LAKE ASSESSMENT PROGRAM

SISEEBAKWET LAKE

LAKE ASSESSMENT REPORT
DNR Department of Waters Lake # 31-0554
Itasca County, Minnesota

LAKE CONDITIONS IN 1999
AND HISTORICAL TRENDS IN
LAKE CHARACTERISTICS

WITH AN EMPHASIS ON THE IMPACTS OF
GROUND WATER AND SURFACE WATER INTERACTIONS
ON A MARL LAKE

by
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Foreword

This report and the work upon which it is based goes beyond the traditional scope of a Lake Assessment Project led by the Minnesota Pollution Control Agency. One of the primary reasons for expanding beyond a typical Lake Assessment Project was the need expressed by the Itasca Soil and Water Conservation District to better understand the processes at work in many of the atypical lakes in the Itasca County region. Many of these atypical lakes exhibit characteristics that are similar to those of Siseebakwet Lake. A characteristic shared among these lakes may be that portions of their source waters travel through calcium-rich sediments. These calcium-rich source waters or calcium-rich lake bed materials could have significant impacts on lake water transparency and user perceptions of lake water quality.

In expanding the scope of study, it was hoped that a better understanding of Siseebakwet Lake and the dynamics that control its transparency and overall appearance may lead to an improved general understanding of the many similar lakes in the region.

Lakes that are often over-saturated with respect to calcium carbonate and have lake-bottom sediments containing a large percentage of calcium carbonate are called marl lakes. Indeed, marl lakes could have reduced transparency at times due to the presence of calcium carbonate precipitate (particulates) in the water column. However, the deep blue-green or aquamarine color that is often imparted to marl lakes because of these particulates can be and often is perceived as a positive and beautifying characteristic of the lake. It need not be perceived as a negative characteristic.

In fact, if lake acidification through acid rain ever became a regional concern in the future, lakes rich in calcium carbonate, such as Siseebakwet Lake, would have superior protection from deleterious acidification effects due to the strong (anti-acid) chemical buffering capability of calcium carbonate. Moreover, since phosphorus is known to co-precipitate out of the lake water solution when calcium carbonate precipitates, marl lakes have a superior potential to naturally reduce the concentration of phosphorus dissolved in lake water. Since phosphorus is typically the key (limiting) nutrient for algae growth in Minnesota lakes, co-precipitation of phosphorus can reduce unwanted algae blooms that degrade the appearance and desirability of a lake.

It is hoped that this report will help in identifying and understanding other lakes similar to Siseebakwet Lake and illustrate that their reduced transparency, if due solely to calcium carbonate precipitation, does not need to be perceived as an environmental concern but can indeed be seen as a sign of a lake with special environmental advantages.
# Siseebakwet lake
## Lake Assessment Report

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In the mid to late 1990s, concerns began to grow that the clarity of water in Siseebakwet Lake might be getting progressively worse. The concerns intensified when, in 1997, the summer mean of Secchi disk transparency measurements was only 6.9 ft. compared to a (recent) historical average summer mean of about 12 ft. In contrast to 1997 conditions, summer mean Secchi disk transparencies as high as 16.1 ft. had been reported as recently as 1989 and 1990. Field work and study to better understand Siseebakwet Lake and the surrounding area were stepped up in 1998 and 1999 to address the concerns.

A review and comparison of pre-existing data sets for lake transparency and other lake monitoring parameters revealed that Siseebakwet Lake did not appear to be a typical Minnesota lake. Based on the pre-existing data, a preliminary review of the lake's hydrogeologic setting and the lake's apparently intermittent color changes, the project team decided to put special emphasis on evaluating how ground-water chemistry affected Siseebakwet Lake.

Does ground water have much influence on Siseebakwet Lake? Is Siseebakwet Lake a marl lake? If so, why is it a marl lake? Can ground water or marl-lake characteristics affect lake transparency? Might impacts on lake transparency caused by ground water or marl-lake characteristics vary over time? These are some of the questions that needed to be answered. The remainder of this report is an attempt to satisfy the normal requirements of an MPCA Lake Assessment Program (LAP) report and to answer the questions raised above.

Siseebakwet Lake undoubtedly has some characteristics that are unusual for Minnesota lakes. But it continues to be an attractive lake considered by many as an especially desirable lake to visit for recreation and for its aesthetic qualities. It is very suitable for and is used for a wide variety of recreational activities including, swimming, boating and fishing.

Overview

Based on 1999 results for traditional lake-monitoring parameters such as total phosphorus, chlorophyll \( a \) and Secchi disk transparency, Siseebakwet Lake is in relatively good condition compared to other lakes in its ecoregion. In fact, the summer means for concentrations of total phosphorus and chlorophyll \( a \), measured at the primary lake sampling location, were extremely good. However, the lake is somewhat unusual because such a high percentage of its source water comes from ground water and the lake water appears to have unusually complex chemistry and biochemistry.

The use of traditional lake monitoring parameters and models may be inadequate to fully describe and evaluate the condition of Siseebakwet Lake. In general, changes in transparency observed at Siseebakwet Lake do not correspond well to variations in concentrations of total phosphorus and chlorophyll \( a \); these parameters generally do correspond well in most Minnesota lakes. More work is needed to clearly understand the changes in transparency observed at Siseebakwet Lake.

Notably, Siseebakwet Lake receives an estimated average of 43% of its water from the ground-water system compared to an estimated 22% of its water from streams. Some zones of the subsurface geologic materials around and beneath the lake are very rich in calcium. Ground water traveling through those calcium-rich zones can become highly enriched in calcium by the time it reaches the lake. At times, the calcium-rich ground water delivers more
calcium to the lake than the lake water can hold. A preliminary conclusion of this report is that when the lake water becomes too saturated with calcium carbonate, it precipitates out of the lake water and worsens lake transparency. Most of the calcium carbonate precipitate is probably comprised of very small particulates but these particulates can still affect lake transparency.

A lot of valuable information was gathered while completing two related projects that focused on Siseebakwet Lake between 1998-1999; this report features the results of those projects. Unfortunately, uncertainties remain about the significance of and reasons for an apparent trend of worsening lake transparency. But this is not surprising. Achieving an understanding of the processes that control the transparency of similarly complex lakes has proven very difficult. For example, in the case of a lake in New York state, relatively clear answers were obtained only after international teams of research specialists completed a long series of highly detailed investigations using highly advanced technology over many years.

Based on what was learned during these investigations and related research, recommendations for further study, lake monitoring and lake protection practices are provided later in this report.

Sources of Lake Water

As with most lakes, Siseebakwet Lake is strongly influenced by its (surface water) watershed. However, since Siseebakwet Lake receives only an estimated 22% of its water directly from its two surface-water inlets, other parts of the hydrologic cycle are also very important to Siseebakwet Lake.

Ground water is the largest source of water entering Siseebakwet Lake. An estimated 43% of the lake's water comes directly from ground water entering through the lake bottom. Ground water that exits the subsurface as springs near the lakeshore and enters the lake through short overland flow paths is very noticeable to some lakeshore residents. However, these springs are believed to contribute only a small percentage of the ground-water recharge to the lake. Some of the ground-water recharge to the lake originates as precipitation falling within the (surface water) watershed. However, since surface topography does not necessarily form a barrier to ground-water flow, considerable amounts of ground-water recharge to the lake may originate from outside of the lake's (surface water) watershed.

The other major source of Siseebakwet Lake water input (recharge) is direct precipitation. An estimated 35% of Siseebakwet Lake water originates from direct precipitation on the lake. Since precipitation generally has a very low concentration of dissolved solids, it generally dilutes the lake recharge water originating from other parts of the hydrologic cycle.

Precipitation is essentially the original source of all the lake's water, but during dry spells, ground water may supply much or most of the stream flow. Following large precipitation events and snow-melt events, streams may contribute substantial amounts of recharge to the ground-water system. Upon entering the lake, the chemistry, temperature, turbidity and other characteristics of each source-water type reflect the environment through which the water has traveled on its way to the lake.

In an effort to better understand the timing of the lake's inputs and outputs, a number of additional analyses and calculations were performed. These calculations helped to identify the time frame over which to look for correlation among various factors such as variations in lake transparency compared to climatic variations or watershed development. Since Siseebakwet Lake's watershed is small, a significant percentage of the rainfall that enters the watershed's surface-water system (or an equal amount of displaced surface water) probably reaches Siseebakwet Lake relatively soon after falling, especially during heavy rainfalls. However, some of the surface-water recharge is delayed by the wetlands and other lakes in the watershed. Based on analysis of tritium content in ground-water samples (refer to Table 3 on page 39), it is estimated that, on average, it takes ground water about 9 -
11 years to infiltrate into the subsurface and travel to Siseebakwet Lake. The hydraulic residence time for Siseebakwet Lake, the average time that a drop of water spends in the lake before exiting by a stream, ground water or the atmosphere, was calculated to be 6.5 years.

**Importance of Siseebakwet Lake's Physical Setting**

Since ground water, direct precipitation and surface water all make very substantial contributions of source water to Siseebakwet Lake, the physical, chemical and biological nature of each of these sources is important to the quality and overall status of the lake. Because the makeup of each source water type is different, temporal variations in contribution percentages among them can impact lake chemistry, lake transparency and other lake characteristics. A complete understanding of changes in the chemistry, biology and transparency of Siseebakwet Lake requires an understanding of temporal and spatial variations in the quality and quantity of source waters entering the lake in addition to the nature of the lake itself.

Climatic variations can cause changes in source water temperatures, chemical equilibria and changes in the relative contributions of different parts of the hydrologic cycle to lake recharge. Variations in the quantities and hydrogeochemistry of ground recharging from various parts of the lake depend on both the hydrogeologic setting and climatic variation. Another less-obvious but potentially important factor affecting the chemical equilibrium of the lake is the composition of the lake bed. The lake bed is a huge storehouse of calcium carbonate and other chemicals that reflect the lake’s long history of calcium carbonate precipitation and deposition.

**SURFACE WATER WATERSHED.** Lake assessment and lake management efforts normally focus on the surface water watershed and the lake water itself. These areas are both highly visible and typically the best places to focus lake monitoring and lake protection efforts. Considerable monitoring, management and assessment efforts have been expended toward protecting and understanding Siseebakwet Lake. A large percentage of these efforts have focused on assessment of the watershed and the lake water. Most of the development in the watershed is comprised of domestic dwellings near the lakeshore and the Ruttger's Sugar Lake Lodge which includes a golf course. Although lake water contamination from septic systems or fertilizers could be a concern, the limited amount of available lake water-quality data do not indicate any widespread persistent problem with elevated nutrient concentrations. Details about recent and historical information for these subjects can be found by referring to the table of contents in this report.

**HYDROGEOLOGIC SETTING.** Ground water is the largest source of the lake's water. The shallow, upgradient ground water, which could provide much of the ground water recharge to the lake, has significantly higher concentrations of dissolved solids than precipitation or stream water. Clearly, the chemistry and volume of the ground water entering Siseebakwet Lake are key factors in determining the overall status of the lake.

The soils and geologic materials that make up the areas within, beneath and surrounding Siseebakwet Lake's watershed are very important in determining the lake water characteristics. The geologic structure, sedimentary stratigraphy, soil structure and grain-size distribution of sediments in this area are important factors in determining the ground-water source areas and flow pathways and the velocity at which ground water moves toward the lake. The chemistry of the ground water entering Siseebakwet Lake is a reflection of the chemistry of the soils and geologic materials through which the ground water passes.

**HYDROGEOCHEMISTRY AND CLIMATIC VARIATION.** Variations in temperature and rainfall patterns, or changes in wind speed and wind direction trends or even the occurrence of an unusually severe storm can affect the equilibrium of a lake. This is especially true for marl lakes that might already be saturated with calcium carbonate and need little to push the chemical or biochemical equilibrium over a threshold to initiate widespread precipitation of calcium carbonate. Worsening of lake transparency is one of the impacts that can result from precipitation of calcium carbonate.
The preceding sections outlined why the relative contributions of different categories of source waters and the physical setting of Siseebakwet Lake can be very important to the overall status of the lake. Climatic variations can affect the percentage of lake water that comes from ground water versus precipitation or stream water. Water-budget modeling results indicated that although ground water might contribute an estimated 43% of lake-water recharge in an average year, the percentage might dip to only 30 to 35% in a wet year or rise to 60 to 65% during a dry year. Refer to the section on Water Budget Modeling beginning on page 159 for more details. Climatic variations could also change the percentage of lake water that comes from separate ground-water zones with distinctly different hydrogeochemistry. This could result in variations in the overall chemistry of ground water recharge to the lake.

Literature and field research on the hydrostratigraphy and associated geochemistry in the Siseebakwet Lake area during this study support the theory that variations in the relative amounts contributed from distinct ground-water zones could substantially affect calcium carbonate concentrations in the lake. Indeed, depending on which subsurface water-yielding zones conducted the bulk of the ground water to the lake, the expected calcium carbonate content of the ground water entering the lake could be expected to vary substantially. This variation was apparently documented during the course of this study. Large temporal and spatial variations in calcium (Ca\(^{2+}\)) concentrations were found in ground water just as it was entering through the lake bottom. On October 28, 1998, ground water entering the lake bottom at site 411 contained 71 ppm Ca\(^{2+}\) while 116 ppm Ca\(^{2+}\) was found in the ground water entering the lake at site 415. But one year later in October 1999, the concentration of Ca\(^{2+}\) entering through the lake bottom at site 415 was only 71 ppm. Based on samples collected from a domestic well located just upgradient (in terms of ground water flow) from the lake, other parts of the lake could be receiving ground water with Ca\(^{2+}\) concentrations of 58 ppm or less depending on current ground water flow patterns.

An explanation implicating a relationship between climatic variations and the equilibrium of the lake’s chemistry becomes even more attractive when it is considered that any climatic variation affecting ground water recharge to the lake might also affect the amounts of rainfall, snowmelt and stream input to the lake. Consideration of the potential variations in input rates for all these water sources combined with their individual differences and variations in chemistry illuminates a very plausible explanation for substantial changes in the bulk chemistry of water entering the lake. In this study, however, the limited historical Secchi disk data were not sufficient to elucidate a relationship between Secchi disk transparency and climatic variation. The relationship, if significant, could be complex and could possibly be obscured by other contributing factors. These topics, along with the supporting information, are discussed in more detail in several sections of this report including the section entitled Hydrogeochemistry beginning on page 37 and the section entitled 'What's Causing the Trend in Transparency?' beginning on page 114.

What Controls the Transparency of Siseebakwet Lake?

The clarity of lake water is traditionally measured as Secchi disk transparency in studies of Minnesota lakes. Typically, in Minnesota, lake-water transparency is controlled primarily by the amount of phosphorus available to phytoplankton - small algae floating in the lake water. Transparency increases or decreases as phytoplankton growth is encouraged or inhibited by the availability of the essential nutrient phosphorus. Of course, sufficient sunlight and favorable water temperatures are also important to phytoplankton growth. Coloring of water due to staining by organic acids from the watershed and 'clouding' of the water by other (non-living) particulates or sediments can also contribute to reduction in lake water transparency. Organic acid staining, when significant, can range from yellow to red and is most typically a shade of brown. Organic acid staining is most likely to be significant in watersheds containing substantial amounts wetlands such as bogs. Lakes with significant amounts of suspended sediments most commonly have surface water inlets that contribute large quantities of sediments fine enough to remain suspended throughout the lake. These lakes may exhibit shades of yellow to brown, brownish red or even gray depending on the type and concentration of suspended materials. Siseebakwet lake, however, is not a typical Minnesota lake; its transparency does not appear to be controlled by any of the "typical" factors described above.
PRECIPITATION OF CALCIUM CARBONATE. Based on this investigation and review of studies of similar lakes, it appears that precipitation of calcium carbonate in lake water is most likely the key factor responsible for most of the variation in the transparency of Siseebakwet Lake. This view explains the lack of correlation between transparency and standard lake monitoring parameters and is consistent with the hydrogeochemical setting and the chemistry of the lake and lake bottom sediments. The large amounts of calcium carbonate encrustation observed on plants and rocks in shallow areas of the lake and the calcium carbonate "ooze" that accumulated monthly in a sediment trap suspended below the lake surface far from shore are direct evidence of ongoing precipitation of calcium carbonate in Siseebakwet Lake.

This hypothesis cannot be proven with existing data alone. In fact, some of the field data and laboratory data contradict this hypothesis. However, after thorough review of all available information, it appears that those field data, specifically turbidity and total suspended solids data, were probably misleading. Based on several independent lines of reasoning, explained in subsequent sections of this text, precipitation of calcium carbonate is believed to be the key to changes in Siseebakwet Lake transparency. Nonetheless, this was a very limited study and a natural system such as the one including Siseebakwet Lake and its source water areas has many complex and dynamic physical, chemical and biological processes that are constantly interacting and changing. An example of a transitory impact on lake transparency that cannot be explained by precipitation of calcium carbonate alone is a widespread "algal bloom" such as the one observed on August 24, 1999 (refer to the section on Subjective Measures of Transparency and Related Observations beginning on page 96). Clearly, at this time, it is not possible to rule out other possible explanations for the variations in transparency observed at Siseebakwet Lake.

ROLE OF PHYTOPLANKTON IN PRECIPITATION OF CALCIUM CARBONATE. Based on the results of more-detailed studies of other marl lakes, the role of phytoplankton in initiating and possibly sustaining the precipitation of calcium carbonate could be very important at Siseebakwet Lake. Since the biochemical impact of phytoplankton on calcium carbonate equilibrium happens on a microscopic level and can be very dynamic, the process is difficult to identify, characterize and quantify. A previous marl lake investigation in New York state required very advanced technology and a team of research specialists to determine and document that microscopic blue-green algae were responsible for driving the precipitation of calcium carbonate. Direct, detailed evaluation of the potential significance of similar phenomena at Siseebakwet Lake was beyond the scope of this investigation.

SUMMARY OF LESS-RECOGNIZED FACTORS THAT MIGHT AFFECT TRANSPARENCY. The transparency of Siseebakwet lake does not appear to be controlled by the same factors as most Minnesota lakes. Siseebakwet Lake does not have a significant amount of color from organic acids. There are not significantly large quantities of stream sediments suspended throughout the lake. Although phytoplankton concentration probably has some impact on Siseebakwet Lake transparency, the impact does not appear to be nearly significant enough to explain the observed trends in transparency. The factors determining the variation in transparency appear to be complex and to include the dynamics of the hydrologic cycle, and the special nature of equilibrium chemistry and biochemistry in a marl-lake setting. Precipitation of calcium carbonate particulates (originating from the dissolved state in lake water), an apparently difficult entity to quantify on a real-time basis, may be the key factor in understanding transparency changes. As discussed above, other key elements contributing to changes in the lake include the following:

- the lake's hydrogeologic setting including spatial variations in hydrogeochemistry
- the relative contributions of ground water, precipitation and surface water to the lake
- the large "store house" of calcium carbonate in the lake bed
- Siseebakwet Lake's other marl lake characteristics
- climatic variations

Trends in Lake Water Chemistry, Transparency and Phytoplankton

Evaluation of available data from 1972 to 1999 suggests that there has been some deterioration in lake water transparency at Siseebakwet Lake. Although the apparent change is significant, the pattern of change has neither been steady nor easy to assign to factors commonly responsible for deterioration of lake water transparency.
Neither of the nutrients phosphorus or nitrogen, nor even chlorophyll $a$ appear to have increased significantly over the years on a lake-wide basis. In fact, the values of these parameters along with water color and suspended solids, as measured by standard methodologies in 1999 at the primary sampling location, are all in a range that is considered very good.

