIKE LK	102	0	4	13	8	<5	384	7.1
9/21/98	PIKE LK	102	3	<5	17	17	<5	387	4.9
9/21/98	PIKE LK	102	6	2	13	18	<5	389	5.4
9/21/98	PIKE LK	102	9	2	13	10	<5	387	5.5
9/21/98	PIKE LK	102	12	153	157	599	<5	1117	0.9
9/21/98	PIKE LK	102	14	235	232	858	<5	992	0

Table 4. Major ions and redox-controlled iron (Fe) and manganese (Mn) concentrations at mid-lake site #102, Pike Lake, St. Louis County, MN, 1996-1998.

1996 NRRI MAJOR CATIONS & ANIONS DATA

DATE	LAKE	STATION	Depth (m)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	SO4 (mg/L)	Cl (mg/L)	Tot Fe (mg/L)	Tot Mn (mg/L)	Dis Fe (mg/L)	Dis Mn (mg/L)	Alkalinity (mg/L CaCO3)
9/18/96	PIKE LK	102	0	15.1	7.7	11.3	1.0	4.4	20.9	0.1	0.1	0.1	0.0	66.8
9/18/96	PIKE LK	102	3	16.3	7.4	10.4	1.0	4.5	22.1	0.1	0.1	0.1	0.0	63.2
9/18/96	PIKE LK	102	6	--	--	--	--	--	--	--	--	--	--	62.6
9/18/96	PIKE LK	102	9	17.1	7.6	10.7	1.1	2.5	22.3	0.1	0.1	0.2	2.4	63.6
9/18/96	PIKE LK	102	12	--	--		--	--	--	--	--	--	--	73.6
9/18/96	PIKE LK	102	15	12.1	7.4	10.4	1.1	2.3	22.2	2.2	1.7	1.4	1.5	78.6
10/7/96	PIKE LK	102	0	19.2	7.1	10.2	1.0	4.5	21.7	0.1	0.0	0.1	0.1	68.2
10/7/96	PIKE LK	102	5	--	--	--	--	--	--	--	--	--	--	69.9
10/7/96	PIKE LK	102	10	19.2	7.0	10.3	1.0	4.6	21.9	0.1	0.1	0.1	0.1	68.2
10/7/96	PIKE LK	102	14	18.9	7.2	10.5	1.1	3.1	22.1	0.9	2.3	0.9	2.1	71.5
10/25/96	PIKE LK	102	0	19.7	6.9	10.4	1.0	4.6	21.5	0.1	0.1	0.1	0.1	69.5
10/25/96	PIKE LK	102	5			--	--	--	--	--	--	--	--	67.9
10/25/96	PIKE LK	102	10	19.5	6.4	10.0	0.9	4.2	19.4	0.1	0.1	0.1	0.2	69.3
10/25/96	PIKE LK	102	14	17.1	6.4	9.8	0.9	4.1	19.7	0.1	0.1	0.1	0.1	61.0

1997 NRRI MAJOR CATIONS & ANIONS DATA

DATE	LAKE	STATION	Depth (m)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	SO4 (mg/L)	Cl (mg/L)	Tot Fe (mg/L)	Tot Mn (mg/L)	Dis Fe (mg/L)	Dis Mn (mg/L)	Alkalinity (mg/L CaCO3)
9/24/97	PIKE LK	102	0	19.6	7.5	11.2	1.0	4.1	19.6	--	--	--	--	64.0
9/24/97	PIKE LK	102	3	19.5	7.4	11.2	1.0	4.9	24.5	--	--	--	--	65.1
9/24/97	PIKE LK	102	6	19.9	7.5	11.4	1.0	5.2	25.0	0.0	0.1	0.0	0.0	65.9
9/24/97	PIKE LK	102	9	19.7	7.5	11.2	1.0	5.1	24.5	0.0	0.1	0.0	0.0	65.8
9/24/97	PIKE LK	102	12	20.7	7.4	11.0	1.2	5.0	24.1	0.4	1.4	0.2	1.4	69.1
9/24/97	PIKE LK	102	15	21.3	7.4	11.0	1.1	3.2	24.3	2.9	2.9	2.2	2.3	73.6
10/22/97	PIKE LK	102	0	17.5	6.6	9.9	0.9	4.3	20.3	--	--	--	--	60.8
10/22/97	PIKE LK	102	3	--	--	--	--	--	--	--	--	--	--	59.6
10/22/97	PIKE LK	102	6	19.8	7.4	11.1	1.0	5.1	25.1	0.2	0.2	--	--	64.9
10/22/97	PIKE LK	102	9	--	--	--	--	--	--	--	--	--	--	65.8
10/22/97	PIKE LK	102	12	20.2	7.7	11.1	1.1	5.3	25.1	0.1	0.1	--	--	69.9
10/22/97	PIKE LK	102	15	20.1	7.7	11.1	1.1	5.1	25.2	0.1	0.2	--	--	81.7

1998 NRRI MAJOR CATIONS & ANIONS DATA

DATE	LAKE	STATION	Depth (m)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	SO4 (mg/L)	Cl (mg/L)	Tot Fe (mg/L)	Tot Mn (mg/L)	Dis Fe (mg/L)	Dis Mn (mg/L)	Alkalinity (mg/L CaCO3)
9/21/98	PIKE LK	102	0	20.7	7.7	11.3	1.1	5.0	24.7	--	--	0.0	0.0	62.6
9/21/98	PIKE LK	102	3	21.1	7.8	11.4	1.1	4.9	24.6	--	--	0.0	0.0	62.5
9/21/98	PIKE LK	102	6	20.7	7.8	11.2	1.0	4.5	21.2	0.1	0.1	0.0	0.0	63.1
9/21/98	PIKE LK	102	9	21.1	7.9	11.3	1.0	5.2	25.7	--	--	0.0	0.0	62.5
9/21/98	PIKE LK	102	12	22.0	7.9	11.3	1.2	1.4	25.4	1.8	2.4	1.5	--	71.9
9/21/98	PIKE LK	102	14	21.8	7.8	11.0	1.2	0.1	25.4	2.4	2.3	2.0	--	73.3

Table 5. Whole-lake nutrient and major ion budgets pre- (i.e. stratified) and post-fall mixing. Nutrient totals are in kilograms, major ions in metric tones, summed over all strata from the morphometry map reported in MPCA (1994) and shown as Figure 3A.

9/18/96 Stratified

Depth	Stratum Vol ($10^6 m^3$)	NH_4-N (ug/L)	NH_4 (kgN)	TN (ug/L)	TN (kgN)	TP (ug/L)	TP (kgP)	Cl (mg/L)	Cl (10^3kg)	SO_4 (mg/L)	SO_4 (10^3kg)
0		10		399		25		20.9		4.4	
	5.3		77		2234		125		114		23.4
3		19		444		22		22.1		4.5	
	4.5		65		1852		90		100		18.0
6		10		379		18		22.2		3.5	
	3.6		1431		1440		148		80		10.8
9		785		421		64		22.3		2.5	
	2.5		1429		1398		214		56		6.2
12		358		697		107		22.3		2.5	
	1.5		865		1336		267		33		3.6
15		795		1084		249		22.2		2.3	
<15	0.7		557		759		174		16		1.6
Total	18.1		4423		9018		1017		398		63.7

10/7/96 Partial mixing

Depth	Stratum Vol ($10^6 m^3$)	NH_4-N (ug/L)	NH_4 (kgN)	TN (ug/L)	TN (kgN)	TP (ug/L)	TP (kgP)	Cl (mg/L)	Cl (10^3kg)	SO_4 (mg/L)	SO_4 (10^3kg)
0		12		437		21		21.7		4.5	
	8.3		187		3474		162		180		37.1
5		33		400		18		21.8		4.5	
	5.93		127		2283		101		129		26.8
10		10		370		16		21.8		4.6	
	2.67		896		1694		143		59		10.3
14		661		899		91		22.1		3.1	
<14	1.2		793		1079		109		27		3.8
Total	18.1		2003		8530		515		395		78.0

10/25/96 Mixing

Depth	Stratum Vol ($10^6 m^3$)	NH_4-N (ug/L)	NH_4 (kgN)	TN (ug/L)	TN (kgN)	TP (ug/L)	TP (kgP)	Cl (mg/L)	Cl (10^3kg)	SO_4 (mg/L)	SO_4 (10^3kg)
0		43		460		24		21.4		4.6	
	8.3		249		3685		208		173		37.0
5		17		428		26		20.4		4.4	
	5.93		172		2502		145		118		25.3
10		41		416		23		19.4		4.2	
	2.67		68		1159		65		52		11.0
14		10		452		26		19.7		4.1	
<14	1.2		12		542		31		24		4.9
Total	18.1		501		7889		449		367		78.2

Table 5 (cont). Pike Lake, MN, whole-lake nutrient and major ion budgets pre- (i.e. stratified) and post fall mixing. Nutrient totals are in kgs, major ions in metric tones, summed over all strata from Bauman (1994) morphometry.