According to a Siseebakwet Lake resident and CLMP participant in December 2001, lake transparency since this 1999 study has generally been similar to the 1999 study period. The lake has apparently not returned to the conditions observed in 1997 that piqued concerns about worsening transparency. No post-1999 data have been used in this report. However, discussion and conclusions regarding long-term trends in transparency and other parameters presented in this report would not change significantly by consideration of additional Secchi disk monitoring data from the past two years. Only continued monitoring over many more years will clarify which time-segments of recent Secchi disk monitoring data are insignificant "blips" in the record and which comprise part of a clear and meaningful trend.

This report identifies and attempts to explain numerous factors that may impact lake transparency. It remains to be seen if the changes in transparency can be assigned to a specific factor or factors. Historical information spanning 1000 years, interpreted from analysis of a lake-bottom sediment core, suggests significant changes in the lake’s depositional patterns occurred in sequence with the accelerated development of the watershed through human activity. The record documenting an apparent deterioration of lake-water transparency (1972 to 1999) spans roughly the same time frame as the depositional changes and accelerated development of the watershed.

Even though traditional measures of lake-water quality have been good at the primary sampling site recently, this does not completely rule out the possibility that human activity could have impacted the lake’s environment in a way that has affected transparency. Processes specific to lakes saturated with calcium carbonate, like Siseebakwet Lake, make it more difficult to assess the lake's environmental status and compare it to other lakes using traditional monitoring and analytical tools. For example, intermittent or constant co-precipitation of phosphorus with calcium carbonate could make it difficult to assess the actual input of phosphorus to the lake. On the other hand, natural processes such as climatic variation and potentially subtle factors such as cycling or succession of lake biology cannot yet be ruled out as significant factors in explaining apparent changes in transparency.

**Important Limitations Identified in Field and Laboratory Methods**

As indicated earlier, suspended solids and turbidity data for this study generally indicated or implied very low concentrations of suspended particulates; but these measurements are thought to be misleading.

It is believed that both field and laboratory turbidity measurements may have led to a false impression that lake water samples were nearly free of particulates. The explanation for the false impression has implications for any water study that might involve very fine suspended particulates. As explained in more detail in the Turbidity section beginning on page 88, the sensitivity of turbidity meters falls off sharply as particle size decreases below about 0.3 microns. Therefore, even though Siseebakwet Lake water might have had a high concentration of very fine particulates, neither the field nor the laboratory turbidity measurements should have been expected to reflect the high concentration of particulates.

Similarly, the pore size or effective pore size of filters used in this investigation appears to have led to misleading suspended solids data. In several sub-disciplines of environmental science, a filter pore size of 0.45 microns has been used, or at least considered, traditionally as a functional dividing line between dissolved and suspended fractions of water samples. However, during this investigation, it is believed that many or most of the particulates suspended in Siseebakwet Lake water were small enough to go right through the 0.45 micron diameter pores in the filters. Therefore, water samples that were filtered in the field with 0.45 micron pore-size filters to represent the "dissolved fraction only" (e.g. data shown in Table 26 - Water Chemistry: Ground Water and Surface Water
Interaction Study, 1998-1999 on page 156), in reality, may have contained a substantial concentration of very fine suspended particulates. In addition, the laboratory that performed the suspended solids analyses (as reported in Table 12, beginning on page 64) routinely uses a filter with a 1.5 micron particle retention size for determinations of suspended solids. This, of course, means that even particles that were three times as large as 0.45 microns could have passed through the filter and not been counted as suspended solids. Clearly, there could have been substantial amounts of fine particulates in lake water samples that did not show up in analyses.

Recommendations for Lake Monitoring and Management

If there is continued interest in better understanding the factors that affect Siseebakwet Lake’s transparency and overall water quality, it is important to maintain a lake monitoring program that addresses the marl-lake characteristics of Siseebakwet Lake in addition to building on existing information. Data gaps, changes in sampling site locations, variability in sampling methods and other factors can bias the data or obscure trends over the years. A good, long-term monitoring plan based on existing data and especially on lake-specific needs is required to understand the workings of the lake.

Since this study cannot rule out impacts to the lake due to human-related activities, it is important that the Lake Association and lake area residents continue working to protect their lake. Education and cooperation among residents to implement and maintain the most appropriate lake-protective strategies may help in the long run more than it appears at this moment in time. The Lake Association and lake area residents are encouraged to contact the Minnesota Pollution Control Agency, the Itasca County Soil and Water Conservation District or other appropriate organizations if help is needed in understanding this report or planning to protect Siseebakwet Lake.

Detailed recommendations for lake monitoring are presented in the Goal Setting section beginning on page 120.

Recommendations for Further Study

If there is sufficient interest for further study, a continuing, consistent lake monitoring program will prove very useful as historical background information. Recommendations for lake monitoring are provided in the Goal Setting section beginning on page 120. Maintenance of the lake monitoring program and consistently good lakeshore and watershed management practices should make interpretations simpler in future studies. It may also be helpful to maintain a log or journal of environmentally significant events in the lakeshore area and throughout the watershed.

INVESTIGATION TOPICS. To further investigate the cause of any trend in Siseebakwet Lake water transparency, it is suggested that future investigators first consider a review of literature available on studies of marl lakes such as those in the List of References for this report on page 123. In particular, a study by Thompson et al. (1997) provides an enlightening perspective on the level of technology, expertise, and time commitment that may be necessary to understand the complex geochemical, hydrological, chemical and biochemical interrelationships that factor into transparency changes in a marl lake.

A literature review may help increase future investigators' chances of success by focusing more strategically and narrowly on testing a specific hypothesis or a set of closely related hypotheses. It will be essential to determine what combination of field reconnaissance, field instrumentation, sampling methodologies and analytical techniques will be necessary to successfully locate (e.g., the most important depths), collect and quantify calcium carbonate and any other important precipitates. This study showed that traditional lake study technology and measurement parameters may fail to provide accurate or meaningful data sufficient to answer important questions about marl lakes.
Multiple lines of evidence suggest that potentially large quantities of very small colloidal-sized calcium carbonate particulates were present in the lake water but passed through filters intended to trap the particulates for quantification in the ground-water and surface-water interaction study. Similarly, turbidity meters appear to have failed to detect most of the colloidal particulates even semi-quantitatively because of the greatly reduced scattered light intensity associated with very small particles. Plans for future studies should address how very fine particulates, including colloidal-size particulates, will be accurately quantified if there is a desire to understand their impact on transparency.

Re-suspension of calcium-carbonate rich sediments from the lake bottom can have a similar effect on transparency as large-scale precipitation of calcium carbonate (Thompson et al., 1997, p. 134). Since it is now clear that there are large amounts of calcium carbonate on the lakebed of Siseebakwet Lake, it is recommended that any comprehensive study consider the importance of addressing this issue.

Since phytoplankton photosynthesis appears to be the key to initiating and possibly sustaining large calcium carbonate precipitation events in marl lakes, it is also important to more thoroughly quantify chlorophyll a and catalogue algae types occurring both above and below the 2 m depth. Based on other studies of marl lakes, it appears important to characterize annual algal succession patterns and depths of maximum concentration of phytoplankton by (important) species to understand the patterns of and reasons for reduced transparency. For example, even though the blue-green algae *Gloeotrichia* did not show up in standard laboratory tests, these relatively large blue-green algae colonies were observed to be abundant during field observations. Some studies have found relatively high or the highest concentrations of algae at or slightly below the thermocline, so carefully identifying the most meaningful depths to test for algae and for calcium carbonate precipitate is an important step.

As the length of the lake-monitoring record grows, it would also be prudent to periodically review climatic data, particularly for any correlation with Siseebakwet Lake transparency readings. Among other things, changes in climate can affect lake temperature, solar insolation, the ratio of lake water recharge from different parts of the hydrologic cycle, and the amount and nature of particulate load entering the lake. These factors can impact many physical, chemical and biological characteristics of the lake which can in turn affect calcium carbonate precipitation and other factors that impact transparency.

**RATIONALE FOR INVESTIGATION TOPICS.** Larger algae colonies may not make it through the sub-sampling, sample preparation and analysis processes in a manner that accurately represents their impact on transparency. We do not currently have historical data on how algae or chlorophyll a concentrations below 2 m (but shallow enough to impact Secchi disk measurements) correlate with Secchi disk readings at Siseebakwet Lake. We do know, however, that in 1999, there were substantial concentrations of chlorophyll a at the 3.5 - 4.0 m depth and at the thermocline. We do not have historical information or any satisfactory quantitative data on the correlation between suspended calcium carbonate precipitate concentrations and Siseebakwet Lake transparency. Since variability in precipitation, snowmelt and ice out dynamics and temperature can affect the balance of ground-water and surface-water interactions and the equilibrium of the lake's chemistry and biochemistry, they may have an impact on lake transparency.

**CALCIUM CARBONATE PRECIPITATION.** The following procedures could be used to test the hypothesis that there is a correlation between the concentration of calcium carbonate precipitate suspended in near-surface (the depth range over which the Secchi disk measurements are made) lake water and Secchi disk transparency measurements:

- Collect filtered and unfiltered samples of shallow lake water at site 101 simultaneously and also collect the material left behind on the filter for quantitative analysis. Carefully measure the tare weight of the filters in advance in coordination with the laboratory. Analyze each sample for total solids and calcium carbonate. Checks can be added by conducting a total suspended solids analysis on the unfiltered sample and seeing how well it matches up with the amounts caught on the filter and the differences between the filtered and unfiltered
total solids analyses. Make sure the primary analyses are conducted by the same laboratory using identical procedures.

- Try replicating the sampling event by using multiple filter pore sizes less than or equal to 0.45 microns effective pore size in the field and adding another duplicate using the pore size used by the laboratory for total suspended solids analysis (the laboratory used a 1.5 micron effective pore size filter in 1999). The key is to ensure that the effective filter pore size of at least one of the sizes you use is small enough to prevent calcium carbonate precipitate to pass through. This may require filter pore sizes of 0.1 microns or smaller if practical. In a marl lake investigation by Thompson et al. (1997, pp. 134), they used a "Nylon 66 microfilter (pore size 0.22 microns) for determination of suspended CaCO₃ (whiting calcite)." Since it can be difficult and time-consuming to pass lake water through filters with very fine pore sizes, special procedures may be necessary, especially for collecting and quantifying the colloidal fraction of particulates.

- If results from early trials are inconclusive, it may be due to difficulties in measuring small changes in suspended particulate concentrations that might still be significant enough to affect Secchi disk transparency readings. Consider increasing sample volume sizes to improve analytical resolution of such differences. It may be necessary to pass rather large volumes of sample water through filters to trap and quantitatively measure small differences in concentrations of suspended material. In 1999, 4 liters of lake water were passed through a 142 mm diameter filter with a pore size of 0.45 microns without considerable difficulty. It may take a substantially greater volume of sample water to provide the needed answers.

- For the procedures described above, take a Secchi disk transparency measurement at the time of sample collection according to consistently applied, established protocols and record field conditions and other relevant observations. Be sure to take all Secchi disk measurements on the shady side of the boat or otherwise out of direct sunlight when possible. This allows meaningful comparability to Secchi disk measurements collected on cloudy days. Repeat the sampling event and Secchi disk measurement under a sufficient variety of lake transparency conditions to statistically test the hypothesis at the desired level of certainty.
INTRODUCTION

This report presents findings from two related studies of Siseebakwet Lake, Itasca County, Minnesota:

1. Lake Assessment Study

2. Ground-Water and Surface-Water Interaction Study

The results of these two studies, conducted primarily in 1999, are also compared with historical information from various other sources. This is primarily a Lake Assessment Project (LAP) report. Where appropriate, however, information from the related ground-water and surface-water interaction study has been incorporated into the body of the LAP report. Additional details from the ground-water and surface-water interaction study have been included in appendices for easy reference.

The two studies were combined because it was believed that more information about the environmental setting of Siseebakwet Lake would be needed to successfully interpret the data from a typical LAP. Because of special concerns about recent trends in lake transparency, this report places special emphasis on evaluating what controls transparency on this lake and whether or not transparency has changed over the years. Due to the special nature of this marl (calcium carbonate rich) lake, there is also an emphasis on examining ground-water and surface-water interactions and calcium carbonate equilibrium chemistry.

The ground-water and surface-water interaction study was initiated partially because Siseebakwet Lake exhibited properties that were difficult to explain using traditional assumptions about the interrelationships among phosphorus, chlorophyll a and Secchi disk transparency for Minnesota lakes. Siseebakwet Lake does not fit the pattern normally seen for a Northern Lakes and Forests ecoregion lake with (apparently) low suspended solids and little coloring from organic staining. In recent years, it became more apparent to the Itasca County Soil and Water Conservation District that many other lakes in Itasca County and neighboring areas don’t fit the traditional assumptions well. These unusual lakes appear to have characteristics similar to Siseebakwet Lake.

The unusual properties of these atypical lakes made them more difficult to evaluate and raised questions about applying traditional formulas and strategies for lake monitoring, classification and management. Since the public puts a lot of emphasis on transparency as an indicator of a lake’s value, a poor understanding of these atypical lakes could lead to an unnecessary decrease in perceived lakeshore property values. In response to these concerns, the Itasca County Soil and Water Conservation District contacted the Minnesota Pollution Control Agency (MPCA) for assistance in 1998. It is hoped that this report can be used to better understand, monitor, investigate and protect Siseebakwet lake. Moreover, it is hoped that this report can serve as a tool to help do the same for similar lakes in Itasca County and elsewhere.
BACKGROUND

Siseebakwet Lake is located in Itasca County, Minnesota, approximately eight miles southwest of Grand Rapids. (Figure 1 - Location of Study Area) The lake lies within the Upper Mississippi River Basin and within the Northern Lakes and Forest Ecoregion (Figure 2 - Minnesota Ecoregions and Basins) at an elevation of 1329 ft. above sea level.

WATERSHED CHARACTERISTICS

Siseebakwet Lake’s watershed is relatively small for a lake of its size. Most of the watershed lies to the west of the lake (Figure 3 - Watershed Boundary for Siseebakwet Lake). It has surface water inlets along the northwest shoreline (identified as location NNW Inlet) and southwest shoreline (identified as location SW Inlet) and an outlet along the eastern shoreline (Figure 4 - Monitoring Sites Location Map for Siseebakwet Lake).

Figure 1 - Location of Study Area

(from Oakes, 1970)
Figure 2 - Minnesota Ecoregions and Basins
Figure 3 - Watershed Boundary for Siseebakwet Lake
Figure 4 - Monitoring Sites Location Map for Siseebakwet Lake
OVERVIEW

A summary of watershed characteristics is presented in Table 1 - Morphometric, Watershed and Fisheries Characteristics of Siseebakwet Lake. The lake has a surface area of 1350 acres, an average depth of about 44 ft., and a maximum depth of about 100 ft. Lake bottom contours can be seen in Figure 5 - Bathymetric Map of Siseebakwet Lake.

*Table 1 - Morphometric, Watershed and Fisheries Characteristics of Siseebakwet Lake*

(Except Where Noted, Information in Tables 1 – 3, below, is modified from Reed and Watkins, 1992)

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1 – from 1995 DNR Fisheries Lake Survey Report and confirmed in 2000 by verbal communication with Justin Watkins, Itasca SWCD
2 – Actual 1999 summer mean (June – September)
3 – Based on a lake area of 1350 acres (see footnote 1 above)
Figure 5 - Bathymetric Map of Siseebakwet Lake
SOILS

The following discussion will first outline the characteristics of soils throughout the Siseebakwet Lake watershed and then focus in on soil types found in the immediate vicinity of the lakeshore.

Watershed Soil Types

The soil types in the Siseebakwet watershed, as mapped in the Itasca County Soil Survey (Nyberg, 1987), are listed in Table 2 - Soil Types of the Siseebakwet Lake Watershed and shown in Figure 6 - Soils Map of the Siseebakwet Lake Watershed. Twenty major soil mapping units and mapping associations are present in the watershed, totaling 4164 acres. The remainder of the watershed area is comprised of small lakes and ponds, which account for 539 acres. Soils are mapped to a depth of five feet.

Soils in the watershed are dominated by silt loams, which make up about three quarters of the soils in the watershed (618B, 870C, 870E, and parts of 866B and 866E). Another 8% of the soils are sandy in texture.

Wetland soils make up the remaining 16% of the watershed. Of the wetland soils, almost all (85%) are organic soils (peat and muck); the remainder are mostly sandy soils with high water tables. Wetland soils are concentrated in the western part of the watershed, mostly as interconnections between smaller lakes.

All of these soils have “restrictions” for on-site individual septic system drain fields, due to their high percolation rates and poor filtering capacity, according to the Itasca County Soil Survey (Nyberg, 1987). However, there may be some areas with suitable soils for drain fields which are too small to map. With these soil conditions, it is important that septic systems be installed, operated and maintained properly to ensure proper treatment and control of the septic wastes.

A complete description of soil suitability for sanitation, woodland management, and building site development is contained in the Itasca County Soil Survey.

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1 Significant portions of this section were taken from: “Siseebakwet Lake Assessment Report, Itasca County”, 1992; Prepared by Rian Reed and Justin Watkins with substantial contributions from Art Norton.
Table 2 - Soil Types of the Siseebakwet Lake Watershed

(from Reed and Watkins, 1992)
(derived from Nyberg, 1987: Itasca County Soil Survey)

<table>
<thead>
<tr>
<th>SOIL MAP SYMBOL</th>
<th>SOIL NAME, DESCRIPTION</th>
<th>ACREAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1031</td>
<td>Histosols, Ponded</td>
<td>25 acres</td>
</tr>
<tr>
<td>1033</td>
<td>Aquents, Sandy</td>
<td>17 acres</td>
</tr>
<tr>
<td>202</td>
<td>Meehan Loamy Sand</td>
<td>26 acres</td>
</tr>
<tr>
<td>240B</td>
<td>Warba Fine Sandy Loam (1-8% slopes)</td>
<td>14 acres</td>
</tr>
<tr>
<td>544</td>
<td>Cathro Muck</td>
<td>33 acres</td>
</tr>
<tr>
<td>618B</td>
<td>Itasca Silt Loam (1-10% slopes)</td>
<td>291 acres</td>
</tr>
<tr>
<td>625</td>
<td>Sandwich Loamy Fine Sand</td>
<td>49 acres</td>
</tr>
<tr>
<td>627</td>
<td>Tawas Muck</td>
<td>46 acres</td>
</tr>
<tr>
<td>72</td>
<td>Shooker Very Fine Sandy Loam</td>
<td>29 acres</td>
</tr>
<tr>
<td>797</td>
<td>Mooselake and Lupton Mucky Peats</td>
<td>365 acres</td>
</tr>
<tr>
<td>799</td>
<td>Seelyeville-Bowstring Association</td>
<td>25 acres</td>
</tr>
<tr>
<td>803B</td>
<td>Warba-Menahga Complex (1-8% slopes)</td>
<td>4 acres</td>
</tr>
<tr>
<td>803D</td>
<td>Warba-Menahga Complex (10-25% slopes)</td>
<td>8 acres</td>
</tr>
<tr>
<td>866B</td>
<td>Menahga-Itasca Complex (1-10% slopes)</td>
<td>148 acres</td>
</tr>
<tr>
<td>866E</td>
<td>Menahga-Itasca Complex (10-25% slopes)</td>
<td>51 acres</td>
</tr>
<tr>
<td>867B</td>
<td>Menahga and Graycalm Soils (0-8% slopes)</td>
<td>209 acres</td>
</tr>
<tr>
<td>870C</td>
<td>Itasca-Goodland Silt Loams (2-12% slopes)</td>
<td>1518 acres</td>
</tr>
<tr>
<td>870E</td>
<td>Itasca-Goodland Silt Loams (12-25% slopes)</td>
<td>1239 acres</td>
</tr>
<tr>
<td>872</td>
<td>Pengilly-Winterfield Association</td>
<td>4 acres</td>
</tr>
<tr>
<td>995</td>
<td>Borosaprients, Depressional</td>
<td>67 acres</td>
</tr>
</tbody>
</table>
Figure 6 - Soils Map of the Siseebkwet Lake Watershed

Soils Near the Lakeshore

Within Siseebkwet Lake’s watershed, approximately 68% of the soils in a one thousand foot vicinity of the lake are Types 866 and 870, C and E (soil mapping units). The distribution of soils near the shoreline is shown in Figure 7 - Soils Map for Shoreline (Buffer) Area of Siseebkwet Lake.