9/24/97 Stratified

Depth	Stratum Vol ($10^6 m^3$)	NH$_4$-N (ug/L)	NH$_4$ (kgN)	TN (ug/L)	TN (kgN)	TP (ug/L)	TP (kgP)	Cl (mg/L)	Cl (10^3kg)	SO$_4$ (mg/L)	SO$_4$ (10^3kg)
0		20		348		18		19.6		4.1	
	5.3		95		1945		95		117		23.9
3		16		386		18		24.5		4.9	
	4.5		79		1557		83		111		22.7
6		19		306		19		25		5.2	
	3.6		63		1193		64.8		89.1		18.54
9		16		357		17		24.5		5.1	
	2.5		300		1146		56.25		60.75		12.625
12		224		560		28		24.1		5	
	1.5		646.5		1141		135.75		36.3		6.15
15		638		961		153		24.3		3.2	
<15	0.7		447		673		107		17		2.2
Total	18.1		1630		7655		543		431		86.1

10/22/97 Mixing

Depth	Stratum Vol ($10^6 m^3$)	NH$_4$-N (ug/L)	NH$_4$ (kgN)	TN (ug/L)	TN (kgN)	TP (ug/L)	TP (kgP)	Cl (mg/L)	Cl (10^3kg)	SO$_4$ (mg/L)	SO$_4$ (10^3kg)
0		90		459		25		20.3		4.3	
	5.3		504		2457		135		114		23.9
3		100		468		26		22.7		4.7	
	4.5		450		2070		115		108		22.1
6		100		452		25		25.1		5.1	
	3.6		360		1633		91.8		90.36		18.54
9		100		455		26		25.1		5.2	
	2.5		255		1114		65		63		13.1
12		104		436		26		25.1		5.3	
	1.5		151.5		667.5		37.5		37.725		7.8
15		98		454		24		25.2		5.1	
<15	0.7		69		318		17		18		3.6
Total	18.1		1789		8258		461		430		88.9

9/21/98 Stratified

Depth	Stratum Vol ($10^6 m^3$)	NH$_4$-N (ug/L)	NH$_4$ (kgN)	TN (ug/L)	TN (kgN)	TP (ug/L)	TP (kgP)	Cl (mg/L)	Cl (10^3kg)	SO$_4$ (mg/L)	SO$_4$ (10^3kg)
0		8		384		13		24.7		5	
	5.3		66.25		2043		79.5		130.645		26.235
3		17		387		17		24.6		4.9	
	4.5		78.75		1746		67.5		103.05		21.15
6		18		389		13		21.2		4.5	
	3.6		50.4		1397		46.8		84.42		17.46
9		10		387		13		25.7		5.2	
	2.5		761.3		1880		212.5		63.875		8.25
12		599		1117		157		25.4		1.4	
	1.5		1093		1582		291.75		38.1		1.125
15		858		992		232		25.4		0.1	
<15	0.7		601		694		162		18		0.1
Total	18.1		2650		9342		860		438		74.3

Table 6. Semi-quantitative phytoplankton Rapid Scans for mid-lake site #102, Pike Lake, St. Louis County, MN, 1996-1998. The 1998 data represents mean cell densities from quantitative scans of seven (7) independent sub-samples.

	DATE/DEPTH	% total biomass	DATE/DEPTH	% total biomass	DATE/DEPTH	% total biomass
	09/18/96 - 0m		**09/18/96 - 6m**		**09/18/96 - 15m**	
Blue-greens	*Anabaena (2species)*	present	*Anabaena (2species)*	present	**blue-greens**	none
	Oscillatoria	"	*Oscillatoria*	"		
	Coelosphaerium	"	*Aphanocapsa*	"		
	Aphanocapsa	"	*Chroococcus limneticus*	"		
	Chroococcus limneticus	"				
	unidentified small filament	"				
					diatoms	none
Diatoms	*Melosira*	"	*Fragillaria*	present		
	Tabellaria	"	*Stephanodiscus*	"		
	Fragillaria	"				
	misc. pennates	"				
Chlorophyta	*Ankistrodesmus*	"	*Pandorina?*	"	**chlorophytes**	none
	Pediastrum	"				
	Pandorina ?	"				
Chrysophyta		none		none	**chrysophytes**	none
Cryptophytes	*Cryptomonas sp*	present	*Cryptomonas sp*	present	Cryptomonas sp ?	
	Rhodomonas minuta	"	*Rhodomonas minuta*	"	Rhodomonas minuta ?	
			unidentified flagellates	"		
other						
	Notes: very diverse slide, % dominance not assigned		**Notes: Anabaena had heterocysts & akinetes; Cell densities too low to assign dominance; Anabaena spp the most abundant form**		**Notes:very low cell density; some empty diatom frustules; a few unidentified flagellates; ID's difficult due to lt brown precipate on slide**	

	DATE/DEPTH	% total biomass	DATE/DEPTH	% total biomass
	10/07/96 - 0m		**10/25/96 - 0m**	
Blue-greens	*Anabaena sp **	10	*Anabaena sp*	5
	Gomphosphaeria	5	*Gomphosphaeria*	5
	Aphanizomenon	5	*Aphanizomenon*	5
Diatoms	*Fragillaria*	20	*Fragillaria*	15
	Melosira sp 1	20	*Melosira*	30
	Melosira sp 2	5	*Tabellaria*	5
	Stephanodiscus	5	*Stephanodiscus*	15
			Asterionella formosa	5
Chlorophyta	*Pandorina*	present	*chlorophytes*	none
Chrysophyta	*Mallomonas*	present	*chrysophytes*	none
	Crytomonas reflexa	15	*Crytomonas reflexa*	5
	Cryptomonas erosa	15	*Cryptomonas sp*	5
other			*unidentified flagellates*	5
	Notes:+akinetes, no heterocysts colonial diatoms and cryptophytes dominate		**notes: diatom dominated; no heterocysts on. Anabaena, few filaments seen however**	

Table 6 (cont). Semi-quantitative phytoplankton Rapid Scans for mid-lake site #102, Pike Lake, St. Louis County, MN, 1996-1998. The 1998 data represents mean cell densities from quantitative scans of seven (7) independent sub-samples.

	DATE/DEPTH	% total biomass	DATE/DEPTH	% total biomass	DATE/DEPTH
	05/20/97 - 1m		**09/24/97 - 0m**		**09/24/97 - 3m, 6m, 9m**
Blue-greens	**absent**	none	*Chroococcus limneticus*	present	
			Microcystis aeruginosa	10	**-almost identical to surface sample in both genera present and biomass**
			Anabaena sp	present	
			Oscillatoria	present	
			Coelosphaerium	present	**09/24/97 - 12m**
Diatoms	*Asterionella*	5	*Asterionella*	30	**-much lower biomass, consisting of cryptophytes and a few diatoms**
	Tabellaria	5			
	Fragillaria	5	*Fragillaria*	35	
	Melosira (2 species)	60	*Melosira*	5	**09/24/97 - 15m**
	Stephanodiscus	10	*Stephanodiscus*	present	
	Synedra	5	*Synedra*	present	**-a few cryptomonad cells mostly unidentifiable detrital material (?)**
Chlorophyta	*absent*	none	*Cosmarium*	present	
Chrysophyta	*Mallomonas*	present	chrysophytes	absent	
	Dinobryon sertularia	5			
Cryptophytes	*Cryptomonas erosa*	present	*Cryptomonas erosa*	5	
	Rhodomonas minuta	5	*Rhodomonas minuta*	5	
			C. curvata	5	
Dinoflagellates	*Peridinium inconspicuum*	present	*Peridinium limbatum*	5	
	Ceratium hirudinella	present	*Ceratium hirudinella*	present	
			Gymnodinium	present	
			Note: diatom dominated		

	DATE/DEPTH	% total biomass	DATE/DEPTH		DATE/DEPTH	% cell density
	10/21/97 - 0m		**10/21/97 - 6m**		**9/21/98 - 0m**	
Blue-greens	*Coelosphaerium*	5	absent		**Blue-greens**	
	Oscillatoria	5			**Anabaena**	185+254
					Microcystis	40+106
Diatoms	*Melosira*	5	*Melosira*	10	*Oscillatoria*	21+56
	Stephanodiscus	5	*Stephanodiscus*	10	*Aphanathece*	56+148
	Asterionella	5	*Tabellaria*	20	*Merismopedia*	present
	Fragillaria	50	*Fragillaria*	30		
					Diatoms	
Chlorophyta	*Ankistrodesmus*	10	*Pediastrum*	present	**Fragillaria**	156+138
	Oocystis	present	*Ankistrodesmus*	15	*Melosira*	103+230
			Dictyophaerium	present	*Asterionella*	100+169
					Cyclotella	present
Chrysophyta	*Mallomonas*	present	*Synura*	5	*Synedra*	24+ 62
	Dinobryon sertularia	present			others	26+66
Cryptophytes	*Cryptomonas erosa*	5	*Cryptomonas erosa*	5	**Chlorophyta**	absent
	C. curvata	5	*Rhodomonas minuta*	5		
	Rhodomonas minuta	5			**Chrysophyta**	53+104
Dinoflagellates		absent	absent		**Cryptophytes**	17+29
	Note: diatom dominated		**Note: diatom dominated**		**Pyrrophyta**	present
					Unknown	22
					TOTAL Cells	**805+652**

Table 7. Zooplankton densities from 0-15 m vertically integrated tows at mid-lake station #102 at Pike Lake, St. Louis County, MN. Values of genera are percentages of total density. A "dash" signifies not found in any sub-samples that were counted. Total animal densities reported as mean ± standard deviation (n= # of tows).

DATE	**9/18/96** **Stratified**	**10/22/97** **mixing**	**9/21/98** **stratified**
Cladocerans			
Daphnia	50%	50%	49%
Bosmina	3.3%	1.1%	3.6%
Chydoras	<1%	-	<1%
Holopedium	-	-	<1%
Polyphemus	-	-	1.6%
Copepods			
Calanoids	6.3%	1.5%	5.0%
Cyclopoids	18%	35%	30%
nauplii	1.9%	5.7%	1.0%
Rotifera			
	21%	7.1%	8.2%
Total Density (animals/L)	**9.1 ± 5.1 #/L** **(n=2)**	**11.6 ± 4.2 #/L** **(n=3)**	**4.3 ± 0.3 #/L** **(n=2)**

Table 8. WLSSD data summary for 1974-1977 from the Suburban Lakes Water Quality Report (WLSSD 1979). Summer (S) is May-Oct, Winter (W) is Nov-Apr.

YEAR	1974	1975		1976		1977	
	S	S	W	S	W	S	W
TP (µg/L)	49	29	40	26	--	27	--
OP (µg/L)	--	--	--	--	--	--	--
Chl-a (µg/L)	--	--	--	--	--	--	--
TKN (µg/L)	--	713	897	495	--	770	--
NO3 (µg/L)	--	16	26	11	--	--	--
NH4 (µg/L)	--	18	212	15	--	--	--
pH	--	8.41	7.23	9.25	--	8.9	--
alkalinity (mg/L CaCO3)	--	54	86	56	--	65	--
chloride (mg/L)	--	4.8	3.1	2.5	--	2	--
sulphate (mg/L)	--	6.8	4.1	6	--	4	--