The most prevalent soils along the shoreline, Soil Types 870 C and E, are Itasca-Goodland silt loams. These Itasca-Goodland silt loams are strongly to slightly acidic in both the surface layer and subsurface. Regarding Soil Type 870 C, the Itasca County Soil Survey (Nyberg, 1987) states

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(1) Portions of this section are (modified) from Watkins and Reed (1999).
These soils are poorly suited to septic tank absorption fields. The Goodland soil does not adequately filter the effluent, and the Itasca soil does not readily absorb the effluent. The poor filtering capacity of the Goodland soil can result in the pollution of ground water. If septic systems are installed in these soils, onsite investigation is needed to determine the soil type and the measures that can overcome the limitations. The distribution lines should be installed across the slope.

Soil Type 870 E is also acidic in both the surface layer and subsurface. The Itasca County Soil Survey (Nyberg, 1987) adds that

Excessive erosion can occur if these areas are overgrazed or are not protected by a plant cover. Because of the slope, these soils are generally unsuitable as sites for dwellings and sanitary facilities. Soils that are better suited to these uses are generally nearby.

Soil Type 866 E, described as "Menahga-Itasca Complex", includes rolling to steep (10 - 25% slopes) soils on concave and convex slopes on glacial moraines. The Menahga soil is very strongly acidic to medium acidic in the surface layer and very strongly acidic to slightly acidic in the subsoil. The Itasca soil is strongly acidic to slightly acidic in the surface layer and medium acidic to neutral in the subsoil. The Itasca County Soil Survey (Nyberg, 1987) mentions a "severe hazard of erosion" associated with these soils and states: “Because of the slope, these soils are generally unsuitable as sites for dwellings and sanitary facilities.”

In general, the near-shore soils described above are quite susceptible to water erosion especially if they are disturbed during shoreline development or if natural plant cover is not properly maintained. They may also contribute to poor on-site septic system performance. These soils are easily compacted. Soil compaction reduces pore space and consequently water and oxygen, which in turn reduces phosphorus uptake. Development in shoreline areas with these soil characteristics may be contributing solids or phosphorus to the lake.
Figure 7 - Soils Map for Shoreline (Buffer) Area of Siseebkwet Lake
GLACIAL SEDIMENTS AND BEDROCK GEOLOGY

Siseebakwet Lake lies at an elevation of 1329 feet, within the Sugar Hills glacial moraine.

**Surficial Geology Overview**

The hills ringing the southern half of Siseebakwet Lake and extending to the southwest, south and southeast were formed by a glacial moraine. In Figure 8 - Glacial Geology and Bedrock Contacts, Oakes (1970) draws an outline of a recessional moraine indicating that its boundary follows close to Siseebakwet Lake’s shoreline along its southern and western perimeters and including South Sugar Lake. In Figure 9 - Geomorphology, Winter, Cotter and Young (1973) indicate that most of the surficial features in the immediate Siseebakwet Lake area were formed by an end moraine. Except where lakes, ponds, streams or swamp deposits are present, the only part of the watershed not shown as an end moraine in Figure 9 is the far western portion of the watershed between Little Siseebakwet Lake and Skelly Lake. This portion of the watershed is characterized by undifferentiated drift features (which most likely means ground moraine and glacial lake plains).

According to Hobbs (personal communication 2000), it appears that a glacier may have excavated material out of Siseebakwet Lake as it pushed generally southward. Hobbs believes that the highlands south of Siseebakwet Lake appear to be stacked up ice thrust slabs formed as glacial ice thrust and possibly deformed the sediments now comprising the hills. This activity can potentially disturb existing sedimentary sequences and even result in stacking a slab of a sedimentary sequence on top of the original sequence (e.g., a little further south). This stacking effect can result in the appearance of a unique sedimentary sequence twice or more in a local stratigraphic column.

Although the horizontal distribution, depth and makeup of the glacial sedimentary materials is not known in detail or with great accuracy for the Siseebakwet Lake area, a general description has been provided below from available information. A summary comparison of information from various sources in the literature used to prepare the following discussions about geology and ground water is provided in Appendix A - Hydrogeology.

**General Makeup and Thickness of Glacial Sediments.**

The glacial sediments are over 200 feet thick through much, if not all, of the watershed: out of 75 water well logs examined, none reached bedrock, and the four deepest wells ranged from 183 to 240 feet deep. The upper 10-20 feet of glacial sediments appear to be clay or sandy clay, according to soil survey and well log interpretations. Below this sand and clay zone, the sediments become sandier, and most wells are finished in sand or sandy gravel between 50 and 100 feet. A few deep wells penetrated a clay/gravel confining unit ranging from 100 to 180 feet below the surface, and from 20 to 90 feet thick. Below that unit is a sandy confined aquifer. Glacial drift thins to the northwest, towards the Giants Range Granite. Scattered patches of bedrock outcrop about 3 miles north of Siseebakwet Lake.

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3 *A recessional moraine* is a moraine formed during a temporary decrease in the rate of glacial retreat.

4 *An end moraine* is a ridge-like deposit formed at the glacier front when the ice front is stationary.

5 By Art Norton from Reed and Watkins, 1992.
Figure 8 - Glacial Geology and Bedrock Contacts

(modified from Oakes, 1970)
Figure 9 - Geomorphology

Modified from Plate 1 of USGS Bulletin 1331 – C by Winter, Cotter and Young, 1973

The original figure is in color. Annotations with arrows are provided to assist those viewing a black and white version of this document. Please see the original Minnesota Geological Survey document for a better copy of the map.

Figure 9 - Geomorphology
Glacial Sedimentary Units

Due partially to the highly variable nature of glacial sedimentary deposits and limited availability of information, authors have presented somewhat different but similar descriptions of glacial sedimentary units near Siseebakwet Lake. A summary of selected glacial unit descriptions is given below beginning with the youngest (shallowest) unit and ending with the oldest (deepest) unit. These descriptions will be based on the geologic unit names used in Winter, Cotter & Young (1973) and in Winter (1973) as shown in Figure 10 - Glacial Geology Cross Section. Descriptions of the bedrock units that lie beneath the glacial units will follow the description of the glacial sedimentary units.

Surficial Glaciofluvial Sediments

SURFICIAL GLACIOFLUVIAL SEDIMENTS (INCLUDING GLACIOLACUSTRINE SEDIMENTS). According to Winter (1973) the surficial glaciofluvial sediments are mostly stratified drift associated with Glacial Lake Aitkin II and cover much of the Mesabi Iron Range area. Figure 9 - Geomorphology delineates the limit of Glacial Lake Aitkin (see hatched line as indicated in “Explanation” box). It appears to indicate that Lake Aitkin did not reach the limits of the current watershed boundary. These surficial glaciofluvial sediments generally have lower transmissivities than glaciofluvial sediments between the surficial till and the bouldery till. The thickness of the surficial glaciofluvial sediments is generally less than about 25 feet.

Surficial Till

SURFICIAL TILL (SILTY BROWN CALCAREOUS TILL). According to Winter, Cotter & Young (1973) the surficial till is derived from the Des Moines Lobe and its age is about 12,000 before present. More specifically, according to Howard Hobbs, Minnesota Geological Survey (October 10, 2000, personal communication), this calcareous till probably originates from the St. Louis sublobe of the Koochiching lobe of glacial deposits. Winter, Cotter & Young (1973) describe the surficial till as light- to medium-brown, sandy, silty, and calcareous. This till also contains pebbles that are mostly granitic and metamorphic. However, it also contains limestone and dolomite pebbles. According to Oakes (1970) who similarly describes this till as silty, brown and calcareous, the till typically forms a widespread thin veneer over upland areas with a thickness ranging from 0 to 30 feet. Winter (1973) describes the thickness as less than 25 feet.

Winter, Cotter & Young (1973) describe the surficial till as light- to medium-brown, sandy, silty, and calcareous. This till also contains pebbles that are mostly granitic and metamorphic. However, it also contains limestone and dolomite pebbles. According to Oakes (1970) who similarly describes this till as silty, brown and calcareous, the till typically forms a widespread thin veneer over upland areas with a thickness ranging from 0 to 30 feet. Winter (1973) describes the thickness as less than 25 feet.

Oakes (1970) in Figure 8 - Glacial Geology and Bedrock Contacts and Winter, Cotter & Young (1973) in Figure 11 - Surficial Geology (1973) indicate that the surficial deposits covering most of the area near Siseebakwet Lake and the watershed as a whole are comprised of a silty brown calcareous till containing some shale. Cross sections that come near but do not enter the Siseebakwet Lake watershed, e.g., Figure 12 - Bedrock Geology Cross Section show surficial deposits described as glacial drift, undifferentiated, containing sand, till, silt, clay and outwash. The remainder of the watershed surface, typically the low-lying areas, is covered by lakes, ponds or swamp deposits of peat and organic silt with a typical thickness of 0 – 25 ft.
Figure 10 - Glacial Geology Cross Section

(modified from Winter, Cotter and Young, 1973)

This figure includes the western portion of a generalized section showing the stratigraphic relation of glacial drift along a line south of Grand Rapids and Aurora. The western (left) half of this section is probably most representative of the Siseebakwet Lake area.
Modified from Plate 1 of USGS Bulletin 1331 – C by Winter, Cotter and Young, 1973

The original figure is in color. Annotations with arrows are provided to assist those viewing a black and white version of this document. Please see the original Minnesota Geological Survey document for a better copy of the map.

**Figure 11 - Surficial Geology (1973)**
Glaciofluvial Sediments

GLACIOFLUVIAL SEDIMENTS (BETWEEN THE SURFICIAL TILL AND THE BOULDERY TILL). According to Winter (1973) the grain size of these glaciofluvial sediments varies greatly horizontally and they are the thickest and most continuous of the stratified drift units. He describes their thickness as commonly greater than 50 feet.

Oakes (1970) describes a unit that could be the same as that described above as glaciofluvial sediments between the surficial till and the bouldery till. Oakes describes it as sand, sand and gravel: surficial outwash and valley-train deposits. This unit occurs chiefly along major streams. It may also include ice-contact sand and gravel exposed at the surface in some areas. He lists the thickness as ranging from 0 to 45 feet. Oakes further explains that ice-contact sand and gravel of recessional features is also found associated with the brown sandy till. It occurs in moraines and ice-contact features including kames, kame terraces and local outwash. The thickness ranges from 0 to 104 feet.

Bouldery Till

According to Winter, Cotter & Young (1973), the bouldery till is gray, yellow, red, orange, or brown; has a sandy, silty matrix and contains abundant cobbles and boulders and is non-calcareous. It contains pebbles that are largely from granitic and metamorphic rocks. It is the thickest and most widespread of the four tills. Winter (1973) indicates that the thickness is generally less than about 50 feet and that lenses of glaciofluvial deposits are common within the bouldery till. There is also a similar, but colored, bouldery till, possibly a subunit, below the gray bouldery till. The bouldery till was deposited by the Rainy Lobe and has a minimum age of 14,000 to 16,000 years before present.

Oakes (1970) discusses a glacial unit that may be the same as the bouldery till described above. He describes it as a sandy, brown till with much gravel, cobbles and boulders that is non-calcareous. The till occurs in moraines or is buried beneath sand, gravel, clay or younger till. This till does not yield significant amounts of water to wells. Oakes lists the thickness as ranging from 0 to 140 feet.

Glaciofluvial Sediments

GLACIOFLUVIAL SEDIMENTS (BETWEEN THE BOULDERY TILL AND THE BASAL TILL). According to Winter (1973) these glaciofluvial sediments are largely sand or sand and gravel. The thickness of these surficial glaciofluvial sediments is generally less than about 50 feet.

Basal Till

BASAL TILL (GRAY, SANDY, CLAYEY CALCAREOUS TILL - WADENA LOBE). Winter (1973) describes the basal till as dark-gray to dark greenish and brownish gray, calcareous unsorted sand and gravel with clay and silt. It also includes some scattered cobbles and boulders. Its thickness ranges from about 50 to 100 feet. Winter, Cotter & Young (1973) add that this till contains pebbles that are mostly granitic and metamorphic, but along with some limestone and dolomite pebbles. They estimate that this till is middle or early Wisconsin but that it could be pre-Wisconsin.

Oakes (1970, Sheet 1) discusses an “older till” that appears to be the same unit as described above. He describes it as a gray, sandy, clayey calcareous till containing limestone pebbles and not yielding water to wells. This till occurs locally as a buried, fairly continuous till sheet with a thickness ranging from 20 to 90 feet according to Oakes.

OTHER TILL LAYERS. In addition to the till layers described above, an additional clayey, calcareous till was identified in the hills south of Siseebakwet Lake as part of the Wadena lobe in approximately 1980 (personal communication, Howard Hobbs, 2000). Hobbs believes that this till would fall between the Bouldery Till and the Basal till in terms of age. The Wadena lobe is also known to extend southward from the Siseebakwet Lake area.
Glaciofluvial Sediments

GLACIOFLUVIAL SEDIMENTS (BENEATH THE BASAL TILL). Winter (1973) discusses the possible of glacial fluvial sediments beneath the basal till and estimates their thickness as less than 30 feet. Oakes (1970) describes a calcareous sand and gravel buried outwash which may represent the same unit. Although not explicitly shown to occur in the immediate vicinity of Siseebakwet Lake on Sheet 2 (Oakes, 1970), a sheet of buried outwash composed of calcareous sand and gravel occurs as an outwash sheet beneath the gray sandy till (basal till) locally, the thickness of the buried outwash is believed to range from 0 to 112 ft according to Oakes (1970).

Bedrock Geology

Directly beneath the glacial sediments, most of Siseebakwet Lake and the watershed are underlain by Virginia Argillite of the Precambrian Era (Figure 12 - Bedrock Geology Cross Section). Argillites are metamorphosed mudstone, and are generally dense, fissile and black. This formation can transmit ground water and has yielded as much as 10 gallons per minute (gpm) with only 0.2 ft. of drawdown.

Beneath the Virginia Argillite is the Biwabik Iron Formation. Proceeding down the geologic column in this region, the next formations would be the Pokegama Quartzite, the Giants Range Granite and the Ely Greenstone. In an area near the western portion of the north shoreline of Siseebakwet Lake, the Virginia Argillite is missing so the glacial sediments are underlain directly by the Biwabik Iron Formation. Further north, near the boundary of the (surface-water) watershed, the Biwabik Iron Formation is missing, so the Pokegama Quartzite lies directly beneath the glacial sediments.

The Biwabik Iron Formation is a ferruginous chert which is also known as taconite. It has been described as a fair source of ground water, yielding up to 500 gallons per minute and elsewhere having a specific capacity of 2.8 gpm per ft. of drawdown. where it is fractured and leached. The Pokegama Quartzite is dense, hard and thinly bedded and not generally considered as a source of ground water.
Figure 12 - Bedrock Geology Cross Section

(modified from Oakes, 1970, Sheet 1)

This cross section extends from NW to SE and, at its closest point, lies about 5 miles NE of Siseebakwet Lake. The point labeled “A” lies approximately 5.8 miles ENE of Siseebakwet Lake. The point labeled “Section D-D” is approximately 5.5 miles NNE of Siseebakwet Lake.
WATER BUDGET

As part of the Ground Water and Surface Water Interaction Study, (Appendix G), a variety of investigative and analytical techniques were used to estimate the water budget for Siseebakwet Lake. The percentages of lake inputs and outputs were estimated for each part of the hydrologic cycle (Figure 13 - Water Budget for Siseebakwet Lake). In addition, the hydraulic residence time (HRT), the average time that a drop of water spends in the lake before exiting through a stream, ground water or the atmosphere, was calculated to be 6.5 years. The water budget and HRT calculations are used later in this report to help evaluate various water-related factors. Related information such as the tritium (ground-water age) data and the water budget calculations are presented in subsequent parts of the report such as Table 3 - Age of Ground Water Adjacent to Siseebakwet Lake Based on Tritium Analysis and Appendix G - Ground Water and Surface Water Interaction Study.

GROUND WATER

According to Winter (1973, pg. A13), the ground-water table in this area “is probably not more than 25 feet below land surface and in most of the area it is within 10 feet of the land surface.” Winter (1973, pg. A13) also states that “Most of the water that enters the ground-water system does not move deeply into the system but discharges to adjacent lowlands.”

Local Ground-Water Recharge and Discharge Patterns

The elevation of Siseebakwet Lake remains relatively constant at 1329 feet above mean seal level (MSL). Uplands extend from southwest to southeast of Siseebakwet Lake and are characterized by a series of steep sided upland ridges which reach elevations in excess of 1700 feet.

GROUND WATER SOURCE AREAS. Although much of this upland area is isolated from Siseebakwet Lake in terms of surface runoff, there is a good possibility that it is the source of significant ground-water input to the south side of the lake. Most of the ground water that recharges Siseebakwet Lake appears to originate from the upland areas directly south of the lake. Areas west, southwest and southeast of the lake also contribute, however, a substantial amount of ground water originating from the west and southwest is likely “captured” by a surface water body and enters Siseebakwet Lake via one of the two surface water inlets. Based on 1998 climatic data, it is estimated that approximately 43% of Siseebakwet Lake water comes from direct ground water recharge to the lake.

LAKE-WATER INPUT TO GROUND-WATER SYSTEM. The land surface immediately north and northeast of Siseebakwet Lake is considerably flatter than the uplands to the south. Based on 1998 climatic data, it is estimated that approximately 23% of Siseebakwet Lake water exits the lake through the ground water system. Shallow ground water near the northern and eastern perimeter of Siseebakwet Lake is believed to generally move to the northeast.

GROUND WATER GRADIENT. Assuming there is reasonably good hydraulic continuity in the ground-water system between the surrounding uplands and the lake, the large elevation difference could lead to a high hydraulic (fluid) potential difference along the ground water pathways. A high hydraulic potential difference would normally be expected to set up a relatively strong ground-water gradient as indicated by the ground water contours in the areas just south and southwest of Siseebakwet Lake (Figure 14 - Ground-Water Contours and Flow Direction). The shallow ground-water gradient appears to be relatively flat north and northeast of the lake.