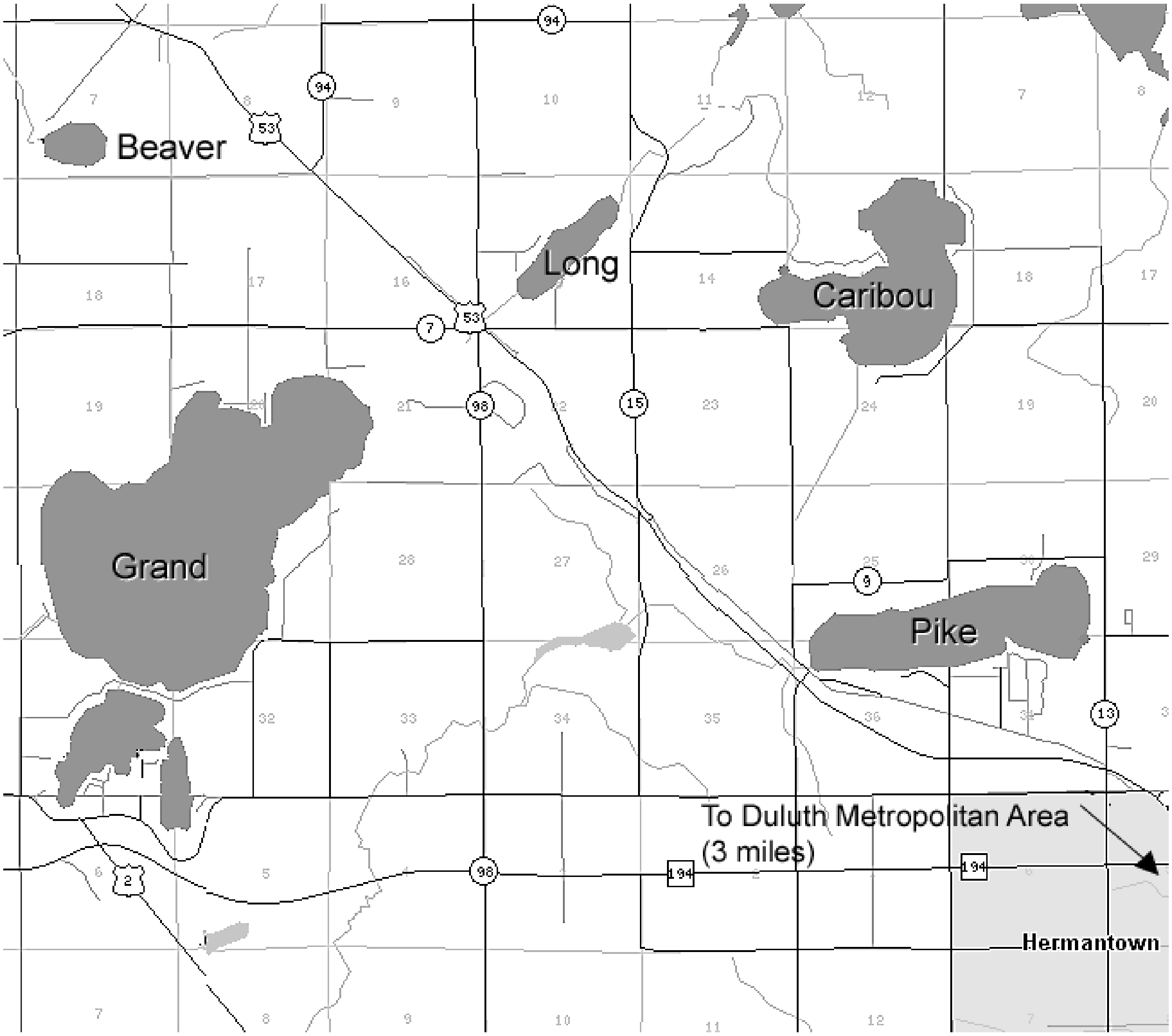


Figure 1. Pike, Caribou and Grand Lakes near Duluth, MN

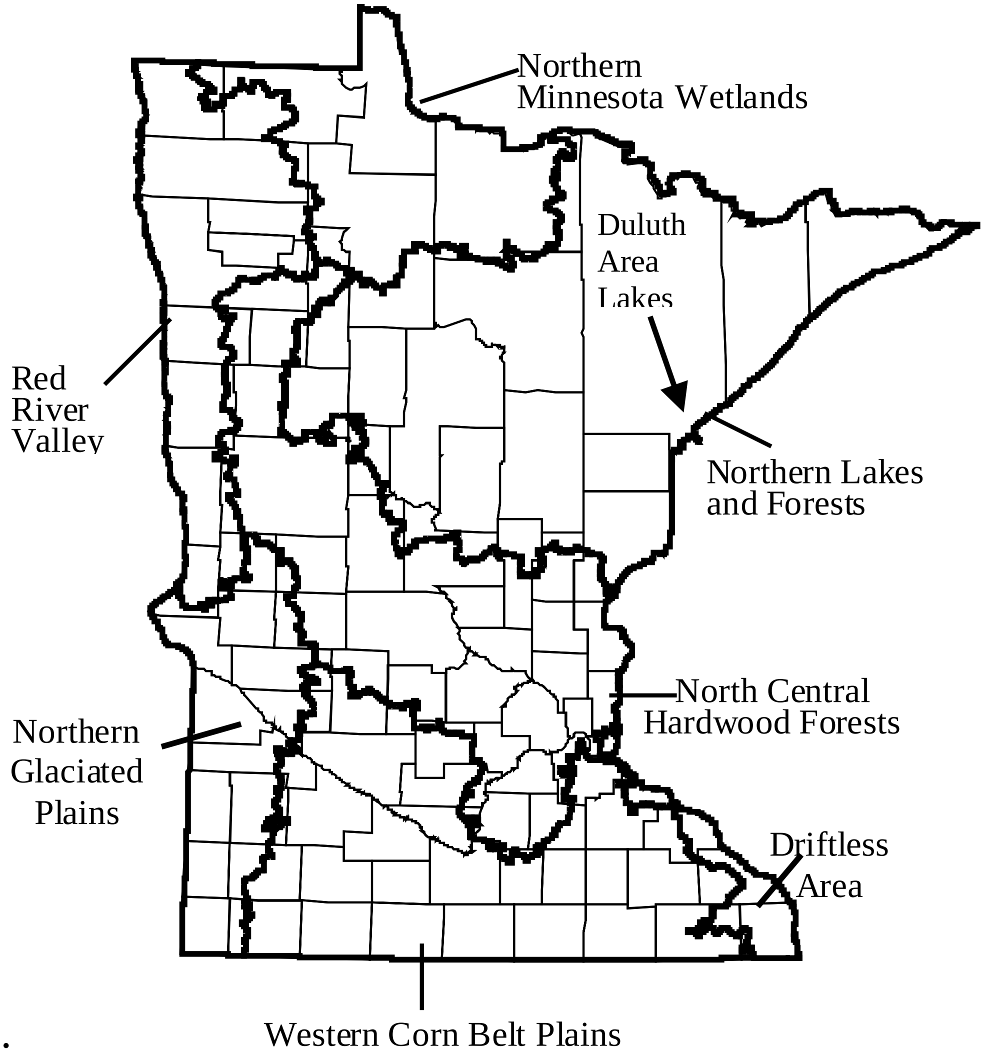


Figure 2. Minnesota's ecoregions

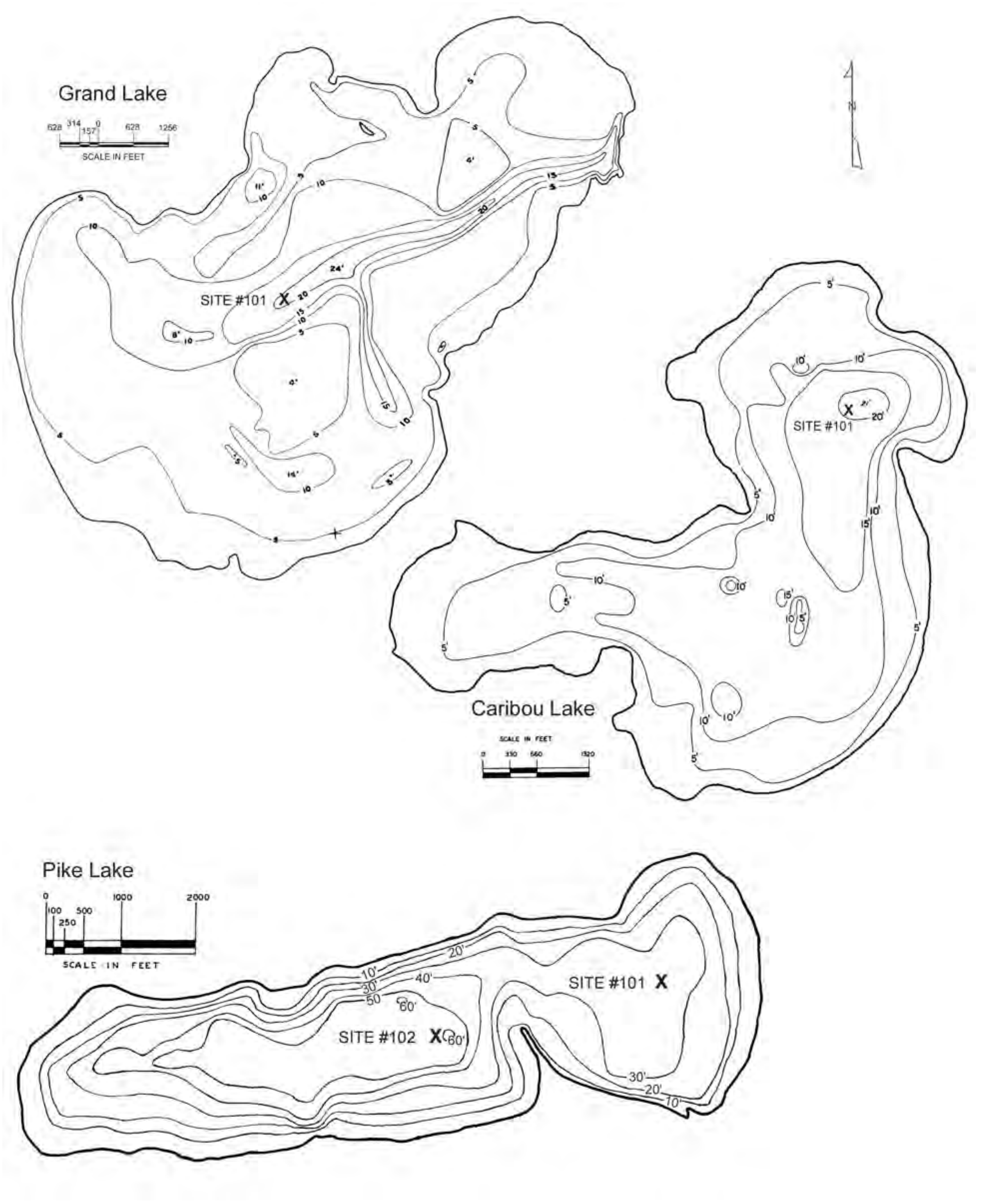


Figure 3. Morphometry maps of Grand, Caribou, and Pike Lake

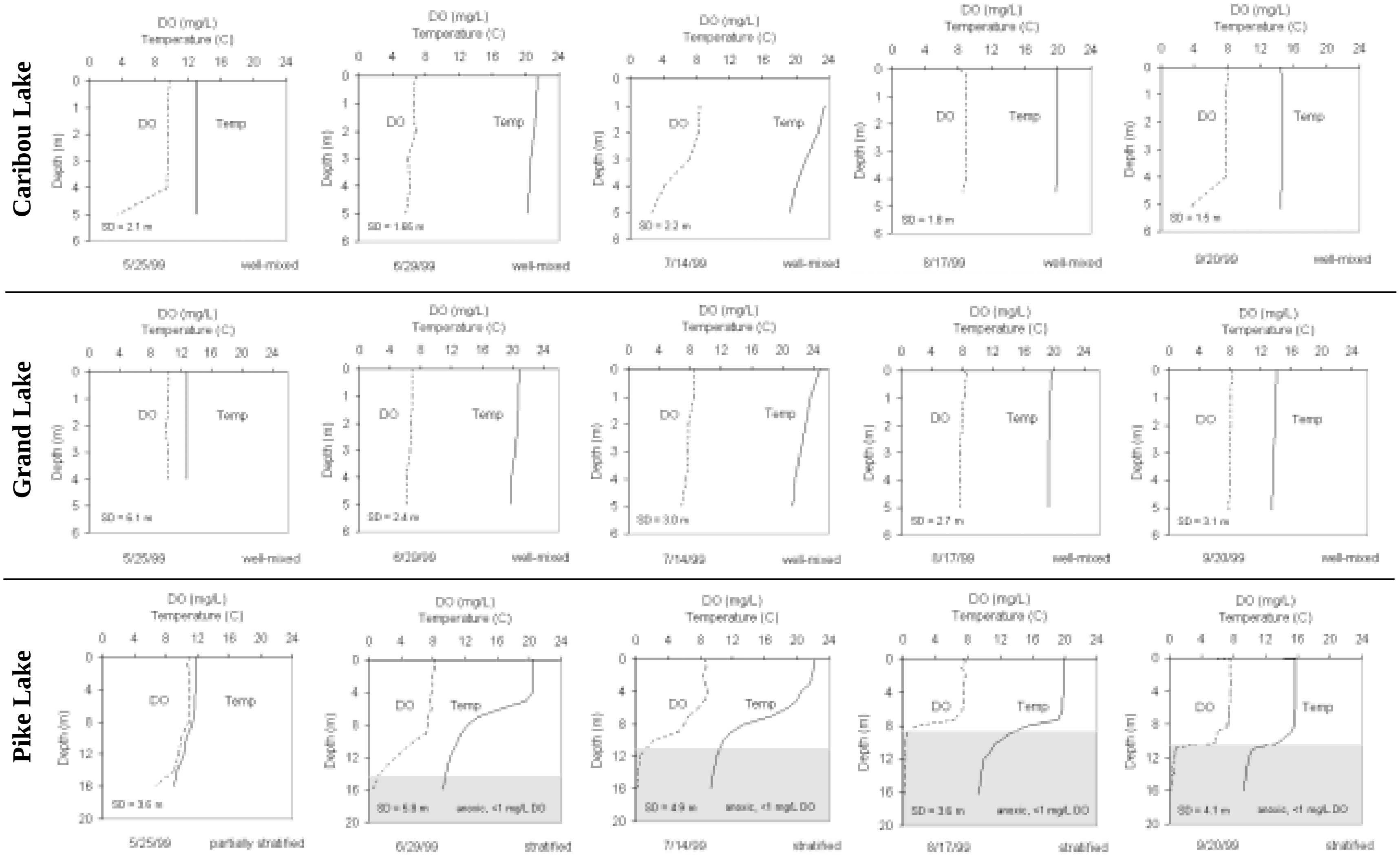


Figure 4. Depth profiles of temperature and dissolved oxygen (DO) for Caribou, Grand, and Pike Lakes from 1999 field surveys