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6 Some excerpts (by Art Norton) from Reed and Watkins, 1992 are included in this section.
Figure 13 - Water Budget for Siseebakwet Lake
(estimates based on 1998 stream inflow and outflow data)
Figure 14 - Ground-Water Contours and Flow Direction
(modified from Oakes, 1970)

Ground water contours show altitude of piezometric surface in glacial drift in feet above mean sea level. Arrows show direction of ground water movement. The map has not been updated to reflect any potential changes in ground-water levels since the date of publication in 1970.
RECHARGE NEAR SOUTHERN SHORELINE. Lakeshore residents report seeing water bubbling up along the southern lakeshore from time to time. These observations would appear to reflect ground-water discharge into the lake under a considerable head differential and possibly under confined conditions. Near-shore field measurements in this area found that, in the sediments just below the lake bed, the total potentiometric head of the shallow ground water was as much as 24 cm (9.4 in.) greater than that of the lake water. This means that the shallow ground water is being pushed up into the lake water via a very substantial difference in potential energy. Some residents specifically reported rust-colored water bubbling up along the southern lake shore; this observation suggests reducing conditions in the ground-water system. Their reports were consistent with field observations (color and odor) suggesting reducing conditions in near-shore sediments during this study. Very dark (probably manganese) staining and a sulfur-like odor were observed in lake-bottom sediments near the southeast shoreline. In the same general area, roughly 60 – 150 feet from the southeast shoreline, plants and cobbles were coated with a white precipitate (most likely calcium carbonate) that reacted strongly with a dilute hydrochloric acid solution. Together, inferences of ground-water discharge under a large head differential, chemically-reduced ground water and calcium-carbonate coated plants and cobbles suggest that calcium-carbonate rich, confined ground water recharges Siseebakwet Lake along its southern shoreline.

Typically, ground water has considerably less dissolved oxygen than surface water. It is not uncommon to find dissolved oxygen concentrations in ground water below 1 mg/L in contrast to surface water concentrations which are often found at 8 - 10 mg/l and even higher under certain circumstances. Correspondingly, in terms of measurements such as Eh or oxidation-reduction potential, ground water is typically more reduced (less oxidized) than surface water. Under certain conditions, shallow ground water that has entered the subsurface recently may exhibit higher dissolved oxygen concentrations than are commonly found further down gradient along the flow path. As the ground water moves further along its flow path, it typically loses oxygen. Certain geochemical environments encountered along a ground-water flow path can use up oxygen faster or to a greater extent than normal. When ground water is seen to be precipitating out black or red-orange chemicals at a surface water interface such as a lakeshore, it indicates that the ground water has passed from a relatively low oxygen (reducing) environment to a relatively high oxygen (oxidizing) environment. The red or black material that is deposited near the ground water and surface water interface has precipitated out of solution because the ground water has become too oxygenated to hold all of the iron (iron oxides can be orange-red) and manganese (manganese oxides can be black) in solution.

DIRECTION OF INFLOW AND OUTFLOW. The small northeastern part of the watershed is characterized by relatively flat topography. Outside of the watershed boundary, which is close to the lake on the north side, the land surface slopes northward towards Pokegama Lake, which lies at an elevation of 1273 feet (56 feet below Siseebakwet Lake). Based on a United States Geological Survey ground-water map (Oakes, 1970, Sheet 2), shallow ground water in the glacial drift appears to generally flow into Siseebakwet Lake from the northwest to the southeast perimeter of the lake. The map indicates a relatively flat ground-water gradient to the north and northeast from Siseebakwet Lake suggesting that, shallow ground water in the glacial drift, flows generally northeast in this area (Figure 14 - Ground-Water Contours and Flow Direction). In addition, field tests during this study indicated hydraulic communication between lake water and the ground-water system near both the southern and northern shorelines of Siseebakwet Lake. These data suggest a net annual flow of shallow ground water into Siseebakwet Lake from the northwest to the southeast and a net annual outflow of Siseebakwet Lake water into the shallow ground-water system to the north and east of Siseebakwet Lake.

CHANGES IN GROUND-WATER FLOW PATTERNS. Annual variation of climatic factors, ground-water withdrawals, potential adjustments of surface-water level control structures, etc., can result in temporary aberrations in local ground-water flow patterns. Seasonal factors such as increases in transpiration rates during the growing season in vegetated near-shore areas can also result in temporary aberrations in the local ground-water flow direction. Because of seasonal variation in factors such as evapo-transpiration, snowmelt and precipitation rates, it is likely that most parts of the lakeshore have been both ground-water discharge and ground-water recharge areas at one time or another. Indeed when prolonged heavy rainfall during this study saturated near-shore soils and created
numerous additional (temporary) surface water pathways into the lake along the northern shoreline, shallow ground-
water, at least the very shallow (underflow) portion, was certainly moving toward the lake from the north in contrast
to the average annual shallow ground-water flow patterns.

**Hydrostratigraphy**

Descriptions of geologic and hydrogeologic units in the immediate study area tend to focus on the till units
(surficial, bouldery and basal) since they are easier to identify and distinguish than the various glaciofluvial units
found between till zones. The glaciofluvial deposits are more important locally as conduits for groundwater
movement, however, the geochemistry of the till units adjacent to each glaciofluvial could still have a significant
impact on local ground water chemistry. Winter (1973, pg. A7) explains that “In general, however, the major sand
and gravel deposits (aquifers) occur between till units (confining beds) or at the surface. Internal characteristics of
the glacial units such as grain size, porosity, and lithology are also highly variable.” Winter (1973, pg. A1) explains
that the stratified fluvial sediments within the glacial sediments are capable of transmitting substantial amounts of
ground water in zones between the till zones which generally prohibit ground water movement:

<table>
<thead>
<tr>
<th>Stratified fluvial sediments occur within the glacial drift at many places in the Mesabi Iron Range area. These sediments, which are important aquifers, occur extensively between the three main till units. The thickest and most extensive aquifer consists of glaciofluvial sediments that lie between the surficial till and the middle till unit, the bouldery till. Thickness of the glaciofluvial sediments at this stratigraphic interval is greater than 50 feet in much of the area, and transmissivity is greater than 1000,000 gallons per day per foot in some places.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glaciofluvial sediments underlying the bouldery till occur largely in the western half of the area [Siseebakwet Lake is in the far western portion of the referenced study area]. These sediments are generally less than 50 feet thick, and transmissivity is generally less than 50,000 gallons per day per foot.</td>
</tr>
</tbody>
</table>

**Hydrogeochemistry**

One of the primary reasons that hydrogeology-related factors such as "hydrogeochemistry" are addressed in this
report is that they can potentially influence important lake characteristics such as transparency. As an example, any
hydrogeologic properties that affect factors such as pH and alkalinity or the calcium, total dissolved solids or
dissolved oxygen content or even the quantity of ground water entering Siseebakwet Lake can have a significant
impact on lake transparency through various chemical or biochemical processes. As you read the following
paragraphs, you will see numerous examples of hydrogeologic factors that could impact the lake's calcium-carbonate
equilibrium and affect the likelihood, rate or duration of calcium-carbonate precipitation in Siseebakwet Lake. An
increase of calcium-carbonate precipitate in the lake water would decrease transparency.

GEOCHEMISTRY OF GLACIAL SEDIMENTS'. The glacial sediments are generally characterized by moderate amounts
of carbonates, and locally high amounts of iron derived from the Biwabik Iron Formation. Ground water derived
from these sediments tends to have moderately high alkalinity values (160 to 324 mg/l in seven wells from the
Grand Rapids area reported by the U.S. Geological Survey by E. Oakes (Hydrologic Investigations Atlas HA-322,
Sheet 2, 1970). Iron values from those same wells ranged from 0.30 to 5.2 mg/l. Winter, Cotter & Young (1973)
provide some detailed information on the makeup of the glacial till in this area. More specifically, they present

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7 A portion of this section is (by Art Norton) from Reed and Watkins, 1992.
detailed results of grain size analysis, pebble lithology analysis, heavy mineral content analysis, and percent of soluble material analysis (using a dilute hydrochloric acid method). The percent of soluble material analysis is especially germane to this study as the analysis result can generally be assumed to represent the percent of carbonate in the material tested.

GROUND WATER CONTRIBUTION OF CALCIUM. Based on 1998 – 1999 data, approximately 43 percent of Siseebakwet Lake water comes from ground water. Because ground water samples generally contained substantially higher calcium concentrations than stream water, rain water, or the lake itself, it would appear very likely that, historically, ground water has been a key factor in contributing to the high concentrations of calcium carbonate that have precipitated out of the lake water and deposited on the lake bottom.

CALCIUM CARBONATE RESERVOIR IN LAKE BED. The lake bottom sediment core obtained during this study in 1999 contained approximately 53 percent calcium carbonate. This high concentration of calcium carbonate in lake sediments, by definition, qualifies Siseebakwet Lake as a marl lake. In addition, the two preliminary lake sediment core samples (retrieved from different locations than the final sample) field-tested positive for the presence of substantial amounts of calcium carbonate. Finally, nearly every rock and plant sample from various locations around the lake bed also tested positive for the presence of significant amounts of calcium carbonate. The field test was conducted by applying a few drops of dilute hydrochloric acid solution onto the sample. If the sample effervesces, it indicates the presence of carbonates. Strong effervescing indicates a substantial presence of carbonates and suggests high calcium carbonate as the dominant carbonate compound. In a fresh water lake such as this, it is normally a good assumption that most of the carbonate is in the form of calcium carbonate. Assuming the samples tested are representative of the lake bottom in general, the lake bottom sediments constitute a large reservoir of calcium carbonate that could be an important factor in the lake water's overall calcium carbonate equilibrium.

WATER RECHARGE LAG TIME AND HYDRAULIC RESIDENCE TIME FOR SISEEBAKWET LAKE. Temporal changes in a local hydrologic system's water budget due to changes in precipitation intensity, net annual precipitation, snow melt timing or other climatic factors, are normally felt much sooner in surface water bodies than in the ground water system. Ground water normally flows much slower than surface water and the lag time between changes in aquifer recharge and an equivalent change in ground-water discharge into a surface water body can be quite long. A short period of drought, for instance, may not initially appear to affect ground-water levels substantially while lake and stream levels are already dropping. On the other hand, when a rain storm or major snow-melt event causes a river to swell to capacity, the time it takes to impact a lake in a small watershed is quite short. But the time it takes the ground water to infiltrate into the ground, migrate through the vadose zone, reach the water table and begin to increase the recharge to a lake at the other end of the aquifer's flow path could be very long.

Analysis of tritium in ground water can be used to assess when the water entered the subsurface, i.e., the age of the ground water. Tritium is a radioactive isotope of hydrogen with atomic mass 3 and a half-life of 12.5 years. The amount of tritium in ground water reflects the amount of tritium that was in the atmosphere at the time the ground water entered the subsurface. Using a database of known tritium concentrations in the atmosphere over time, the date that the ground water entered the subsurface can be calculated. Tritium data were collected as part of the Siseebakwet Lake Ground Water and Surface Water Interactions Study (Appendix G).

Tritium analysis of ground water sampled from three domestic wells close to Siseebakwet Lake on October 20, 1999, suggests that the age of ground water that enters Siseebakwet Lake ranges from approximately 9 – 11 years (Table 3). The estimated time (year) of ground-water entry into the subsurface for each domestic well sample is shown in parentheses in Table 3. If ground water from multiple recharge sources or multiple flow pathways contributes to the well, then the estimated date and the corresponding age of the ground water would actually represent volume-weighted averages of the distinct ground water components reaching the well.
Table 3 - Age of Ground Water Adjacent to Siseebakwet Lake Based on Tritium Analysis

<table>
<thead>
<tr>
<th>DOMESTIC WELL DESCRIPTION</th>
<th>WELL SCREEN OPEN INTERVAL (Depth Below Land Surface)</th>
<th>ESTIMATED AVERAGE AGE OF GROUND WATER</th>
<th>SPECIFIC CONDUCTANCE (µmhos/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site # 466: Shallow Well Adjacent to Northwest Shoreline</td>
<td>50 – 58 ft.</td>
<td>11 years (1988)</td>
<td>410</td>
</tr>
<tr>
<td>Site # 467: Deeper Well Adjacent to South Shoreline</td>
<td>122 – 130 ft.</td>
<td>10 years (1989)</td>
<td>410</td>
</tr>
<tr>
<td>Site # 468: Shallow Well Adjacent to South Shoreline</td>
<td>56 – 60 ft.</td>
<td>9 years (1990)</td>
<td>740</td>
</tr>
</tbody>
</table>

The tritium age data suggest that changes in climate and other atmospheric variables that impact and translate through the ground-water system in a conservative manner (i.e., move with the water at the same speed as the water without being diminished significantly) would impact the lake approximately 9 – 11 years after the event in question. The lag time could be considerably shorter for that fraction of the lake's ground-water recharge that originates very close to the lake and enters the lake through very shallow ground-water flow paths. Examples of how climatic and other atmospheric changes could affect ground-water chemistry include dilution (or increased concentration) of various ions in ground water in response to induced changes in ground-water flux along a flow path. Similarly, increased (or decreased) ground-water acidity could result from more (or less) acidic precipitation over time. The estimated time lag of 9 - 11 years would be more reliable for impacts that are carried with the ground water such as conservative chemical constituents dissolved in the water and possibly much less reliable for impacts that can be transmitted faster or slower than the movement of the water itself. As explained elsewhere in this report, water-level changes caused by transmission of total hydraulic head changes through confined ground-water systems can propagate much more rapidly than the movement of ground water itself. However, based on the youthful ages of the ground water sampled in these wells, the likelihood that a lot of the lake's ground water recharge passes through confined systems of sufficiently large dimensions for this to be an important factor does not appear high.

Based on evaluation of the water budget for Siseebakwet Lake in conjunction with the analysis of oxygen and hydrogen isotopes from every phase of the hydrologic cycle, the average hydraulic residence time of Siseebakwet Lake water was estimated to be 6.5 years (Appendix G - Ground Water and Surface Water Interaction Study).

Together, the estimated age of ground water that recharges Siseebakwet Lake (9 – 11 years) and the lake's hydraulic residence time (6.5 years) can be used as benchmark time periods within which to examine local historical climatic, hydrologic, land use and environmental chemistry data for correlation with Siseebakwet Lake monitoring data. Lake monitoring data for comparison might include measures such as Secchi disk readings, depth profiles for specific conductance (or total dissolved solids), turbidity, temperature, pH and dissolved oxygen, total and volatile

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8 This value differs from the residence time of 14.2 years estimated by the MNLEAP model (discussed in a subsequent section). The value of 6.5 years is believed to be more reliable because it is based on a more sophisticated method.
suspended solids, calcium carbonate concentrations, and other factors that may impact or be indicators of Siseebakwet Lake transparency or water quality.

CHEMICAL EQUILIBRIUM OF SISEEBAKWET LAKE. Given that the typical calcium concentration of local ground water is significantly higher than concentrations found in the precipitation and surface water, climatic variations that temporarily change the relative contribution of ground water compared to other sources of lake recharge could impact the calcium carbonate equilibrium in the lake. In addition to calcium, other lake water constituents or properties that can affect the calcium carbonate equilibrium, such as pH, alkalinity, etc., could also be affected as the relative amount ground water entering the lake changes over time.

Assuming the local hydrologic system was initially in equilibrium, increased precipitation in the watershed would temporarily increase the percent of lake recharge from (calcium poor) direct precipitation on the lake, stream inflow and shoreline runoff relative to (calcium rich) ground water recharge. This would cause the relative amount of calcium input to the lake to decrease for some time following this time period. If, on the other hand, a period of low precipitation and minimal snowmelt ensues, the percent of ground water recharge to the lake would temporarily increase relative to the aforementioned other sources of lake water recharge. This would cause the relative amount of calcium input to the lake to increase temporarily.

HYDROGEOCHEMICAL VARIABILITY OF GLACIAL UNITS. In addition to the variability in relative amounts of ground water versus other recharge sources that replenish Siseebakwet Lake, there may be other more subtle factors that could contribute to the impact of ground water on lake chemistry. As explained above in the discussion of the geology of individual glacial units, the surficial till and the basal till are calcareous (rich in calcium). The bouldery till that lies stratigraphically between the surficial and basal tills, however, is not calcareous.

VARIATION OF AVERAGE GEOCHEMISTRY IN GROUND-WATER RECHARGE. The geochemistry of ground water traveling through glaciofluvial deposits or other water-yielding zones between or within the till units would tend to move toward equilibrium with the geochemistry of adjacent till units. It is likely then, that ground water having more contact (temporal or physical) with the surficial or basal tills would increase its calcium content relatively more compared to ground water travelling through other water-yielding zones that are more in chemical equilibrium with the bouldery till.

IMPACT OF WATER-LEVEL CHANGES ON GROUND WATER FLOW. If and when local ground water levels drop enough, some portions of one or more aquifers or lesser known water-yielding zones may become partially or completely de-watered. The de-watered zones no longer contribute to the net ground-water flow until water levels recover. Conversely, when water levels are exceptionally high, some portions of the subsurface that are normally unsaturated may temporarily become a significant water-yielding zone. As an aquifer's ground-water levels increase in recharge areas, the ground-water gradient can increase. This can result in an increase in the average linear ground-water velocity toward a discharge area and an increase in the flux of ground water to a discharge area such as a lake.

IMPACT OF GROUND-WATER GEOCHEMISTRY VARIATION ON LAKE CHEMISTRY. If, as indicated above, the aquifer area, contact time or flux through various water-yielding zones varied in response to precipitation intensity, net annual precipitation, snow melt timing or other climatic factors, then it is possible that the hydrogeochemistry of the average ground water recharging Siseebakwet Lake could change in response to climatic variation. In particular, the concentration of calcium, the pH, the alkalinity, dissolved oxygen concentration or other factors that could change the equilibrium of calcium carbonate in Siseebakwet Lake could be impacted. If, combined with other factors in the overall hydrologic, chemical and biologic cycles that interplay in Siseebakwet Lake, the net effect of climatic variation sometimes leads to over saturation of calcium carbonate in a previously undersaturated lake, or vice versa, then climatic variation could be an important factor affecting the precipitation of calcium carbonate in Siseebakwet Lake.
LAND USE

The types of land use in a watershed often affect the quality of the receiving water. In general, undisturbed forested and wetland watersheds will provide less nutrient and sediment delivery than developed or agricultural watersheds.

In general, the Siseebakwet Lake watershed is dominated by forest and wetlands with very little development (Figure 3) and is very similar to the land use throughout the Northern Lakes and Forest Ecoregion of the state, Table 4. However, the shoreline area of Siseebakwet Lake hosts most of the residential developed area (Figure 15 - Land Use Near Siseebakwet Lake). There are approximately 149 homes and a resort surrounding the lake and 17 other residences in the watershed.

There are no known existing or closed landfills or waste dumps in the watershed.

Table 4 - Comparison of Land Use in Siseebakwet Lake Watershed and the Northern Lakes and Forest Ecoregion.

(from Reed and Watkins, 1992)

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Siseebakwet Lake Watershed Acres</th>
<th>Siseebakwet Lake Watershed Hectares</th>
<th>Siseebakwet Lake Land Use %</th>
<th>NLF Land Use %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>3437</td>
<td>1390.9</td>
<td>73%</td>
<td>54 - 81%</td>
</tr>
<tr>
<td>Water, Marsh &amp; Wetland</td>
<td>1139</td>
<td>460.9</td>
<td>24%</td>
<td>14 - 31%</td>
</tr>
<tr>
<td>Cultivated</td>
<td>0.0</td>
<td>0</td>
<td>0%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Pastured</td>
<td>0.0</td>
<td>0</td>
<td>0%</td>
<td>0 - 6%</td>
</tr>
<tr>
<td>Developed</td>
<td>127</td>
<td>51.4</td>
<td>3%</td>
<td>0 - 7%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>4703</td>
<td>1903.2</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

9 Parts of this section are (modified and updated) from Reed and Watkins, 1992.
Figure 15 - Land Use Near Siseebakwet Lake

(Arrows have been added for those viewing a black and white version of the map.)
Economic Land Use

Over 80% of the watershed is forested. The forest is managed extensively for pulpwood production. The land is publicly and privately held and managed by county, state and Blandin Paper Company forestry divisions.