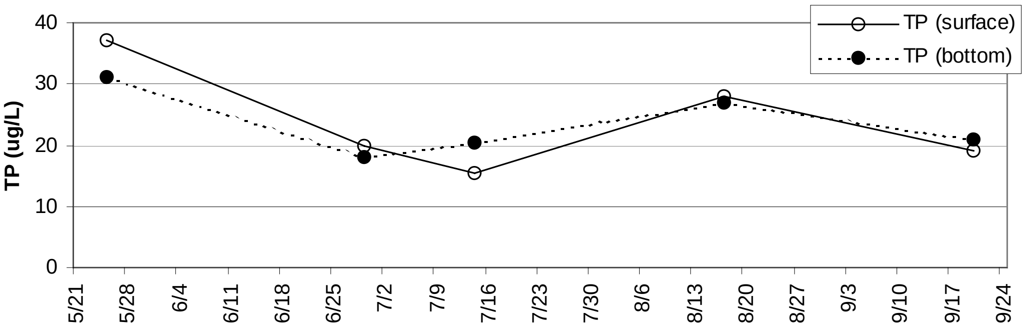


Figure 5. Caribou Lake total phosphorus - 1999

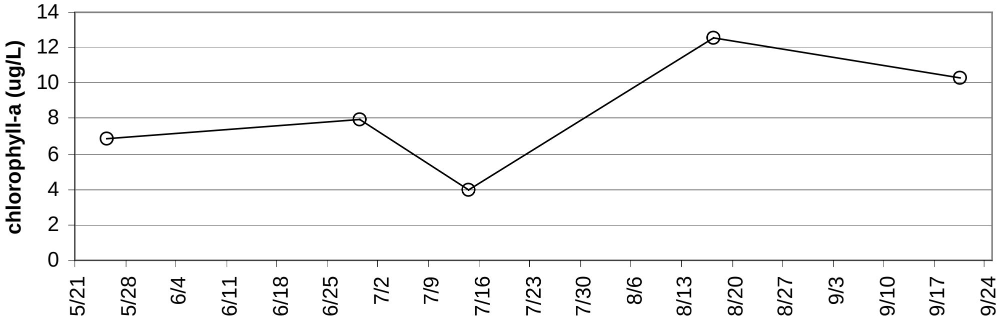


Figure 6. Caribou Lake surface chlorophyll-a - 1999

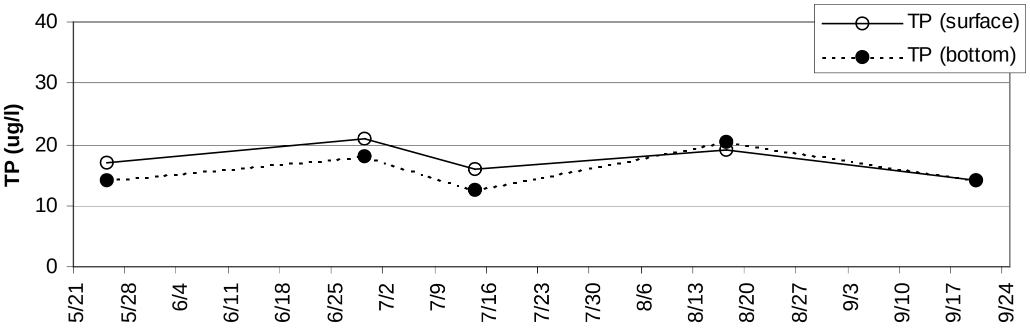


Figure 7. Grand Lake total phosphorus - 1999

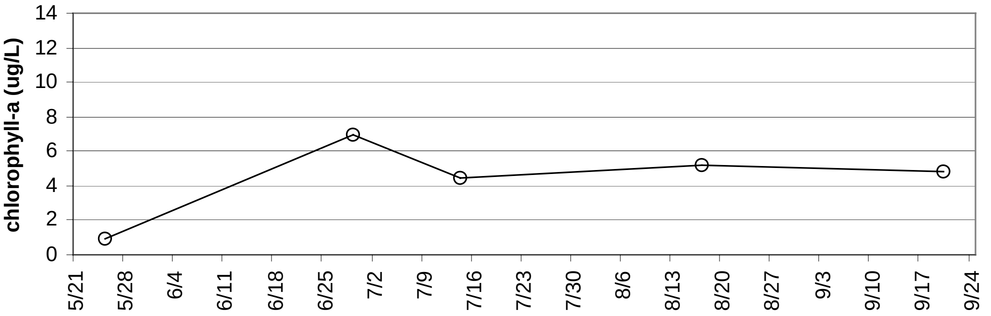


Figure 8. Grand Lake surface chlorophyll-a - 1999

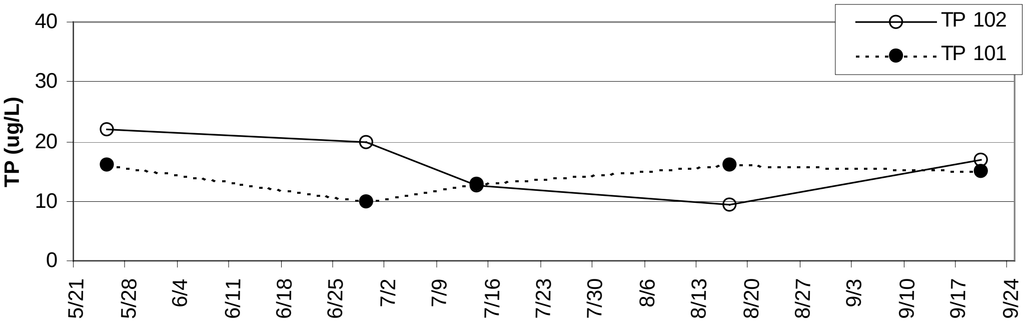


Figure 9. Pike Lake surface total phosphorus

Figure 10. Pike Lake 1999 bottom water TP (16 - 17 m depth) and DO (mean of 12 - 16 m depth data) at midlake station #102

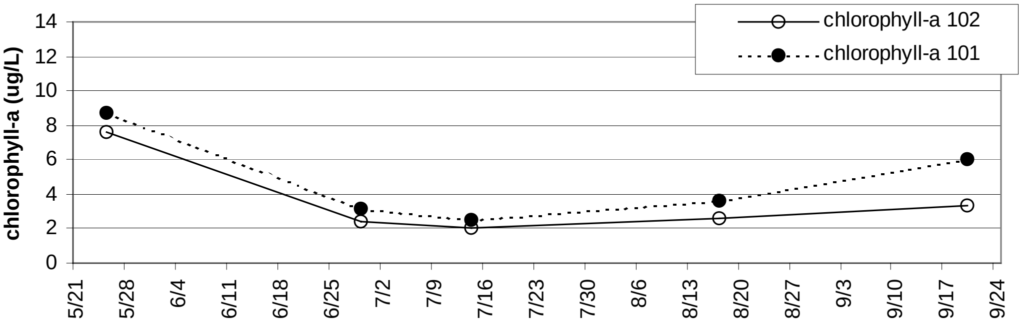


Figure 11. Pike Lake surface chlorophyll-a - 1999

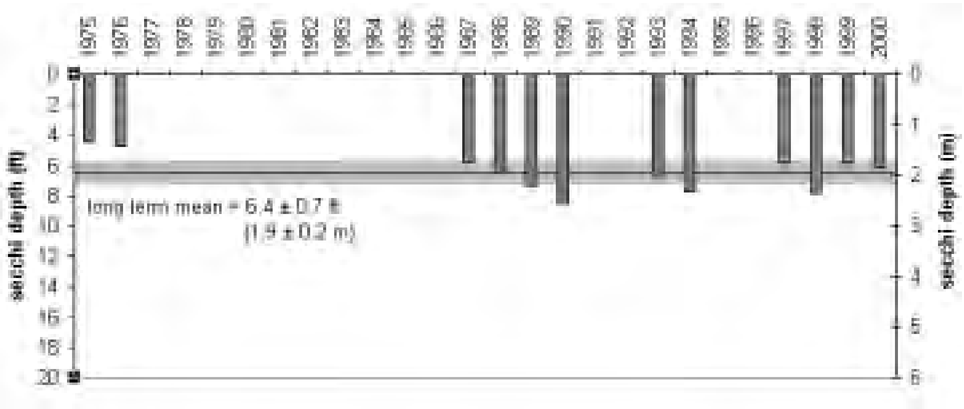


Figure 12. Caribou Lake historical secchi disc data (summer mean values). Error bars indicate 95% confidence interval

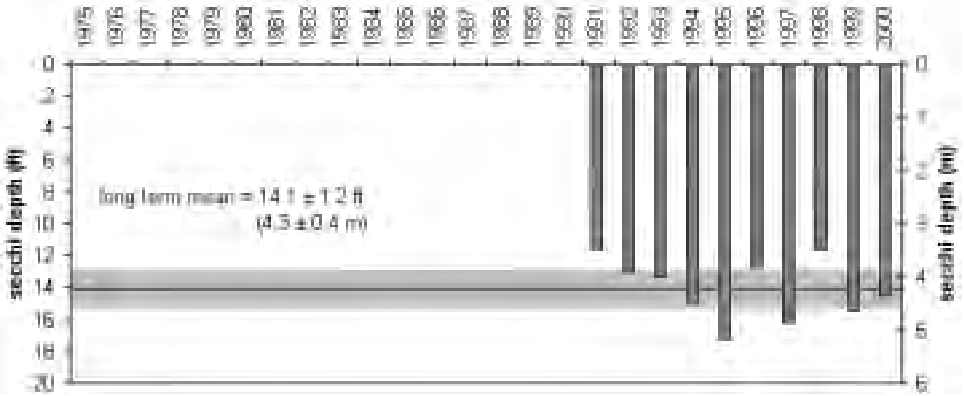


Figure 13. Pike Lake historical secchi disk data (summer mean values). Error bars indicate 95% confidence interval

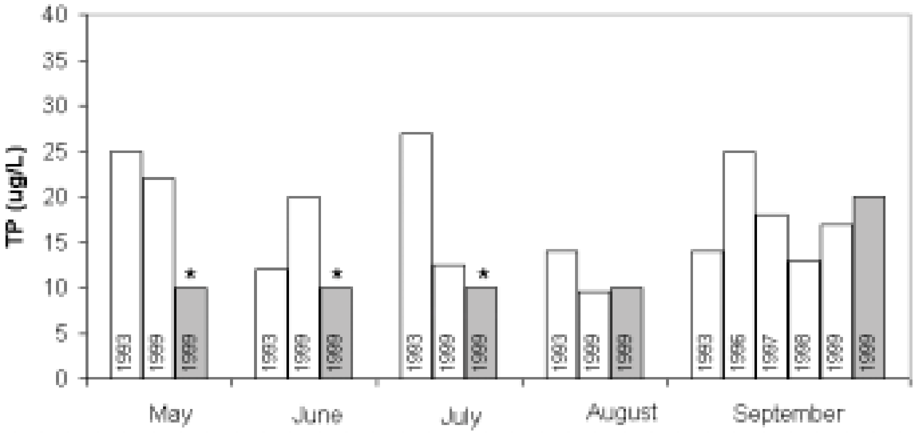


Figure 14. Pike Lake historical summer surface water TP. Shaded 1999 values from SWCD study; 1993 from MPCA study (Bauman 1994); 1996-1998 from NRRI and MPCA studies (this report); * denotes values < 10 ug TP/L (SWDC's level of detection)

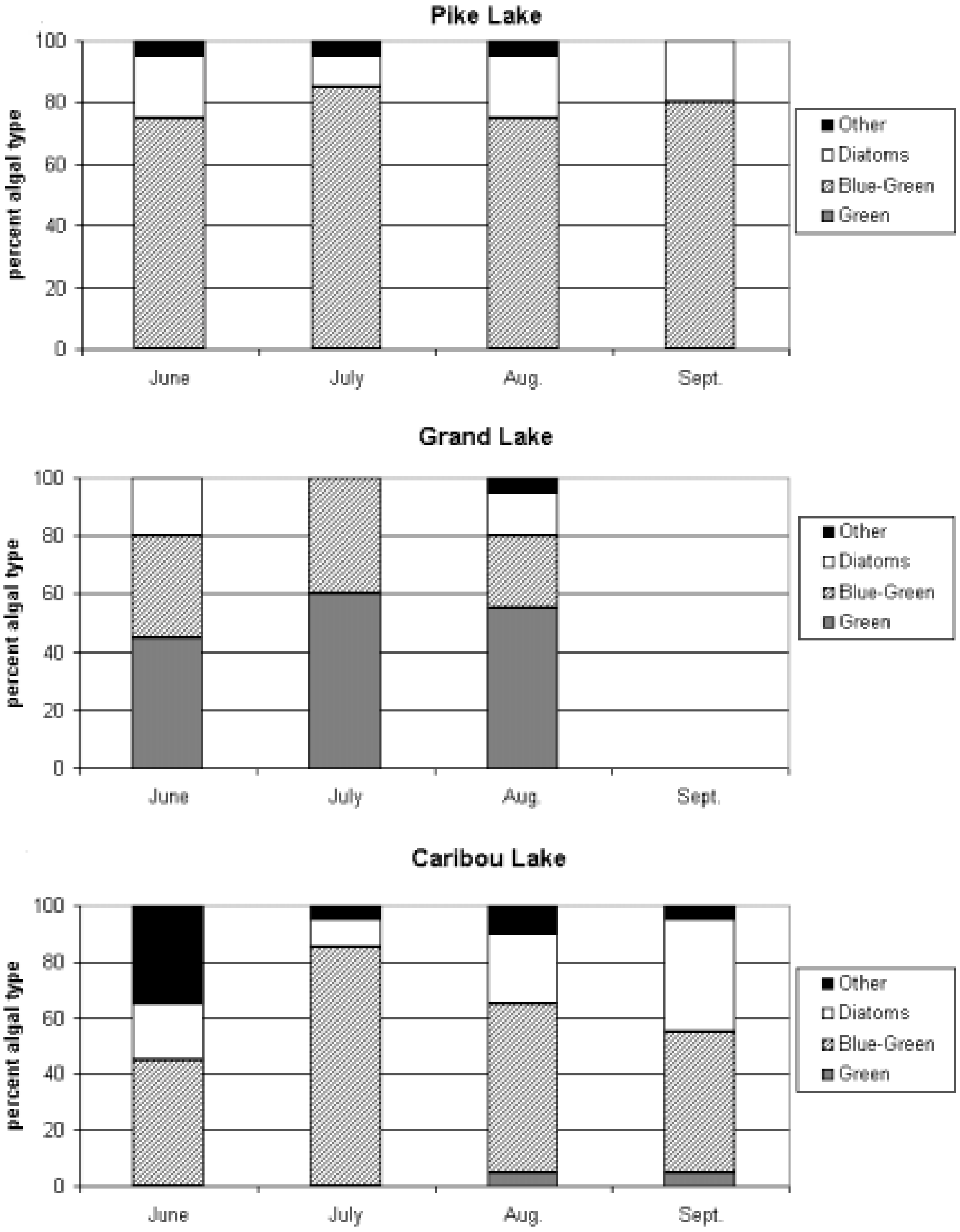
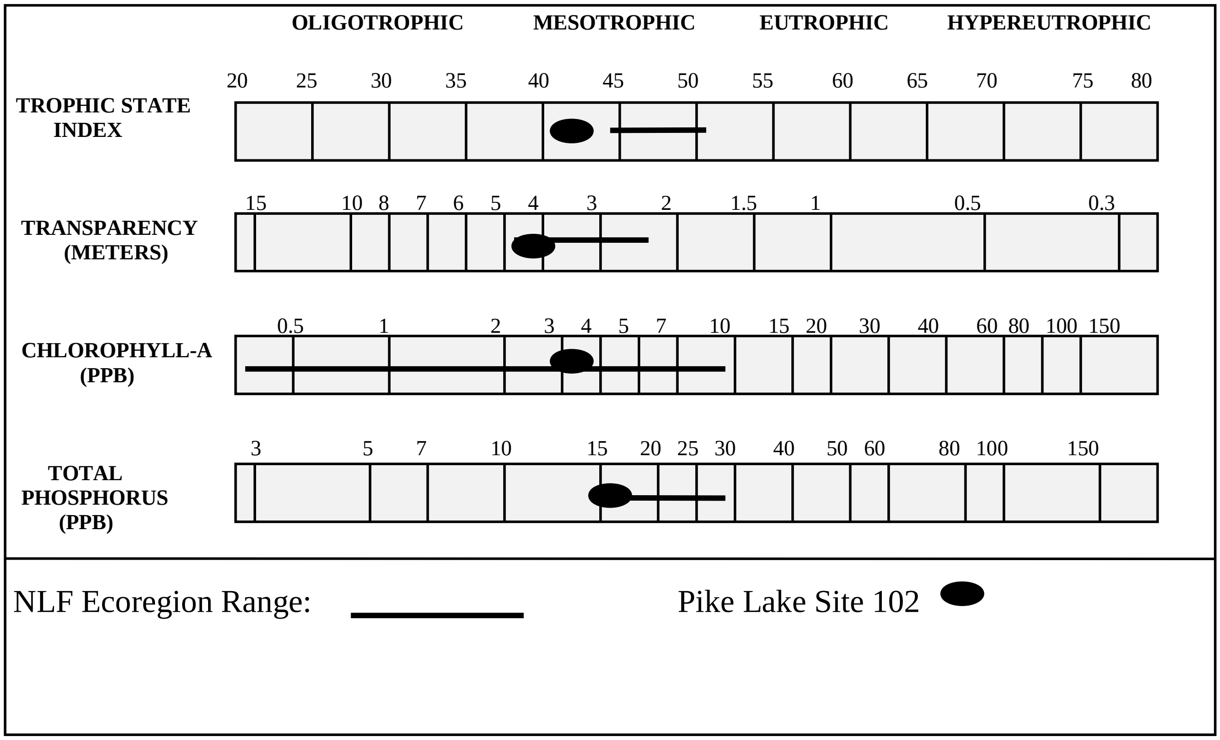


Figure 15. Pike Lake, Grand Lake and Caribou Lake Phytoplankton -1999

Figure 16. Carlson's Trophic State Index for Pike Lake in 1999
R.E. Carlson

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.

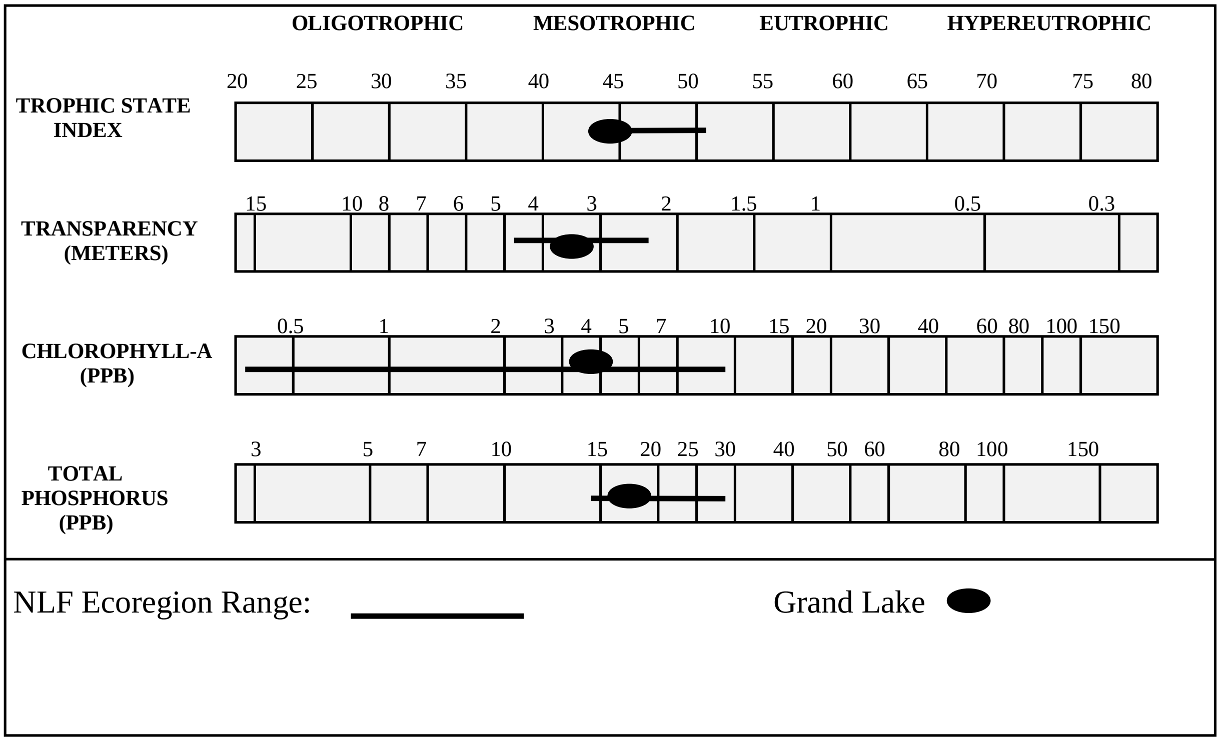


After Moore, l. and K. Thornton, [Ed.]1988. Lake and Reservoir Restoration Guidance Manual. USEPA>EPA 440/5-88-002.