According to the Siseebakwet Lake Association (Appendix B – Land Use) there are 167 properties on Siseebakwet Lake and (the connecting) South Sugar Lake combined. Seventeen of the 167 properties are referred to as “second tier properties” because they are relatively far away from the lake and one property is Ruttger's Sugar Lake Resort (Ruttger’s). In addition to the 167 “properties”, there are 57 "townhomes" associated with Ruttger’s including 20 individual owners listed in the tax roles. Ruttger’s Lodge has an additional 8 cabins associated with it. Ruttger’s resort also includes a golf course. More discussion of residences in the watershed can be found directly below in the Historic Land Use section, however, the numbers will not match exactly as it appears that “properties” and “residences” are counted differently. There are no other significant industries in the watershed.

Historic Land Use

The lake and watershed has historically been limited to recreational use. The first lakeshore homes were built in 1930. According to Kohler (1995) (or see Appendix F) the “Siseebakwet Lake shoreline ownership is primarily private and the majority is developed. The 1984 survey states that 100% of the shoreline is mixed hardwood and conifers. At that time, there was 1 resort with 20 cabins and 102 private homes and cabins.” Kohler (1995) also explains that

“the resort on the northeast was purchased by Rutgers in the early 1990’s. As part of the renovation of the resort, the golf course was upgraded from a 9-hole course to an 18-hole course. One fairway and one green are in close proximity to the lake and to Sugar Brook. Most of the riparian vegetation has been removed in this area. This raises some concerns about the amount of nutrients that reach the lake. It is also likely that much of the rest of the course drains into either the lake or Sugar Brook, (which flows into Pokegama Lake) [Editorial Note: these assumptions were not assessed or field-checked as they were not within the scope of this project]. The Resort is attempting to minimize negative impacts on the lake.

…… There are also plans to plant some riparian vegetation along the stream. However, nutrient levels in the lake should be monitored in future years.”

Table 5 - Development of Residences in Watershed is a summary of the number of lakeshore homes at various times when records were available. For additional information about the development of residences in the watershed, see Appendix B – Land Use and Appendix C - History.

With the large number of older homes, there may be significant potential for septic pollution. Based on available information, there have been no reported spills of toxic or hazardous materials in the watershed.
Table 5 - Development of Residences in Watershed

<table>
<thead>
<tr>
<th>YEAR</th>
<th>SEASONAL</th>
<th>FULL YEAR</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>~15(^1)</td>
<td>~4(^1)</td>
<td>~19(^1)</td>
</tr>
<tr>
<td>1967(^2)</td>
<td>46</td>
<td>3</td>
<td>49</td>
</tr>
<tr>
<td>1984</td>
<td>~70% (85)(^1)</td>
<td>~30% (37)(^1)</td>
<td>122(^3)</td>
</tr>
<tr>
<td>1992(^4)</td>
<td>~57% (103)(^1)</td>
<td>~43% (77)(^1)</td>
<td>180(^5)</td>
</tr>
<tr>
<td>1998(^5)</td>
<td>106</td>
<td>79</td>
<td>185(^5)</td>
</tr>
</tbody>
</table>

2 – From Reed and Watkins (1992) and confirmed (estimate) by Jan Smith and Jim Parson (Siseebakwet Lake Association, 2000)
4 – For 1992, Reed and Watkins (1992) listed 50 seasonal and 67 full-year residents for a total of 117 residents but other sources of information, including a recent submittal from the Siseebakwet Lake Association (Appendix B), indicate that those numbers were not correct.
5 – Based on Siseebakwet Lake Association records from Jan Smith and Jim Parson (Siseebakwet Lake Association, 2000). The 1998 numbers include the 20 town homes that are privately owned but do not include the remaining 37 town homes or 8 cabins that are rented by the lodge on a sporadic basis.

Individual Sewage Treatment Systems

A survey of individual sewage treatment systems (ISTS), also known as on-site septic systems, was conducted by the Siseebakwet Lake Association in 1999. Survey details are provided in Appendix B – Land Use. Some of the survey information is summarized below.

SURVEY PARTICIPATION. According to the Lake Association, face-to-face surveys were conducted with residents representing 124 out of a total of 167 lake resident properties including residents on both Siseebakwet Lake and South Sugar Lake. Nine properties around the lake have more than one ISTS: a total of 20 ISTS in the survey for these nine properties. Seventeen of the 167 properties are located more than 500 ft. from the lakeshore and are therefore referred to as “second-tier properties”. Five of the second-tier properties were included in the survey. One of the 167 properties is Ruttger’s Sugar Lake Resort (Ruttger’s), however, none of the Ruttger’s facilities were included in the actual survey.

RUTGER’S. Ruttger’s has 57 town homes with 20 owners listed in the tax roles, a main lodge, and eight nearby cabins. Each of the 57 town homes has an ISTS. Sewage from Ruttger’s Sugar Lake Lodge and eight nearby cabins is pumped to a point 250 ft. from the lakeshore to a shared sewage treatment system that was built in 1992.

RESIDENCE AND ISTS TYPE. Fifty percent of respondents indicated that their property was used as a primary year-around residence. The most common types of ISTS units reported by respondents were as follows:

- Septic tank - drainfield --------------- 49%
- Septic tank - dry well --------------- 18%
- Septic tank - dry well with drainfield --- 25%

ISTS AGE AND DISTANCE FROM LAKE. ISTS ages were quite variable: 39% were 10 years or less and 12% were more than 30 years old (2 systems were reported as age unknown). Only 4 (3%) ISTS were listed as between 0 and 50 ft. from the lake. A fairly large percent, 43%, were located between 51 and 100 ft. from the lake.
ISTS PUMPING AND PROBLEMS. Respondents indicated that 54% of the ISTS were pumped every 2 years or more frequently. Based on those that responded, approximately 11% (4 units) were either pumped less frequently than every 10 years, never pumped or only pumped when a problem occurred. Another 3% (4 respondents) did not state how often their system was pumped. Reported problems included the following:

- Freeze ups -------------- 0
- Back ups ---------------- 4 (3%)
- Inadequate drainage ------ 1 (1 %)
- Some – not bad ---------- 1 (1 %)
- None in the past 2 years ---- 115 (93%)
- No response ------------- 4 (3%)

Evaluation. Only 49.2% of the ISTS have a septic system with a drainfield. The other systems using dry wells and other non-ideal ISTS configurations can be improved by upgrading to septic tanks with drainfields. Of special concern are the 18% of the dry wells that have no drainfield. Based on data in Appendix B – Land Use, there are 51 ISTS that are 16 years and older. Careful inspection of these systems, especially those that are used year around, may prevent problems in the near future. The 29 ISTS that are 26 years and older should be given the highest priority for inspection. Since 54% of respondents pump their ISTS every two years, it is clear that many residents are adequately concerned and proactive about maintaining their systems. Other users, for example those identified as not pumping their system for ten years or more, would probably benefit by a focused effort to educate lake residents about ISTS maintenance. If reporting was accurate, the fact that 92% of systems had no problems in the past two years is encouraging.

Since some ISTS are located very close to the lake shore, careful consideration should be given to the possibility of finding a location that is more protective of the lake. If appropriate, a review and mailing of local ISTS regulations to selected lake residents may help encourage them to find a better location. Since many systems are relatively close to the lake, short and long term strategies to find and encourage a change to locations that are more protective of the lake could prove essential to future preservation of the lake.

GENERAL RECOMMENDATIONS FOR ISTS. The soils around an ISTS drainfield have a finite phosphorus assimilation capacity to treat ISTS effluent. In general, a good ISTS with a drainfield is expected to exhaust its ability to adequately treat septage after about 20 - 25 years of year around use. If the treatment system is only a pit, problems are likely to occur much sooner. If the ISTS is only used seasonally, its ability to assimilate phosphorus can last longer.

Septic tank scum and sludge levels should be checked every three years (when the ISTS is used year around) and pumped out when necessary to ensure a well operating system. It is very important to be sure that there are no ISTS pipes extending to the lake. Systems should be located above the water table to help avoid problems with pathogens. Where the water table is high, a mound system may be needed to ensure there is sufficient clearance between the bottom of the drainfield (including the gravel) and the top of the water table. A minimum of 6” of soil cover is needed to provide frost protection.

It is also recommended that interested parties check on current county ordinances pertinent to septic systems and related shore-land regulations.
HISTORY

A History of Siseebakwet Lake written by Mr. John W. Otis in November 1999 is included in Appendix C - History.

SELECTED PREVIOUS SISEEBAKWET LAKE STUDIES

Previous studies of Siseebakwet Lake include the following as represented by reports:


The 1995 Minnesota Department of Natural Resources (DNR) Lake Management Plan lists several earlier DNR reports on Siseebakwet Lake including an initial survey in 1951, re-surveys in 1975 and 1984 and a previous Lake Management Plan in 1986.

CURRENT PROJECT HISTORY

The initial meeting between MPCA staff and Itasca County SWCD in Grand Rapids to discuss this project was held on September 9, 1998. Field work at Siseebakwet Lake on September 10, 1998, along with pre-existing information lead to a preliminary hypothesis that calcium carbonate may be precipitating out in the lake and could potentially be contributing to apparent changes in lake water transparency. This hypothesis lead to the inclusion of additional work beyond a typical MPCA Lake Assessment Study.

PERIODIC GROUND-WATER AND SURFACE-WATER SAMPLING. Ground-water and surface-water sampling, measurement of ground-water and surface-water field water-quality parameters, and measurement of piezometric head differences between lake water and very shallow ground water for the Ground-water - Surface-water Interaction Study were conducted on four dates between October 1998 and October 1999. These ground-water samples and ground water measurements were taken from just beneath the lake bottom near the shoreline. Surface-water sampling and measurement of field water-quality parameters for the Siseebakwet Lake, Lake Assessment Program were conducted on six dates between May and October 1999:

SPECIAL SAMPLING. A rainfall sample was collected near the southern shoreline on September 25, 1999 for analysis of basic chemistry and hydrogen and oxygen isotopes. A sample core of lake bottom sediment was collected from Siseebakwet Lake on October 19, 1999, for age dating and chemical analysis. Ground-water samples were collected from three private domestic wells adjacent to Siseebakwet Lake on October 20, 1999.

More details about the current project history are included in Appendix C - History.

CLIMATE

Based on State Climatological records from the Grand Rapids Forestry Sciences Laboratory weather recording station, 1961-1990, the area receives 27.54 inches of rain annually with a mean annual temperature of 38.6°F. A mean monthly summary is shown in Table 6. The last killing frost is typically May 23, the first killing frost is
normally September 16, for a growing season of 116 days. Rainfall of greater than 1 inch in 24 hrs., occurs an average of 4.3 times per year. The mean run off for the area is about 6.5 inches (16.4 cm) with low and high run off rates of 2.2 inches (5.58 cm) and 11.2 inches (28.54 cm).

Table 6 - Mean Monthly And Annual Weather Conditions (1961-1990).

(Grand Rapids Forestry Sciences Laboratory Weather Recording Station)

<table>
<thead>
<tr>
<th>Month</th>
<th>Temperature °F</th>
<th>Precipitation inches</th>
<th>Snow inches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
<td>Low</td>
<td>Mean</td>
</tr>
<tr>
<td>January</td>
<td>15.0</td>
<td>-7.4</td>
<td>3.8</td>
</tr>
<tr>
<td>February</td>
<td>23.0</td>
<td>-1.6</td>
<td>10.7</td>
</tr>
<tr>
<td>March</td>
<td>36.1</td>
<td>13.9</td>
<td>25.0</td>
</tr>
<tr>
<td>April</td>
<td>52.4</td>
<td>28.9</td>
<td>40.7</td>
</tr>
<tr>
<td>May</td>
<td>65.8</td>
<td>40.3</td>
<td>53.1</td>
</tr>
<tr>
<td>June</td>
<td>75.0</td>
<td>49.7</td>
<td>62.3</td>
</tr>
<tr>
<td>July</td>
<td>79.8</td>
<td>55.0</td>
<td>67.4</td>
</tr>
<tr>
<td>August</td>
<td>76.8</td>
<td>52.4</td>
<td>64.6</td>
</tr>
<tr>
<td>September</td>
<td>65.9</td>
<td>43.2</td>
<td>54.6</td>
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<tr>
<td>October</td>
<td>54.0</td>
<td>33.0</td>
<td>43.5</td>
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<tr>
<td>November</td>
<td>35.5</td>
<td>19.1</td>
<td>27.3</td>
</tr>
<tr>
<td>December</td>
<td>19.7</td>
<td>0.8</td>
<td>10.3</td>
</tr>
<tr>
<td>Mean Annual</td>
<td>49.9</td>
<td>27.3</td>
<td>38.6</td>
</tr>
</tbody>
</table>

TEMPERATURE

According to climatic data collected at the Grand Rapids Forestry Sciences Laboratory Weather Recording Station and plotted on Figure 36 in Appendix D - Climatic Data, the long term average temperature (1916 – 1999) in Grand Rapids has been 38.4 degrees Fahrenheit (°F) or 3.6 degrees Celsius (°C). Earlier in the 20th century, 1916 – 1945, it was slightly cooler with an average temperature of 37.6 °F. More recently, 1970 – 1999, the average temperature has been warmer: 39.4 °F. The highest annual average temperatures on record since 1916 were 44.6 °F in 1998 and 43.9 °F in 1987. The average for 1999 was also high: 43.3 °F. The 1990s was a warmer than average decade with temperatures averaging 40.5 degrees F. All years between 1990 – 1999, except for 1996 (37.0 °F), had an average temperature above the 84-year average of 38.4 °F. The most recent, sustained periods of lower than average temperatures include 1965 – 1972 (6 out of 7 years below average) and 1978 – 79 (both years below average).

PRECIPITATION

COMPARISON TO 1961 – 1990 PRECIPITATION DATA. Compared to 1961 – 1990 precipitation data from a nearby weather station in Grand Rapids (Figure 37 on page 139 in Appendix D - Climatic Data), local precipitation on Siseebakwet Lake during this study was unusually high. Figure 40 - Precipitation Departure from Normal for Water Year 1998-99 on page 142 also shows that this region received unusually high rainfall during 1998 - 99. Table 7 summarizes precipitation data from water years 1997-98 and 1998-99 as measured by lake resident Don Olson adjacent to the southern Siseebakwet Lake shoreline and listed with the Minnesota State Climatology Office. Upon comparison to local precipitation statistics from 1961 – 1990, precipitation during the water year preceding the
study was about three inches higher than average but still about eight inches less than the 1961 – 1990 mean annual high precipitation. However, the annual (water year) precipitation for the study period was about 12.5 inches greater than normal and nearly two inches greater than the mean annual high between 1961 and 1990. Statewide precipitation maps in Appendix D - Climatic Data show Minnesota precipitation and departure from normal precipitation during the water year October 1998 to September 1999. Precipitation data collected at Siseebakwet Lake appear to agree well with the statewide maps. The “departure from normal” map indicates that a large area around the Siseebakwet Lake watershed received about 10 to 14 inches more precipitation than normal during this study (between October 1998 to September 1999).

Table 7 - 1997 - 1999 Precipitation Summary

<table>
<thead>
<tr>
<th>TIME FRAMES</th>
<th>PRECIPITATION TOTAL (Siseebakwet Lake)</th>
<th>ANNUAL MEAN (Grand Rapids: 1961 – 1990)</th>
<th>ANNUAL LOW - HIGH (Grand Rapids: 1961 – 1990)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 97 – Sept. 98</td>
<td>30.25 in.</td>
<td>27.54 in.</td>
<td>14.62 – 38.03 in.</td>
</tr>
</tbody>
</table>

COMPARISON TO HISTORICAL PRECIPITATION DATA. Only if we look back to the turn of the twentieth century can we find local annual rainfall amounts as high as recorded in the 1998 - 1999 water year. A plot of annual average precipitation from 1887 through 1996 at the nearby Pokegama Dam is provided in Appendix D - Climatic Data. This historical plot shows that local precipitation has varied from over 40 inches in a year (once in about 1900 and once about 1907) to less than 20 inches a year (numerous times) between about 1910 and about 1937 and once in both the 1960s and 1970s. From approximately 1978 to 1996, the annual rainfall amounts (at the Pokegama Dam) remained in a relatively small range between about 22 inches and 34 inches per year.

Precipitation data from the Forestry Sciences Laboratory in Grand Rapids indicate that, on average, precipitation has increased in recent decades. Average precipitation from 1916 – 1945 was only 23.65 inches per year but the average from 1970 – 1999 was 28.6 inches per year. The Forestry Sciences Laboratory data is tabulated on a calendar year basis (as opposed to a water year basis). A plot of these data from the Forestry Sciences Laboratory in Grand Rapids in Appendix D - Climatic Data, shows that every year from 1993 through 1999 has had more precipitation than the long term annual average of 26.17 inches. Based on tracking annual precipitation at the Forestry Sciences Laboratory in Grand Rapids on a calendar year basis, the year with the highest precipitation total in recent history was 1977: 38.0 inches. Precipitation totals for calendar years 1997-1999 were 28.14, 28.23 and 33.86 inches respectively.

PRECIPITATION DURING THE STUDY. There were some months with particularly high precipitation during the Ground Water – Surface Water Interaction Study sampling period (October 1998 – October 1999) and during the Lake Assessment Study sampling period (May 1999 – October 1999). Surface and near-surface water data collected during and just subsequent to these months may reflect the character of the recent rainfall event to a higher degree than normal. In some cases, the impacts of large rainfall events on shallow wells and ground-water recharge to the lake could also be fairly immediate depending on how close the ground water recharge (infiltration) area is to the well or lake. Table 8 - Sampling Months with Unusually High Rainfall, compares selected Siseebakwet Lake rainfall data to the long-term monthly averages. Bold numbers indicate precipitation amounts that were considerably higher than long term averages:
Table 8 - Sampling Months with Unusually High Rainfall
(1998/1999)

<table>
<thead>
<tr>
<th>MONTH</th>
<th>PRECIPITATION (Sisebakwet Lake)</th>
<th>LONG TERM AVERAGE PRECIPITATION (Grand Rapids Forestry Sciences Lab)</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 1998</td>
<td>3.78 in.</td>
<td>2.96 in.</td>
</tr>
<tr>
<td>October 1998</td>
<td>4.40 in.</td>
<td>2.14 in.</td>
</tr>
<tr>
<td>April 1999</td>
<td>2.37</td>
<td>1.94 in.</td>
</tr>
<tr>
<td>May 1999</td>
<td>7.30 in.</td>
<td>2.94 in.</td>
</tr>
<tr>
<td>June 1999</td>
<td>2.66</td>
<td>3.95 in.</td>
</tr>
<tr>
<td>July 1999</td>
<td>6.68 in.</td>
<td>3.86 in.</td>
</tr>
<tr>
<td>August 1999</td>
<td>4.96 in.</td>
<td>3.40 in.</td>
</tr>
<tr>
<td>September 1999</td>
<td>4.55 in.</td>
<td>2.96 in.</td>
</tr>
<tr>
<td>October 1999</td>
<td>1.11 in.</td>
<td>2.14 in.</td>
</tr>
</tbody>
</table>

LAKE LEVEL

Sisebakwet Lake typically has an elevation of 1329 ft. above mean sea level (MSL). The lake is elevation is known to vary within a fairly narrow range from approximately 1328 to 1331 ft. MSL. Based on Minnesota Department of Natural Resources (DNR), Division of Waters data (Minnesota Department of Natural Resources, 2000) recorded between August 31, 1937 and October 10, 1999 (Table 9 - DNR Lake Elevation Data), as of January 21, 2000, the ordinary high water mark, based on a 1929 datum, was 1330.20 feet and the runout elevation is 1328.80 ft. also based on a 1929 datum. Reed and Watkins (1992) report a slightly different ordinary high water mark of 1331 ft. MSL.

HIGHS AND LOWS. According to the DNR data as of January 21, 2000, the highest and lowest recorded lake water level elevations were 1330.59 and 1328.40 ft. Reed and Watkins (1992) report slightly different values of 1331 and 1328 ft., both in 1992.

Table 9 - DNR Lake Elevation Data

<table>
<thead>
<tr>
<th>Data Type</th>
<th>VALUE (FT.)</th>
<th>DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary High Water Mark</td>
<td>1330.20</td>
<td>1929</td>
</tr>
<tr>
<td>Runout Elevation</td>
<td>1328.80</td>
<td>1929</td>
</tr>
<tr>
<td>Highest Recorded</td>
<td>1330.59</td>
<td>10/11/99</td>
</tr>
<tr>
<td>Lowest Recorded</td>
<td>1328.40</td>
<td>10/23/78</td>
</tr>
<tr>
<td>Average Of Recorded</td>
<td>1329.54</td>
<td></td>
</tr>
</tbody>
</table>
Historical lake-level elevation plots in Appendix E - Lake Level Elevation indicate that, in the 1990s, the lake elevation remained mostly between 1329.2 ft. and 1329.8. The lake elevation exceeded 1330.0 briefly in 1992 and 1995, and in 1999, it remained above 1330.0 for an extended period of time. Lake level elevation fell slightly below 1329.2 in 1996 and 1997.

Looking back as far as 1937, unusually high lake levels were also observed in about 1943 (approximately 1330.6 ft.) and in about 1968 (approximately 1330.3 ft.). The low lake level elevations recorded in late 1978 apparently represent the only time since 1937 that the lake was measured as being significantly below the runout elevation of 1328.8. Lake levels came down to near or just barely below the runout elevation in about 1962, 1970 and 1975.

GENERAL TRENDS. In general, the 1940s appear to have had slightly higher lake levels than average and the late 1950s to early 1960s had slightly lower levels than average. Lake levels during the 1980s and 1990s appear to generally have stayed close to the long term mean except when the lake level reached its maximum elevation in October of 1999. In summary, since 1937, the level of Siseebakwet Lake has mostly remained in a narrow range of elevation exhibiting only about two inches of variation. Nonetheless, a pattern of high periods and low periods can be discerned.

This study did not explore the role that inlet and outlet structures may have played in either minimizing or causing changes in lake water-level elevation over time. However, according to Koller (1995) (or see Appendix F – Fisheries Information), “in 1950, the outlet, Sugar Brook, was cleared of snags and partially dredged resulting in a drop in water level. Rip rap was then placed at the mouth of the stream to return the lake to its former level.” The Minnesota Department of Natural Resources suggested placing a permanent dam at the outlet, but instead, a gauge was installed and, reportedly, the residents agreed to use the gauge to maintain the water near its historic level.

FISHERIES

A lake management plan that addresses fisheries is included in Appendix F – Fisheries Information. The lake management plan explains that, as of 1995, two lake surveys and six population assessments have been conducted on Siseebakwet Lake over the last forty-five years. Six of these were conducted in the last twenty years [preceding 1995]. In addition, Siseebakwet Lake was chosen in 1980 to be one of twelve "study lakes" in the Grand Rapids area to be closely evaluated to determine the relative contribution of fry stocking versus natural reproduction to the walleye population. All of the study lakes were to be stocked on a biennial basis with walleye fry at a rate of 1000 fry/surface acre. Assessments were conducted every three to four years and shoreline seining was done weekly during the summer in each of the ten study years. The management plan also notes that “because of the clouded stocking history of this lake, it is difficult to determine if natural reproduction is limited in Siseebakwet Lake.”

According to the Minnesota Department of Natural Resources “Lake Finder” World Wide Web page for Siseebakwet Lake (http://www.dnr.state.mn.us/perl/lk_search.pl?lake=siseebakwet&county=itasca&start=1), at the time of this writing, “Special sampling will be conducted on this lake, summer 2000. Population assessment will be conducted on this lake, summer 2000.” Please see additional or more current details on the Minnesota Department of Natural Resources’ web page or in Appendix F – Fisheries Information.
RESULTS AND DISCUSSION

This section presents the results of the investigation, data evaluation and goals based on study findings. The data evaluation includes an assessment of water-quality trends and modeling of phosphorus loading.

1999 LAKE CONDITIONS

Conditions in and around Sisiebawkwet Lake were studied from May to November 1999 primarily through field observations, field measurements and laboratory analyses of environmental samples.

A brief overview of results for many of the key study parameters measured at site 101 is shown in Table 10 - Average Summer Water Quality: Sisiebawkwet Lake (Based on June – September 1999 Epilimnetic Data at Site 101). This table also compares these results to the typical range found in other lakes of the Northern Lakes and Forests Ecoregion. This portion of the Results and Discussion section will discuss the results for the parameters shown in Table 10 and other 1999 data such as lake temperature and dissolved oxygen concentrations.

Data in this report span a wide range of numerical values and originate from a variety of sources; consequently the data were reported in a variety of units. For the reader's convenience, the following unit comparisons and conversions are presented:

- Parts per million (ppm) x 1000 = parts per billion (ppb).
- Milligrams per liter (mg/L) x 1000 = micrograms per liter (µg/L).
- In addition, at the concentration levels reported in this study,
  - parts per million (ppm) = milligrams per liter (mg/L).
  - parts per billion (ppb) = micrograms per liter (µg/L).
### Table 10 - Average Summer Water Quality: Siseebakwet Lake
*(Based on June – September 1999 Epilimnetic Data at Site 101)*

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Summer Mean (June - Sept. 1999)</th>
<th>Typical Range for NLF Ecoregion&lt;sup&gt;1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Phosphorus (µg/L)</td>
<td>8.3&lt;sup&gt;2&lt;/sup&gt;</td>
<td>14 - 27</td>
</tr>
<tr>
<td>Chlorophyll a (µg/L)&lt;sup&gt;3&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>2.13</td>
<td>4 - 10</td>
</tr>
<tr>
<td>Maximum</td>
<td>3.09</td>
<td>&lt; 15</td>
</tr>
<tr>
<td>Secchi disk (ft.) (MPCA only)</td>
<td>9.8&lt;sup&gt;4&lt;/sup&gt;</td>
<td>8 - 15</td>
</tr>
<tr>
<td>Secchi disk (ft.) (CLMP)</td>
<td>10.3</td>
<td>8 - 15</td>
</tr>
<tr>
<td>Total Kjeldahl Nitrogen (mg/l)</td>
<td>0.31</td>
<td>0.4 – 0.75</td>
</tr>
<tr>
<td>Nitrate + Nitrate-N (mg/l)</td>
<td>Not Analyzed</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Alkalinity (mg/l)</td>
<td>130</td>
<td>40 – 140</td>
</tr>
<tr>
<td>Color (Pt-Co Units)</td>
<td>6.3</td>
<td>10 – 35</td>
</tr>
<tr>
<td>pH (SU)</td>
<td>8.48</td>
<td>7.2 – 8.3</td>
</tr>
<tr>
<td>Chloride (mg/l)</td>
<td>2.3</td>
<td>0.6 – 1.2</td>
</tr>
<tr>
<td>Total Suspended Solids (mg/l)</td>
<td>1.7</td>
<td>&lt; 1 – 2</td>
</tr>
<tr>
<td>Total Suspended Inorganic Solids (mg/l)&lt;sup&gt;5&lt;/sup&gt;</td>
<td>0.7</td>
<td>&lt; 1 – 2</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>1.7</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Conductivity (µmhos/cm)</td>
<td>257</td>
<td>50 – 250</td>
</tr>
<tr>
<td>TN:TP Ratio&lt;sup&gt;6&lt;/sup&gt;</td>
<td>37:1</td>
<td>25:1 – 35:1</td>
</tr>
</tbody>
</table>


<sup>2</sup> Since the June total phosphorus concentration was reported as < 10 µg/L, the total phosphorus summer mean was calculated using only the July, August and September values.

<sup>3</sup> Chlorophyll a measurements have been corrected for pheophytin.

<sup>4</sup> Based solely on measurements by the MPCA (June – September 1999)

<sup>5</sup>Total Suspended Inorganic Solids (TSIS) were calculated by subtracting total suspended volatiles (TSV) from total suspended solids (TSS). Since the TSV values for July and September were reported as < 1.0, a value of one-half the detection limit (0.5mg/L) TSV was used to calculate TSIS for July and September.

<sup>6</sup>The TN:TP ratio was calculated under the assumption that total Kjeldahl nitrogen (TKN) is approximately equal to total nitrogen. The Itasca SWCD (1992) reported summer means in 1992 of 2.95 µg/L nitrate-nitrite nitrogen and 294 µg/L total nitrogen. Assuming that nitrate-nitrite nitrogen is still roughly 1% of total nitrogen, the value reported here for the 1999 TKN summer mean (305 µg/L) should be a good estimate of total nitrogen. A separate MPCA study at the same sampling location also supports this assumption: filtered lake-water samples contained < 5µg/L nitrate-nitrite nitrogen in May and July 1999.

**DISSOLVED OXYGEN AND TEMPERATURE**

Data for dissolved oxygen and temperature profiles were collected at one-meter intervals at site 101 on each sampling date to a depth of approximately ten meters. Below ten meters, the measurement interval was typically two meters. Logistical difficulties precluded completion of the profile all the way down to the lake bottom in May. Measurements were made to a depth of 18 meters in May.
Lake Temperature

Lake surface temperatures at site 101 ranged from 9.34 degrees Celsius (°C) in May to a peak of 25.1 °C in July.

SEASONAL PROFILES. Based on temperature measurements shown in Figure 16 - Temperature Profiles, Site 101, May - October 1999, the lake appeared to be fairly well mixed on the May (earliest) sampling date and had begun to thermally stratify by the June sampling date. The lake remained relatively well stratified through at least mid September. By the last sampling date, October 15, the lake was once again fairly well mixed based on temperature readings.

On the June 10 sample date, the thermocline (zone of rapid change in temperature over a short range in depth) was located between 5 – 8 m (16 – 26 ft.). For the purposes of selecting a thermocline sampling point for June, a depth of 7.5 m (24.6 ft.) was selected. Figure 16 shows that the thermocline was better defined in July, August and September. Sampling depths representing the thermocline for these three months were selected at 8 m (26 ft.), 11 m (36 ft.), and 11 m respectively. A depth of 16.5 m (54 ft.) was selected as the thermocline sampling point for October although the thermocline was much less defined than in earlier months.

HYPO-LIMNION AND MIXING. Temperatures ranged from 6.1 – 7.1 °C in the hypolimnion (deeper, cooler layer). Siseebakwet Lake has a West to East fetch (distance wind can blow in a straight line) of approximately 1.9 miles and a North to South fetch of 1.5 miles. This relatively long fetch can allow for deeper mixing in the lake if the wind blows in the general orientation of the fetch. This could account for the thermocline area being less than ideally distinct.

Dissolved Oxygen Concentrations

Figure 17 - Dissolved Oxygen Profiles, Site 101, May - October 1999, provides an overview of depth-specific dissolved concentrations measured throughout the study in the deepest part of the lake. Dissolved oxygen concentrations ranged from 7.49 mg/L (July) to 10.75 mg/L (May) in the epilimnion (upper, well-mixed layer) throughout the summer. Concentrations fell below 2 mg/L in the hypolimnion (generally, the zone below 8 – 9 m) during the months when stratification was complete: July - October.

SEASONAL PROFILES. Based on the vertical distribution of Siseebakwet Lake dissolved oxygen concentrations, (Figure 17), physical mixing of lake water and its dissolved oxygen was not as complete as thermal stratification by June 10. Several factors could contribute to this disparity. Dissolved oxygen readings reflect any ongoing production and consumption of oxygen plus equilibration with the atmosphere when the lake surface is not covered with ice. Dissolved oxygen concentrations can also vary in time and space due to lake-water mixing. Since about 43% of the lake's water comes from ground water with estimated dissolved oxygen concentrations below 1 mg/l, increases in ground-water flux to the lake could result in significant decreases in lake-water dissolved oxygen concentrations.

The substantial decreases in dissolved oxygen concentrations observed in the hypolimnion between the May and August sampling dates could reflect progressively increasing percentages of ground water in this zone. Consumption of oxygen by biologic process at these depths (Figure 17) at rates sufficient to explain the decreases seems unlikely in a lake that appears to have very low concentrations of total phosphorus throughout most of its depth. Ground water could reach the hypolimnion near site 101 by entering the lake at its margins and moving toward deeper parts of the lake or by direct recharge from the ground-water system to the deeper, more central portions of the lake.

Dissolved oxygen concentrations were poorly mixed (vertically) from July through the last sampling event on October 13. The dissolved oxygen profile indicates that fall turnover had not occurred as of October 13 even though the water column had cooled substantially and was approaching an isothermal condition.
It is interesting to note that a parallel but opposite pattern was noted in a 1972 investigation: National Biocentric (1972). Although the location and date were not clearly specified, sometime between May 23 and September 6 they collected data for a dissolved oxygen and temperature profile to a depth of about 50 ft. Based on temperature readings, the thermocline was reasonably well defined with a sharp drop in temperature beginning at 25 ft. deep and leveling off at about 40 ft. The dissolved oxygen concentrations began to rise at 20 ft. deep and reversed the direction of change three times before showing a sustained decline between about 40 ft. to 45 ft. deep. They attributed the lack of correlation between temperature and dissolved oxygen with depth to Siseebakwet Lake’s “larger size and more extensive surface action”.

The occurrence of multiple dissolved oxygen maxima in the metalimnion, as observed in June, is common in relatively clear, mesotrophic lakes due to the relatively deeper extent of algal production and cooler temperatures in this zone.
Figure 16 - Temperature Profiles, Site 101, May - October 1999
Figure 17 - Dissolved Oxygen Profiles, Site 101, May - October 1999
SHALLOW AREAS AND GROUND-WATER RECHARGE. Shallower areas of the lake, especially high-energy near-shore areas, do not normally have a hypolimnion. But dissolved oxygen concentrations in ground-water samples collected from just a few feet or less beneath the lake bottom in near-shore areas were consistently below 2 mg/L. Therefore, when and where these areas of the lake are receiving significant amounts of ground-water recharge, it is very possible that dissolved oxygen concentrations are also below 2 mg/L at the interface between the lake and the bottom sediments. Even in ground water recharge areas, however, it is likely that dissolved oxygen concentrations increase rapidly with distance above the lake bottom as rapid mixing of lake water is common in near-shore environments. On July 21, 1999, dissolved oxygen measurements were recorded near the southeast shoreline (location 410 - not shown on map) for shallow lake water and for ground water at a depth of about 0.25 meters below the lake bottom. The dissolved oxygen concentration was 7.5 mg/L in lake water and 1.56 mg/L in the shallow ground water.

Preliminary analysis of field observations suggests that ground water recharge in shoreline areas is most common in the southern and western two-thirds of the lake perimeter and is unlikely near the surface-water outlet in the far east.

CONSEQUENCES OF LOW DISSOLVED OXYGEN. Dissolved oxygen concentrations below 2 mg/L would be too low for game fish, which typically require a dissolved oxygen concentration of 5 mg/L or greater for long-term survival. In addition, when dissolved oxygen concentrations fall below 2 mg/L, an important equilibrium chemistry threshold is reached which can release phosphorus bound up in bottom sediments. This can cause internal recycling of phosphorus at the interface between the lake water and the bottom sediments.

SPECIFIC CONDUCTANCE AND pH

Field measurements for specific conductance and pH, made at a depth of approximately one meter below the lake surface at site 101, are presented in Table 11 - Specific Conductance and pH: Site 101. The highest specific conductance occurred in August (271 \(\mu\)Mhos/cm) and the lowest was measured in September (230 \(\mu\)Mhos/cm). The lowest pH was measured in October (8.1) and three months (June, July and September) shared the highest pH: 8.6.

<table>
<thead>
<tr>
<th>DATE</th>
<th>SPECIFIC CONDUCTANCE ((\mu)Mhos/cm)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-May-99</td>
<td>255</td>
<td>8.3</td>
</tr>
<tr>
<td>10-Jun-99</td>
<td>261</td>
<td>8.6</td>
</tr>
<tr>
<td>21-Jul-99</td>
<td>262</td>
<td>8.6</td>
</tr>
<tr>
<td>24-Aug-99</td>
<td>271</td>
<td>8.4</td>
</tr>
<tr>
<td>15-Sep-99</td>
<td>230</td>
<td>8.6</td>
</tr>
<tr>
<td>12-Oct-99</td>
<td>250</td>
<td>8.1</td>
</tr>
</tbody>
</table>
SPECIFIC CONDUCTANCE. The specific conductance of a lake-water sample, at a given location and time, reflects the specific conductance of its mixture of source waters, past evaporation of these source waters while residing in the lake, and other factors such as the potential dissolution of lake-bottom materials. Precipitation falling directly on the lake would normally have a very low specific conductance. Based on a single rainfall sample collected adjacent to Siseebakwet Lake in September 1999, the specific conductance of rainfall at Siseebakwet Lake is estimated to be about 10 \( \mu \text{Mhos/cm} \) or less. Based on data from the ground-water and surface-water interaction study (Table 26 - Water Chemistry: Ground Water and Surface Water Interaction Study, 1998-1999), the primary surface-water inlet (WNW Inlet) can have specific conductance values (250 - 320 \( \mu \text{Mhos/cm} \)) similar to and somewhat greater than lake site 101 and local ground water can have specific conductance values (410 - 720 \( \mu \text{Mhos/cm} \)) substantially greater than site 101.

Since it has been estimated that 35% of the lake water is lost to evaporation (Figure 13 - Water Budget for Siseebakwet Lake), the impact of evaporation on specific conductance can be substantial. As late spring transitions to summer, both solar insolation and the temperature of the air/lake-water interface increase which leads to increased evaporation. Evaporation concentrates dissolved solids in the water remaining in the lake; this leads to elevated specific conductance in near-surface lake water. Assuming that the average wind speed over the lake surface did not vary too much from month to month, the role of evaporation in inducing increased specific conductance and total dissolved solids near the lake surface would be expected to diminish as solar insulation and temperatures decrease in autumn. Although changes were relatively small (255 - 271 \( \mu \text{Mhos/cm} \)), data in Table 11 show a pattern of increasing specific conductance near the lake surface from May 1999 through August 1999 which is consistent with the expected impacts of evaporation as explained above.

Another possible explanation for changes in near-surface lake water specific conductance is the temporal variation in the mixture of former stream water, former ground water, recent precipitation falling directly on the lake and sediment-laden near-shore runoff. As shown earlier in Table 8 - Sampling Months with Unusually High Rainfall, Siseebakwet Lake received some extremely high amounts of precipitation during this study. May 1999, which had a relatively low specific conductance of 255 \( \mu \text{Mhos/cm} \) was preceded and followed by months with relatively moderate precipitation. However, leading up to the sampling event in May 1999, four inches of rain had fallen locally that week during six consecutive days of rain and the lake surface elevation was reported to be near an all-time high. The total amount of precipitation for May 1999 was 7.30 inches. This may explain why specific conductance was lower in May compared to the next several months. Leading up to and including September 1999, which had the lowest near-surface specific conductance of the study (230 \( \mu \text{Mhos/cm} \)), there were three very rainy months in a row. For the month of October 1999, which had only half the average precipitation for that month, the near-surface specific conductance increased to 250.