Figure 17. Carlson's Trophic State Index for Grand Lake in 1999

R.E. Carlson

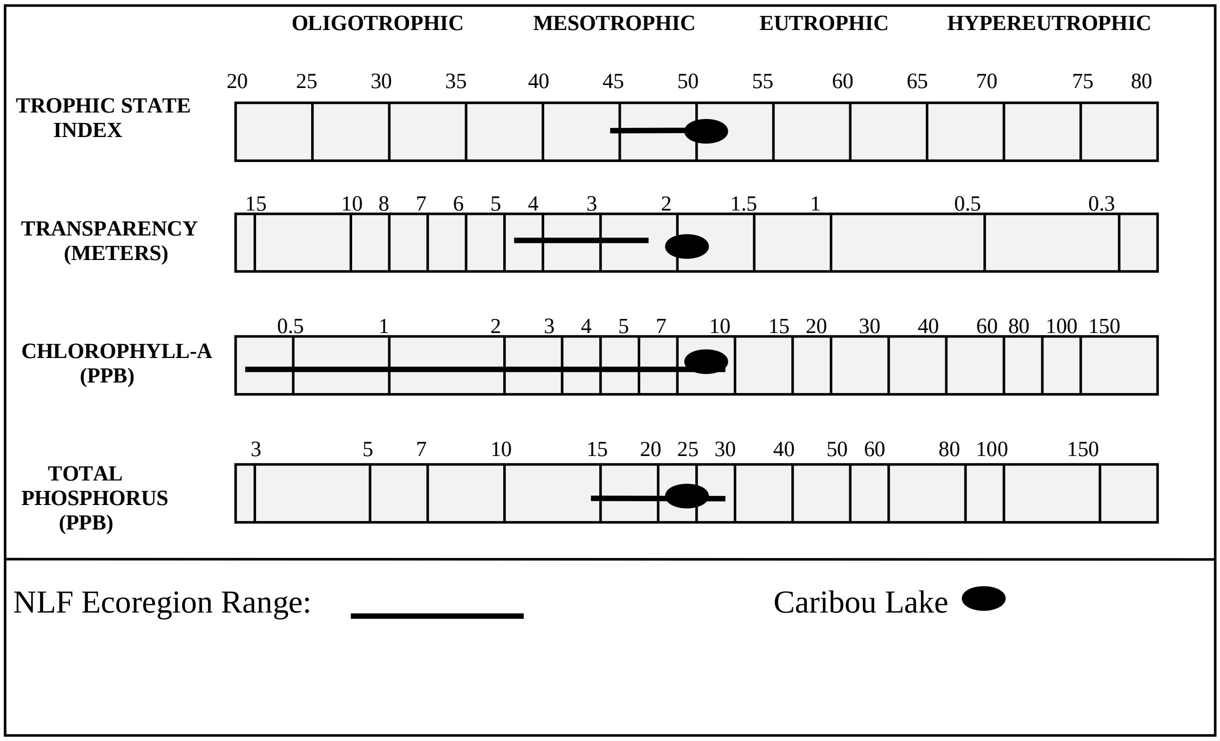
TSI < 30	Classical Oligotrophy: Clear water, oxygen throughout the year in the hypolimnion, salmonid fisheries in deep lakes.
TSI 30 - 40	Deeper lakes still exhibit classical oligotrophy, but some shallower lakes will become anoxic in the hypolimnion during the summer.
TSI 40 - 50	Water moderately clear, 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 18. Carlson’s Trophic State Index for Caribou Lake in 1999
R.E. Carlson

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.



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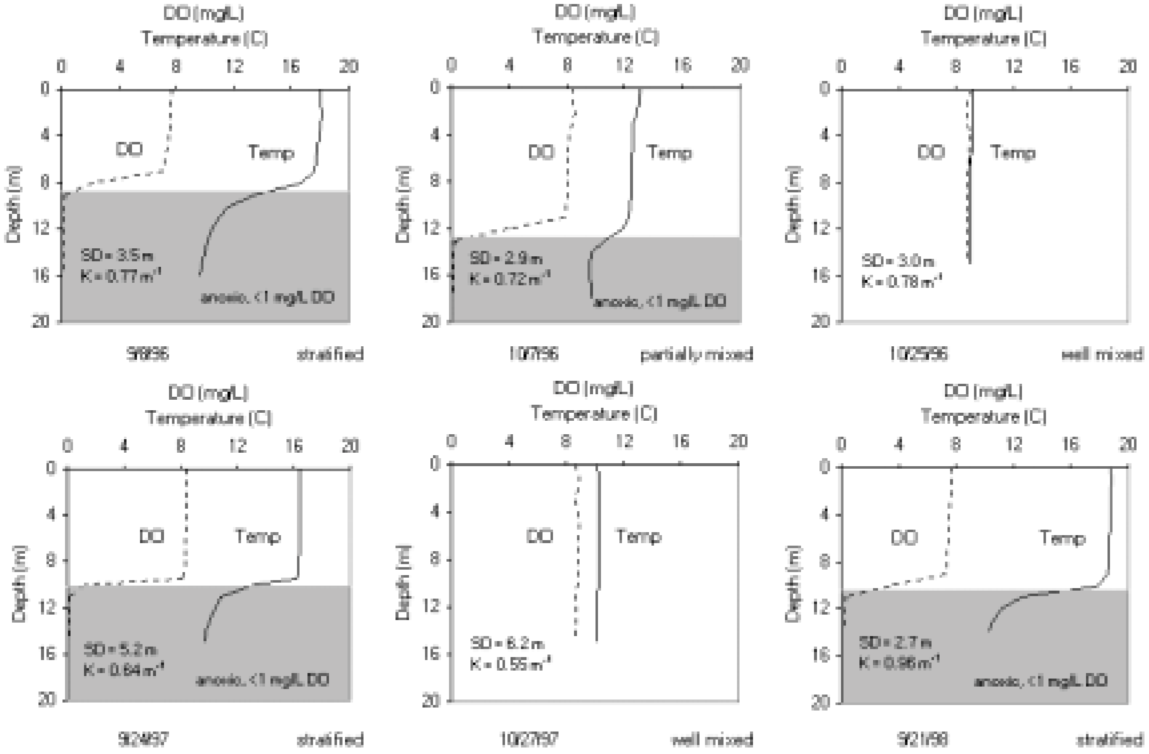


Figure 19. Period of fall mixing, 1996-1998, for temperature and dissolved oxygen, mid-lake site #102, Pike Lake, St. Louis County, MN.