The specific conductance for August 24, 1999, does not seem to fit the simplistic potential explanation based on precipitation amounts (given above). August follows a month with high precipitation (July 1999: 6.68 inches) and 4.96 inches of rain fell in August alone. Nonetheless, August had the highest specific conductance at the 1 meter depth: 271 \( \mu \text{Mhos/cm} \). Possible explanations for this include unavoidable measurement inaccuracies, delay of arrival and mid-lake mixing of other recharge sources such as ground water, natural variation of lake chemistry and the many other factors that affect the chemical equilibrium of the lake.

Unlike the multiple-depth specific-conductance data sets available for other months (May, June, September and October), the variation of specific conductance with depth in August was quite high (Figure 18 - Specific Conductance Profiles for Site 101). Specific-conductance measurements were 271 \( \mu \text{Mhos/cm} \) at the surface, decreased rapidly to 215 at 2 m deep, then increased very rapidly from 209 to 291 \( \mu \text{Mhos/cm} \) between 5 m deep and 6 m deep. Specific-conductance continued to increase until it reached 369 at 16 m deep. Measurements then held relatively steady through the deepest measurement of 367 \( \mu \text{Mhos/cm} \) at about 29 m. A set of three confirmation measurements were made five hours later (5:30 PM on August 24, 1999) at site 101 and indicated similar conditions. The confirmation measurements ranged from 210-214 \( \mu \text{Mhos/cm} \) near the surface to 339 at a depth of 11 meters.
Figure 18 - Specific Conductance Profiles for Site 101
A similar trend was observed at site 26, across the lake, roughly 1/5 mile from the south southeast shoreline on August 24. The specific conductance measurements were 275 μMhos/cm at a 2 m depth, 265 at 4.1 m, but increased to 344 at the 11 m depth.

Although equipment error or re-dissolution of calcium carbonate precipitate while the precipitate is falling through the water column or while the precipitate is residing on the lake bottom could possibly account for measured increases in specific-conductance, this does not appear to be the most likely explanation. Various lake processes routinely cause changes in temperature and dissolved oxygen. However, it is difficult to explain the concurrent changes observed in temperature and dissolved oxygen and in pH and specific conductance at site 101 in this time frame at depth without assuming the influx (at depth) of a large amount of water with substantially different chemistry. For more on this topic related to pH, please see the end of the pH discussion that immediately follows this section on specific conductance.

Based on the correspondence by depth among dissolved oxygen, temperature, pH and specific conductance measurements in August, it appears likely that a large amount of ground water moved into the area beneath site 101 between the June and August sampling dates. Unfortunately, only one (near-surface) measurement of specific conductance is available for July 1999, so the vertical distribution of specific conductance values during July 1999 is unknown. Even though it would imply exchange with (and possibly the replacement of) existing lake water with very large volumes of relatively undiluted ground water, field measurements suggest that lake water at all depths below about 8 m at site 101 was strongly influenced by ground water between the June and the August sampling dates. Below about 12 m, the lake water appeared even more similar to local ground water. In terms of the field measurements described above, the gross physical and chemical characteristics of August 1999 lake water at site 101 below about 12 m appeared much more like the surrounding ground water system than it did typical lake water as defined by measurements from other months.

In contrast to August measurements, the numerous specific-conductance measurements made at site 101 during May, June and October 1999 for all depths stayed within fairly narrow ranges. May and June readings all fell between about 255 - 265 μMhos/cm. October readings ranged from about 250 to 284 μMhos/cm. The four measurements during September ranged from 230 near the lake surface to 260 μMhos/cm at 30 m.

PH. One consideration of interest in this study was the extent to which algal photosynthesis may temporarily raise the pH of near-surface water and possibly catalyze the precipitation of calcium carbonate. Photosynthesis raises water pH incrementally in the immediate area of the algae as carbon dioxide is absorbed by the algae. If this pH alteration effect is significant at Siseebakwet Lake, its results would be expected to be most apparent during the most productive months for algae when solar insolation and water temperature are highest.

The range of near-surface water pH readings at primary lake sampling point 101 for this study was not particularly wide: 8.1 - 8.6 (Table 11 - Specific Conductance and pH: Site 101, One Meter Depth). The lowest pHs of the study occur in the relatively cool months of May and September as might be expected and three of the relatively warmer months have the highest pH. However, the fact that August, the month where the lake had the most visibly obvious impact from algal growth at the surface had a pH between the two extremes does not seem to corroborate a simplistic relationship between algal productivity and near surface lake pH.

There are many factors which could explain this including the unavoidable pH measurement inaccuracies, natural variation of lake chemistry and the many other interrelated physical, chemical and biochemical factors affect the chemical equilibrium of the lake.

The lowest pH values observed at site 101 during the 1999 study, all near 7.5 pH units, were recorded at the same time and depths as the highest specific conductance values (364 - 369 μMhos/cm) and lowest dissolved oxygen values (0.03 - 0.73 mg/L): August 24 at depths ranging from 16-29 m. It is probably no coincidence that the values for these three parameters found at depth are quite distinct from values found near the lake surface yet very similar to values found in local ground water that is estimated to supply 43% of the lake water.
TOTAL PHOSPHORUS

Phosphorus is an important nutrient for plant growth and it is normally the nutrient that is most crucial in controlling plant growth in Minnesota lakes. The 1999 summer mean total phosphorus concentration in the surface water (0 – 2 m zone) at site 101 on Siseebkwet Lake was 8.3 µg/L (micrograms per liter or parts per billion). Table 10 shows this concentration is significantly below the typical range of 14 – 27 µg/L found in reference lakes in the Northern Lakes and Forests Ecoregion. As expected, the 1999 study (May – October 1999) mean total phosphorus concentrations for the two surface water inlets, 17 µg/L and 29 µg/L, were considerably higher than for site 101. Nonetheless, these concentrations are very low for streams in this ecoregion. Figure 19 - Total Phosphorus: May - October 1999 at Site 101, Siseebkwet Lake, illustrates how total phosphorus concentrations varied throughout the study period by depth in the lake. October concentrations from samples collected at the thermocline, 68 µg/L, and in the hypolimnion, 123 µg/L, stand out in Figure 19 as very high compared to all other samples. These higher concentrations may reflect mobilization of phosphorus from lake bed storage as deep lake water began to move upward and mix with shallower waters in October.

Despite the low phosphorus concentrations found in the epilimnion at site 101, the higher phosphorus concentrations found at depth in October 1999 and the strikingly higher phosphorus concentrations found at the surface water inlets (210 µg/L at the SW inlet and 233 µg/L at the WNW inlet) and outlet (61 µg/L) in October 1998 during a study by Itasca Soil and Water Conservation District (Watkins and Reed, 1999) reinforces the point that site 101 epilimnion data for Siseebkwet Lake alone may not well represent the overall impact of phosphorus on the lake. Refer to the Phosphorus section on page 104 of the Trends in Water Quality and Related Factors section for further discussion about phosphorus data from other investigations.
During this 1999 study, the thermocline sampling depth varied by month according to the actual thermocline depth based on in-lake temperature measurements but was always between the shallow and hypolimnion (deepest lake zone) sampling depths.

Total phosphorus concentrations found at various depths in the deepest area of Siseebakwet Lake are shown by date on the second page of Table 12 - Site 101 Water-Quality Data for Siseebakwet Lake (May – October 1999): Minnesota Department of Health Laboratory. Total phosphorus concentrations found in the two surface-water inlets are shown in Table 13 - Inlet Streams Water-Quality Data for Siseebakwet Lake (May – Oct. 1999): Minnesota Dept. of Health Laboratory.

Estimated annual phosphorus loading rates and other nutrient-related modeling results for Siseebakwet Lake are presented in a subsequent section of this report entitled "Modeling and Phosphorus Loading".

**Inlet Streams**

Total phosphorus concentrations in the two inlet streams ranged from a high of 42 ppb in the West-Northwest Inlet Stream (WNW Inlet) in May 1999 to a low of 14 ppb in the Southwest Inlet Stream (SW Inlet) in July 1999. In each month of the study period, May through October 1999, the WNW Inlet had a higher total phosphorus concentration than the SW Inlet. The mean total phosphorus concentrations for the May through October 1999 study period were as follows:

- **WNW Inlet mean:** 29 ppb total phosphorus
- **SW Inlet mean:** 17 ppb total phosphorus

These mean values are clearly low for the state as a whole but not too unusual for Northern Lakes and Forest Ecoregion streams. An ecoregion-based survey of total phosphorus concentrations in streams by McCollor and Heiskary, 1993, shows that these values rank at or below the 25th percentile for Northern Lakes and Forest Ecoregion streams. Thus, approximately 75% of streams assessed in the Northern Lakes and Forest Ecoregion had higher total phosphorus concentrations than the two stream inlets to Siseebakwet Lake.

**Site 101, Siseebakwet Lake**

**SHALLOW EPILIMNION (0 – 2 m) ZONE.** Total phosphorus concentrations in the 0 – 2 m zone at site 101 were highest in May (12 ppb) and October (14 ppb). Even though the differences were very small, there was an apparent steady increase in total phosphorus from July (7 ppb) through October (14 ppb). This upward trend may have actually begun in June (<10 ppb) but it is not known how far below 10 ppb the actual total phosphorus concentration was. There is some degree of uncertainty about this trend since the concentration differences are similar to the normal range of analytical error (normal precision of the analytical method) for total phosphorus.

**THERMOCLINE.** In each month from June through October, total phosphorus was measured at the thermocline which ranged in depth from 7.5 to 16.5 m. In each of these months, the total phosphorus concentration was higher at the thermocline than in the 0 – 2 m depth range. From July through September, the concentration at the thermocline was only 3 - 4 ppb higher which is probably not a significant difference. However, in October, the total phosphorus concentration at the thermocline was 68 ppb versus only 14 ppb in the 0 – 2 m zone.

**HYPOLIMNION.** Total phosphorus concentrations in the hypolimnion at site 101 were very high in October: 123 ppb. Sometimes, unusually high phosphorus readings in water collected from the hypolimnion are due to accidentally stirring up phosphorus-rich sediments on the lake bottom just before collecting the lake-water sample. Total phosphorus concentrations in the hypolimnion were considerably lower (10 - 20 ppb) from May to
September. Nonetheless, hypolimnion concentrations were higher than both shallow epilimnion and thermocline concentrations in July, September and October and higher than the shallow epilimnion concentration in May. It is not uncommon in Minnesota lakes to find the highest total phosphorus concentrations in the hypolimnion.
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<th>Total Volatile Suspended</th>
<th>Total Inorganic Suspended Solids (calculated*)</th>
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--- : No analysis performed
ND: Not detected at detection limit shown preceding "ND"
* : Total inorganic suspended solids was estimated by subtracting the volatile suspended solids from the total suspended solids
Table 12 - Site 101 Water-Quality Data for Siseebakwet Lake (May – October 1999): Minnesota Department of Health Laboratory (continued)

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<th>Total Phosphorus (ppm)</th>
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<th>Sodium (ppm)</th>
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---: No analysis performed  
ND: Not detected at detection limit shown preceding "ND"  
†: See Table 33 - Comparison of Calcium Ion (Ca²⁺) Concentrations, for concentrations expressed as Ca²⁺
Table 13 - Inlet Streams Water-Quality Data for Siseebakwet Lake (May – Oct. 1999): Minnesota Dept. of Health Laboratory

<table>
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<th>Site Number</th>
<th>Station Name</th>
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<th>Turbidity</th>
<th>Color</th>
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<th>Total Volatile Suspended Solids ppm</th>
<th>Total Inorganic Suspended Solids (calculated) ppm</th>
<th>Total Kjeldahl Nitrogen ppm</th>
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<td>50</td>
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<td>1.3</td>
<td>40</td>
<td>1.0ND</td>
<td>1.0ND</td>
<td>0.510</td>
<td>---</td>
<td>0.025</td>
<td>---</td>
</tr>
<tr>
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<td>1.2</td>
<td>40</td>
<td>1.2</td>
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<td>1.7</td>
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<td>0.500</td>
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<td>21</td>
<td>SW Inlet</td>
<td>13-May-99</td>
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<td>---</td>
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<td>0.024</td>
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<td>20</td>
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<td>1.6</td>
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<td>1.6</td>
<td>0.420</td>
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<td>0.480</td>
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<td>1.6</td>
<td>0.460</td>
<td>---</td>
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--- : No analysis performed
ND: Not detected at detection limit shown preceding "ND"
* : Total inorganic suspended solids was estimated by subtracting the volatile suspended solids from the total suspended solids
NITROGEN

Nitrogen is an important nutrient for plant growth but is normally not the limiting nutrient in controlling plant growth in Minnesota lakes. As explained below, the total Kjeldahl nitrogen concentrations determined in this study appear to provide reasonably good estimates (within about 3 - 9% margin of error) of total nitrogen concentrations in both Siseebakwet Lake and the inlet streams.

Comparison of Nitrogen Concentrations

The 1999 summer mean total Kjeldahl nitrogen concentration in the surface water (0 – 2 m zone) at site 101 on Siseebakwet Lake was 310 µg/L (micrograms per liter or parts per billion). Table 10 shows this concentration is significantly below the typical range of 400 – 750 µg/L (0.40 – 0.75 mg/L) found in reference lakes in the Northern Lakes and Forests Ecoregion. The mean total Kjeldahl nitrogen concentrations for the surface water inlet streams during the 1999 study (May – October 1999) were higher: 530 µg/L (WNW Inlet) and 440 µg/L (SW Inlet).

Inlet Streams

At the stream inlets, the total Kjeldahl nitrogen concentrations ranged from 390 µg/L in the SW Inlet in July 1999 to 650 µg/L in the WNW Inlet in May 1999. Stream data for all study dates are presented in Table 13 - Inlet Streams Water-Quality Data for Siseebakwet Lake (May – Oct. 1999): Minnesota Dept. of Health Laboratory.

Site 101, Siseebakwet Lake

At site 101, total Kjeldahl nitrogen concentrations ranged from 280 µg/L at the epilimnion in June 1999 and at the thermocline in September 1999, to 410 µg/L in the epilimnion in May 1999. Total Kjeldahl nitrogen concentrations for specific lake depths are presented by date on the second page of Table 12 - Site 101 Water-Quality Data for Siseebakwet Lake (May – October 1999): Minnesota Department of Health Laboratory.

Total Nitrogen

Total nitrogen in natural water systems can effectively be determined by summation of total Kjeldahl nitrogen, nitrate nitrogen and nitrite nitrogen. For this study, samples were collected and analyzed for total Kjeldahl nitrogen which includes organic nitrogen and ammonia nitrogen. No analyses for nitrate or nitrite nitrogen were conducted. In a separate, but concurrent study of Siseebakwet Lake ground-water and surface-water interactions (Appendix G - Ground Water and Surface Water Interaction Study), samples from Siseebakwet Lake site 101 collected approximately 0.6 m beneath the lake surface were analyzed for nitrate and nitrite. All nitrate and nitrite results from samples collected in October 1998 and May, July and October 1999 were reported as less than the reporting limit of 5 ppb except for the October 1999 nitrate value which was reported as 8 ppb. In addition, the average concentration of nitrate plus nitrite (2.95 µg/L) was only 1% of the average concentration of total nitrogen (294 µg/L) found in a 1992 study of Siseebakwet Lake by the Itasca
Soil and Water Conservation District (Reed and Watkins, 1992). Based on these data, and the fact that the summer mean for total Kjeldahl nitrogen at site 101 (310 ppb) should be a reasonably good estimate for total nitrogen since it appears to account for about 97 - 99% of the total nitrogen.

In the ground-water and surface-water interactions study, (Table 26 - Water Chemistry : Ground Water and Surface Water Interaction Study, 1998-1999 in Appendix G) stream inlet concentrations of nitrite were all below the reporting limit of 5 µg/L and nitrate concentrations in the WNW Inlet were as follows: 37 µg/L in May 1999, 20 µg/L in July 1999, and 46 µg/L in October 1999. These values range from only 3% to 9% of the total Kjeldahl nitrogen concentrations found in the WNW Inlet for this study from samples collected within one day. Thus, as with the site 101 data, the study mean for total Kjeldahl nitrogen for the WNW Inlet (530 µg/L) appears to be a reasonably good estimate for total nitrogen.

CALCIUM CARBONATE EQUILIBRIUM

While planning for this investigation, there was considerable concern and speculation about why the transparency of Siseebakwet Lake appeared to be worsening significantly in recent years. A trend of worsening Secchi disk readings paralleled anecdotal reports from residents that felt they used to be able to see the lake bottom in places where they could no longer see it. One of many possible explanations considered was that precipitation of calcium carbonate in Siseebakwet Lake causes a reduction in lake water transparency at times. Indeed, when substantial amounts of calcium carbonate precipitate are suspended as particulate matter in the shallow lake water, it may reduce lake water transparency as measured by a Secchi disk. If this was an important factor, then why might it reduce transparency more now than in earlier years?

Sources of Calcium in the Hydrologic Cycle

In an effort to better understand how the environmental setting might contribute to the distribution of calcium carbonate in Siseebakwet Lake, data were collected during the Ground Water and Surface Water Interaction Study (Appendix G beginning on page 155) to support the Lake Assessment Study (LAP). Earlier, on page 34, "Figure 13 - Water Budget for Siseebakwet Lake" was presented to show that Siseebakwet Lake has three very substantial and distinct sources of water recharge (input water):

- stream flow (22%)
- direct precipitation onto lake (35%)
- ground water (43%)

Other minor sources of recharge such as direct overland flow from rainfall landing near the shoreline, temporary input pathways during flooding, and springs have not been quantified separately but are assumed to be small compared to the three categories shown above.

In the "Hydrogeochemistry" section beginning on page 37, it was pointed out that ground water, on its 9-11 year (estimated average) journey to Siseebakwet Lake, may travel through geologic materials that are either calcium-poor or calcium rich depending on a number of factors. The hydrogeochemistry of these materials, in a large part, determines the chemistry of about 43% of the water entering Siseebakwet Lake. Changes in other variables such as climatic conditions can also affect the chemistry of input water from streams, precipitation and ground water.
Figure 20 - Ca\textsuperscript{2+} Concentrations Throughout the Hydrologic Cycle, shows a summary of the 1999 Ca\textsuperscript{2+} concentrations found in various parts of the hydrologic cycle in the LAP study and the Ground Water and Surface Water Interaction Study. Ranges of concentrations are shown where more than one value was measured for the studies. A tabular summary of these data with notations about which represent filtered and unfiltered samples and additional details is available in Table 33 - Comparison of Calcium Ion (Ca\textsuperscript{2+}) Concentrations on page 180.

Figure 20 highlights the wide range of Ca\textsuperscript{2+} concentrations found in the various sources of water that recharge the lake. While receiving precipitation with as little as 1.9 ppm Ca\textsuperscript{2+} and receiving ground water with as much as 115 ppm, it appears that the equilibrium concentration of Ca\textsuperscript{2+} in the lake during the warmer months of 1999 was in the range of 30-36 ppm Ca\textsuperscript{2+}.