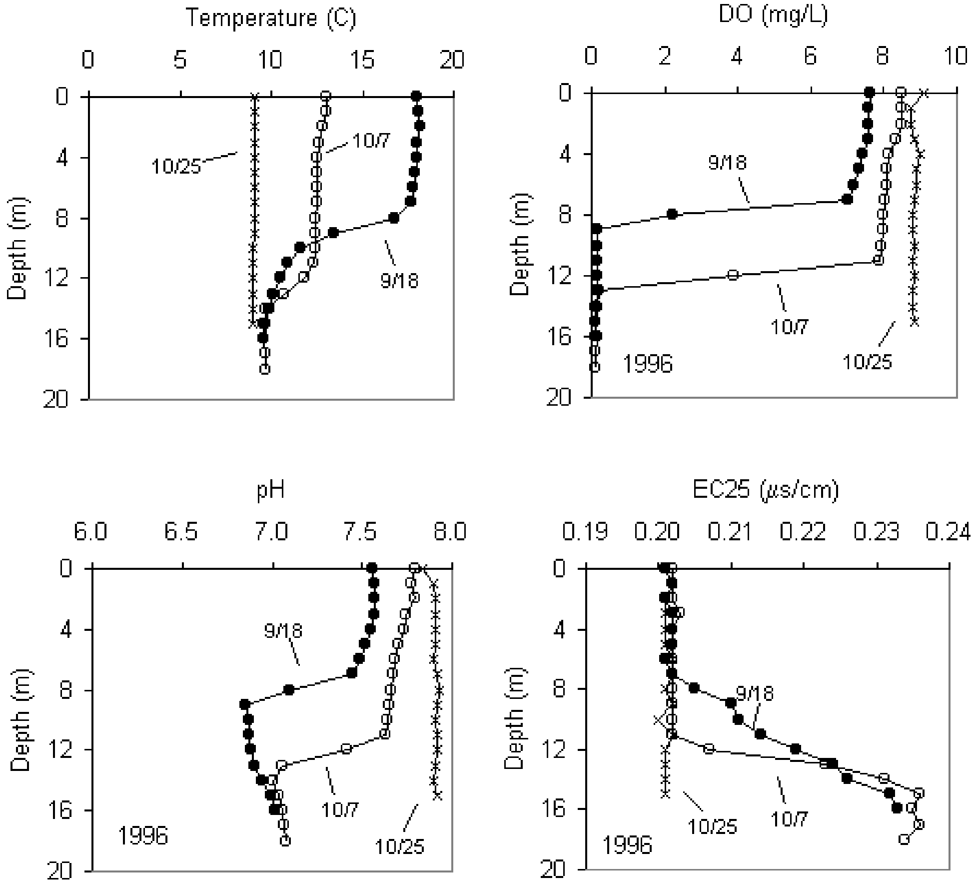


Figure 20. Plots of temperature (°C), DO, pH and EC25 (micros/cm) during the process of fall mixing and thermal destratification in 1996 at mid-lake site #102, Pike Lake, St. Louis County, MN.

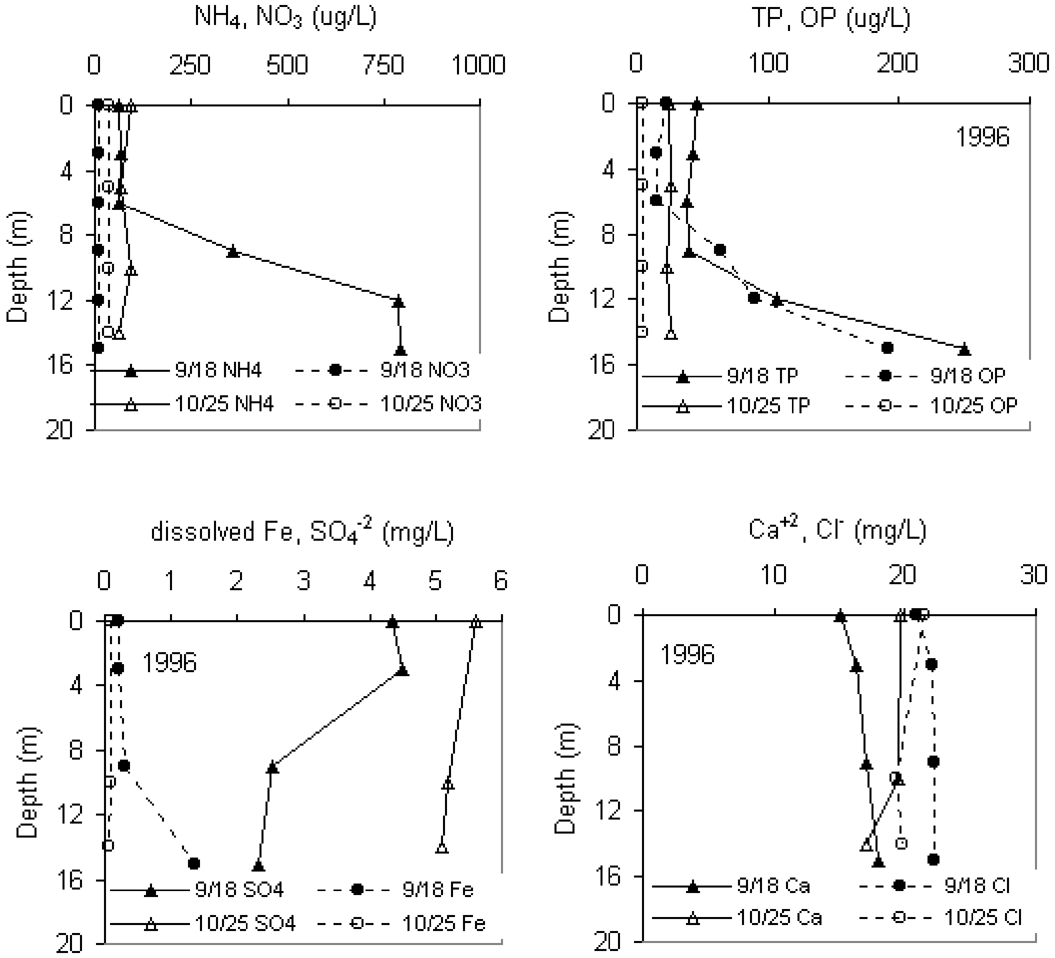


Figure 21. Plots for mid-lake site #102 for Pike Lake, MN in 1996 depicting stratified (9/18/96) versus non-stratified (10/25/96) condition effects of inorganic nitrogen (NO_3^- and NH_4^+), phosphorus (ortho-P and total-P), redox-controlled dissolved iron (Fe) and sulfate (SO_4^{-2}) and non-redox controlled calcium (Ca^{+2}) and Chloride (Cl^{-1}) concentrations.

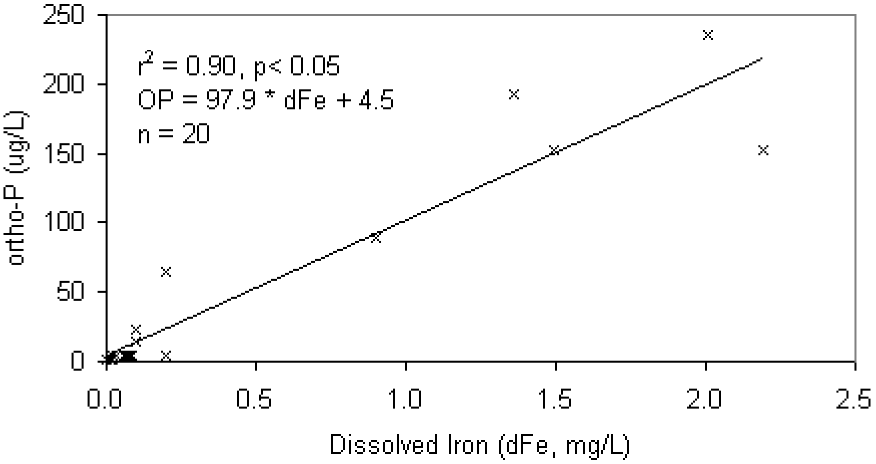
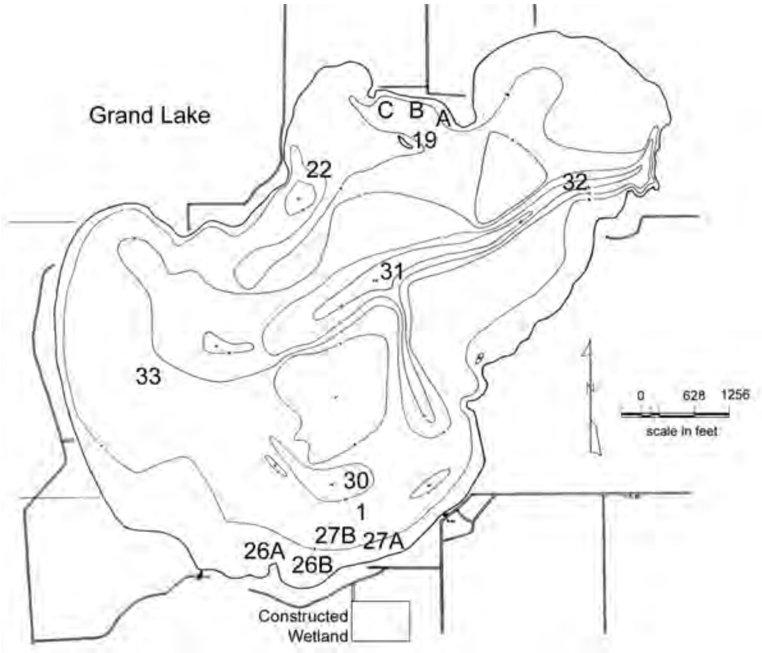


Figure 22. Relationship between dissolved iron (dFe) and orthophosphate for all data pairs at the mid-lake site #102 at Pike Lake, fall 1996-1998.



Parameter/Site	Site/Location							
	19			26		27		33
	A	B	C	A	B	A	B	
fecal coliform (cfu/100ml)	190	200	70	<10	<10	<10	10	30

Parameter/Site	Site/Location						
	1	19 offshore	22	30	31	32	33
chl-A (µg/L)	4.6	5.6	6.7	4.1	8.3	7.7	6.2
OP (µg/L)	2	3	2	2	2	3	3
TP (µg/L)	16	19	30	19	18	21	15
NH4-N (µg/L)	28	19	11	20	22	14	19
NO3-N (µg/L)	4	4	9	5	3	3	4
TN (µg/L)	537	560	573	569	529	600	530

Figure 23. Site/location of sampling points on Grand Lake, numbered after Suburban Lakes Water Quality Report (WLSSD, 1979) and tabulation of water quality data from NRRI survey on July 7, 1997. Lake image from MN DNR.