STREAM FLOW AND PRECIPITATION. The range of calcium concentrations found in the (filtered) stream inflow water, 34-50 ppm, was similar to that found in the lake at site 101. Concentrations at site 101 ranged from 30-36 ppm. Only 1.9 ppm Ca\textsuperscript{2+} was found in the September 2001 (unfiltered) rainfall sample collected adjacent to Siseebakwet Lake. Clearly, direct precipitation on the lake would dilute the concentration of Ca\textsuperscript{2+}, at least temporarily.

GROUND WATER NEAR THE SOUTHERN SHORE. Based on available data presented in the "Local Ground-Water Recharge and Discharge Patterns" section beginning on page 33 and specifically in Figure 14 on page 35, it appears that most of the ground water recharging Siseebakwet Lake is probably entering from south or southwest of the lake. Two wells along the southern shore were sampled to estimate the chemistry of ground water assumed to be entering the lake from the south. Ground water collected from a water-yielding zone about 96-104 ft. below the lake level near the southern shore contained 66 ppm Ca\textsuperscript{2+}. Ground water from a nearby well open to a shallower water-yielding zone, about 45-49 feet below the lake surface, had a Ca\textsuperscript{2+} concentration of 106 ppm.
These differences in calcium content may reflect differences in the hydrogeochemistry of geologic materials encountered along the flow path of water entering the two wells. In any case, if ground water flowing past these two wells enters Siseebakwet Lake, it would either raise the concentration of Ca$^{2+}$ compared to the receiving lake water, drop significant quantities of CaCO$_3$ out of solution or both depending on the chemical equilibrium of the new mix of ground water and lake water. The chemical equilibrium depends on water temperature and pH as well as the concentration of Ca$^{2+}$ and HCO$_3^-$ and other factors in the new mix of water. These factors are discussed in more detail just below in the section on Calcium Carbonate Saturation and Precipitation.

To assess ground water even further along its flow path, just before it enters Siseebakwet Lake, hand-held probes were temporarily pushed just beneath the lake bottom at numerous locations to sample ground water just as it was about to mix with lake water. This point is essentially the interface between the ground-water system and the surface-water system. First, the difference between the total potentiometric head just below the lake bed was compared to the lake water level to assess whether ground water was entering the lake or lake water was exiting into the ground-water flow regime at that location and time. At selected locations and times where ground water was determined to be entering the lake, samples were collected to assess its chemistry and other water-quality related factors. Along the southern shore, Ca$^{2+}$ concentrations in the "ground water" ranged from approximately 67-80 ppm at the interface between ground water and surface water. In all likelihood, these samples represented a mix of mostly ground water with some lake water.

According to lake residents, especially those living near the south shore, at times, water can be seen bubbling up at the shoreline. Some specifically noted heavily-stained water bubbling up near the shoreline in winter. It was also noted that springs originating further back from the south shoreline may also contribute directly to the lake in some areas from time to time. While distinctive and much more highly noticeable as ground water that reaches the surface before entering the lake, for the practical purposes of this study, this water is considered essentially the same water as that evaluated in wells or at the interface between the ground water and the lake bottom.

GROUND WATER NEAR THE NORTHWEST SHORE. One well near the northwest shore was also sampled. Ground water collected from a water-yielding zone at a depth of about 24-32 feet below lake level had a Ca$^{2+}$ concentration of 58 ppm. Ground water samples were also collected using hand-held probes from just below the lake bottom in this general area; these samples contained Ca$^{2+}$ concentrations ranging from about 67 - 115 ppm.

**Calcium Carbonate Saturation and Precipitation**

The chemical formula for calcium carbonate is CaCO$_3$. Under appropriate conditions, calcium ions (Ca$^{2+}$) and carbonate species, such as bicarbonate ions (HCO$_3^-$) and carbonate (CO$_3^{2-}$) ions, combine in lake water to form a solid precipitate called calcium carbonate:

$$\text{Ca}^{2+} + \text{CO}_3^{2-} \rightarrow \text{CaCO}_3$$

(simplified formula)

More details about the chemistry involved are discussed below and in Appendix I - Calcium Carbonate Equilibrium, in the Equilibrium Chemistry Interpretation section beginning on page 166.

**CALCIUM CARBONATE SATURATION.** Lake water normally contains calcium ions (Ca$^{2+}$) and (when the pH is greater than 8.3) carbonate (CO$_3^{2-}$) ions in solution. A wide variety of factors can affect whether or not calcium carbonate will reach or exceed its saturation point in lake water and whether or not a calcium carbonate crystal will re-dissolve as it travels toward or rests on the lake bed. Some
of the primary factors include the pH and temperature of the water plus the concentration of calcium (most typically as Ca\(^{2+}\)) and total inorganic carbon (which can be represented by various species including CO\(_2\), H\(_2\)CO\(_3\), HCO\(_3^-\), CO\(_3^{2-}\)) in lake water.

Wetzel (1983) explains that the concentration of total inorganic carbon is dependent on the pH of the water and the pH is "governed largely by the buffering reactions of carbonic acid and the amount of bicarbonate and carbonate derived from the weathering of rocks [and that] the most important carbonate of aquatic systems is CaCO\(_3\) ..." Therefore, the geochemistry of the surrounding geologic materials, including the lake bottom sediments, plays a major role in controlling the inorganic chemistry of the lake. More details about calcium carbonate saturation can be found in the Calcium Carbonate Saturation section beginning on page 167 of Appendix I.

**PRECIPITATION OF CALCIUM CARBONATE.** To understand or accurately predict precipitation of calcium carbonate, many factors besides the degree of saturation must be considered. Some of these considerations are less well understood or more difficult to quantify; a few of them are discussed directly below. More of these additional factors are discussed further in the Calcium Carbonate Precipitation section beginning on page 169 of Appendix I and listed on page 173 in Table 32 - Summary of Factors Affecting Sedimentation and Precipitation of Calcium Carbonate.

Among the major factors affecting precipitation of calcium carbonate in lake water are water temperature, pH, and the availability of "seed" particles or precipitation sites upon which the reaction can initiate. There may also be important biochemical considerations such as the availability of ample sunlight and the number of appropriate, viable organisms for photosynthesis. With a sufficiently high concentration of calcium carbonate in solution, photosynthesis, as it uses up carbon dioxide, can push the equilibrium over the threshold so that calcium carbonate begins to precipitate.

**WHAT ACTUALLY CAUSES PRECIPITATION OF CALCIUM CARBONATE?** Comparatively speaking, it has not been especially difficult for researchers to determine whether or not a lake is saturated or over-saturated with calcium carbonate. What has really challenged many researchers in the past is understanding the processes that initiate and sustain or stop the precipitation of calcium carbonate. Precipitation of calcium carbonate on a large scale is also referred to as a whitening event or whittings. As late as 1997, Thompson et al. (1997) sums up the situation by quoting Shinn et al. (1989) as saying:

> However, despite numerous studies, both lacustrine and marine whittings have remained a sedimentological dilemma for more than three decades.

Nonetheless, several investigators have essentially concluded that the most important factors are essentially (1) physical-inorganic, i.e., primarily temperature-related or (2) biogenic. As water temperature increases, calcium carbonate solubility decreases which normally results in increased calcium carbonate saturation which in turn favors precipitation. The biogenic factor is usually described in more general terms as a photosynthesis-related process that plays an important role in precipitation of calcium carbonate. It is known that photosynthesis raises the pH in the immediate vicinity of the responsible organisms because CO\(_2\) is removed during photosynthesis; this in turn would also favor precipitation of calcium carbonate. However, it is common in the literature to see statements or inferences that suggest more (biogenically) is going on besides just a pH change. It has also been postulated that having the appropriate type and amount of particulates, "seed particles", precipitation sites or some other type of media upon which the precipitation reaction can initiate might be a key factor.
Although concentrations of various chemical species can be measured to determine whether or not a lake is at or above the saturation point for calcium carbonate, investigators have long been challenged to understand what actually causes precipitation of calcium carbonate to begin or to be sustained. Numerous studies have found certain lakes to be saturated or supersaturated with calcium carbonate all the time or for a large percentage of each year while only precipitating calcium carbonate a fraction of that time. More recent studies give stronger evidence that the onset of large scale precipitation of calcium carbonate in lakes, often referred to as "whiting events", can be attributed to a photosynthesis-driven process. Details about photosynthesis-driven precipitation of calcium carbonate, including specific chemical equations that describe the chemical reactions are included in the section on Calcium Carbonate Precipitation beginning on page 169 of Appendix I.

**RECENT STUDY IDENTIFIES KEY TO CaCO₃ WHITING EVENTS.** A series of long, detailed studies reported by Thompson et al. (1997) appear to have had great success in finally identifying a specific mechanism, even a specific blue-green algae, that is the key to whiting events in a New York State lake. Using advanced technology and highly sophisticated investigative methods, they were able to discover and verify, on a microscopic scale, the biochemical processes that initiated and sustained lake-wide calcium carbonate precipitation. The whiting events worsened Secchi disk transparency from 18 m to only 8 m in three weeks and ultimately to a transparency of only 4.5 m later in the summer.

It should not be assumed that calcium carbonate precipitation in Siseebakwet Lake happens exactly the same as in this heavily studied New York State lake. However, the study by Thompson et al. (1997) provides valuable new insight into the types of processes that might be important in understanding the variability of Siseebakwet Lake water transparency. In addition, the New York State study provides both a hypothesis to consider for how Siseebakwet Lake’s calcium carbonate precipitation process may function and a model for the type of study and technical sophistication that might be necessary if it was desired to scientifically test the hypothesis. Additional information about this study can be found in the section on Calcium Carbonate Precipitation beginning on page 169 of Appendix I.

**Conclusions About Calcium Carbonate Precipitation**

During this study, a considerable amount of information was gathered about the historical and present day distribution of precipitated calcium carbonate in Siseebakwet Lake. Data was also obtained about the concentration of calcium carbonate dissolved in the lake and its source waters in 1999. Since it is clear that significant amounts of calcium carbonate have been precipitating out of the lake water for many years, there is little doubt that precipitation of calcium carbonate has, and does, impact the transparency of Siseebakwet Lake water. However, at this time, we are not able to conclude whether or not or how calcium carbonate precipitation may be responsible for any recent changes in Secchi disk transparency in the 1990s. Discussion about how rates of calcium carbonate precipitation could vary over time and what types of conditions could cause the variability can be found in Appendix I - Calcium Carbonate Equilibrium.

It is possible that additional monitoring and further study could clarify the role of calcium carbonate precipitation on temporal changes in Secchi disk transparency. On the other hand, natural systems such as watersheds, their normal cycles and variations and the complex interactions among chemical, biological, geological and human factors can be difficult to completely understand even with very intensive study. The journal article, Thompson et al. (1997), that alluded to the many years of intensive, highly technical research (via references to important results of related studies) that led up to the successful study by Thompson et al. (1997), cited above, makes that particularly clear.
Having completed this investigation, we do indeed know considerably more about the distribution of calcium carbonate in Siseebakwet Lake. In a word, Siseebakwet Lake is a “marl” lake. According to the U.S. Department Of The Interior, Bureau of Mines (1996), marl is

A soft, grayish to white, earthy or powdery, usually impure, calcium carbonate precipitated on the bottoms of present-day freshwater lakes and ponds, largely through the chemical action of aquatic plants, or forming deposits that underlie marshes, swamps, and bogs that occupy the sites of former (glacial) lakes. The calcium carbonate may range from 90% to less than 30%.

Dean and Megard, 1993, describe marl as follows:

The sediment in these lakes typically contains more than 30% CaCO₃. Such CaCO₃ rich sediment is called marl, and lakes that contain marl are often referred to as marl lakes.

After collection and analysis of a lake bottom sediment core, Siseebakwet Lake sediments were found to be accumulating (and contain) approximately 53% calcium carbonate over hundreds of years. Siseebakwet Lake has long had vast excess amounts of calcium carbonate in “storage” beneath much of the lake and the lake water itself appears to be saturated or over-saturated with calcium carbonate much or most of the time. The following discussion summarizes numerous sources of information that support these conclusions. For additional information on findings related to calcium carbonate, the conditions and processes which are responsible for calcium carbonate precipitation and the creation of marl lakes, sediment trap results and more, see Appendix I - Calcium Carbonate Equilibrium.

Visible Calcium Carbonate Along the Shoreline.

During brief, preliminary reconnaissance work along the lakeshore, it was apparent that in many parts of the lake, rocks and plants were coated with a tan (sometimes stained darker) calcareous encrustation (rocks) or with a white powdery calcareous substance (plants). The photo included with this paragraph shows examples of rocks that are encrusted with calcium carbonate. These rock samples were collected from near the north-central shoreline of Siseebakwet Lake. Although the background in the photo has a similar appearance, it is only the floor covering on a pontoon boat. Calcium carbonate effervesces strongly when exposed to a dilute solution of hydrochloric acid. Many samples of encrusted rocks and plants from the lake were tested with hydrochloric acid and all of them effervesced strongly. Numerous calcium carbonate encrusted samples were identified near the north-central, south-central and western portions of the lakeshore but not near the two stream inlets. Chara, a rooted algal macrophyte known to secrete significant amounts of calcium carbonate, was identified along portions of the northern shoreline and also reacted strongly to hydrochloric acid. Obvious signs of calcium carbonate encrustation on rocks and plants were not observed in the eastern portion of the lake.
Calcium Carbonate In Offshore Locations

SEDIMENT TRAP ACCUMULATIONS. Beginning on June 10, 1999, a sediment trap was suspended by a rope to a depth of roughly 45 ft. from a buoy at site 26, about 1/5 of a mile from the southern shore, to see what accumulated over time. This sediment trap was basically a plastic tube closed on the bottom and open at the top. The tube was checked, cleaned and re-deployed several times during the study at roughly monthly intervals. Each time the tube was checked, July through September, substantial accumulations of a light-brown ooze-like material was observed on the inside and outside of the tube. In July, the light-brown material was described as also having a green tint. Each month, the ooze-like material reacted strongly with hydrochloric acid indicating a relatively high concentration of calcium carbonate.

The amount of ooze-like material accumulated was significantly greater on July 22 and August 24 as compared to September 15, 1999. On September 15, a high concentration of small, light-green, highly active insect-like organisms, barely visible to the naked eye, was noticed in the ooze-like material.

The sediment trap observations suggest that, throughout several months of deployment, calcium carbonate was present in offshore lake water at relatively-shallow depths in sufficient concentrations to precipitate out or otherwise become incorporated into an ooze-like material. The ooze-like material also appeared to contain a significant amount of organic material. These observations, along with the observation of the small, insect-like organisms, suggest that specific biological processing of lake water rich in calcium carbonate may be a key in initiating and controlling transformation of some or much of the calcium carbonate from the dissolved phase to the suspended phase in Siseebakwet Lake. It is not known at this time what effect the small, insect-like organisms have on the equilibrium chemistry of the lake. It is not yet known for sure if the insect-like organisms seen in September were helping to create or to consume the ooze-like material. However, it is well known (see the definition of “marl” above) that aquatic plants can play an important role in precipitation of calcium carbonate.

The ooze-like material found at the sediment trap could possibly be representative of much of the calcium carbonate and organic fractions that combine with silt, clay and other materials to make up the offshore lake bottom sediments described directly below. For more details and a tabular summary of sediment trap results, see Appendix I - Calcium Carbonate Equilibrium.

Lake Bottom Sediment Core: Composition and Age

Lake bottom sediments in the deeper areas away from shore can often reveal a history of what has been settling out of the lake water and falling on the lakebed over the years. A lake bottom sediment core was collected at site LS3 from a depth of 61 ft. below the water surface to analyze its composition and evaluate any trends in its composition over time. Approximately 1000 years of accumulated lake sediments were reviewed in this core.

At the successful sediment core location, LS3, the percent of calcium carbonate (CaCO₃) depositing as lake bottom sediment has remained essentially constant between 52% and 54% of the total sediment as far back as at least 1800, and probably earlier. Partially-recovered cores from two other
preliminary lake bottom sediment core locations appeared similar and had a high calcium carbonate content based on a field test using dilute hydrochloric acid.

Based on data from LS3, it appears that neither the accumulation of lake bottom sediments or the percentage of calcium carbonate accumulating in the sediments have increased significantly since at least 1900.

**TIME TRENDS.** In approximately 1880, an upward trend in sediment accumulation began in the area of the sediment core (LS3). The *rate of increase* in the sediment accumulation rate leveled out by about 1920 but the sediment accumulation rate remained higher than in the pre-1880 period. The rate of sediment accumulation was then fairly stable from 1900 to about 1960 with a slight increase beginning about 1965 - 1970. Then, about 1970 a relatively sharp increase in sediment accumulation began. Between about 1970 and 1990, the *rate of sediment accumulation doubled.* Could this reflect a response to human activity? It is interesting to point out that the total number of residences in the watershed more than doubled from 49 to 122 residences between 1967 and 1984 and continued to increase rapidly until reaching about 180 in 1992.

During the time period from 1800 on, changes in the CaCO₃ accumulation rate closely paralleled the overall sediment accumulation rate. Because of this, the *percent* of the total sediment that was composed of CaCO₃ remained essentially constant from 1800 on. In other words, even though the total amount of sediment accumulating at this location was increasing between 1970 and 1990, the *percent* of CaCO₃ was not increasing. Similarly, the proportions of organic and inorganic matter remained constant.

Even though the rate of sediment accumulation has increased at our single sampling point (LS3), it *appears probable that, on a lake-wide basis, there has not been an increase in sediment accumulation in modern times.* Likewise, *there has not been an increase in the percent of CaCO₃ compared to total sediment accumulation since at least the year 1800.* If the actual amount of particulate matter in the lake as a whole changed significantly over time, it would be very unlikely that the fractions (percents) of the three measured components: 1) organic material, 2) calcium carbonate (CaCO₃) and 3) other inorganic material would stay almost exactly the same over time.

Collection and examination of additional lake bottom sediment cores would be needed to more clearly assess whether or not these preliminary conclusions holds for the lake as a whole. For a more detailed discussion of the lake bottom sediment analysis and interpretation, see Appendix I - Calcium Carbonate Equilibrium.

### Calcium Carbonate Found in Suspension at Siseebakwet Lake

As part of a concurrent but different study (Appendix G - Ground Water and Surface Water Interaction Study), Siseebakwet Lake water from site 101 was collected and filtered in the field through a 0.45 micron pore-size filter to evaluate the calcium carbonate content of materials suspended in the lake water at a depth of about one meter. The material that did not pass through the filter is assumed to represent the suspended solids fraction of Siseebakwet Lake water. Samples from May 13, 1999, and October 11, 1999, were qualitatively analyzed for calcium carbonate content. The analysis indicated that a substantial amount of calcium carbonate was in suspension in Siseebakwet Lake at the times of sample collection. There appears to have been considerably more calcium carbonate in suspension on October 11 compared to May 13. These data provide direct evidence that calcium carbonate was indeed in solution in shallow lake water far from shore at site...
101. It is unlikely that substantial amounts of calcium carbonate traveled from a stream inlet or shoreline to site 101 in the suspended phase. Therefore, it appears that the source of the calcium carbonate at site 101 on these dates was dissolved calcium carbonate that subsequently precipitated out of solution in the lake water. It is important to note that some authors (as noted in Wetzel 1983, p. 206), believe that "appreciable CaCO3 occurs in stable colloidal form in hard water lakes" and that many or all (depending on which size definition is used) colloids are small enough to pass through a 0.45 micron filter.

An additional sample was collected in mid-summer for the same type of analysis but was not able to be analyzed due to a post-sampling filter-handling problem. It was anticipated that the mid-summer sample might show the highest concentration of calcium carbonate in suspension but this theory was not able to be verified.

A less direct but valid method to qualitatively assess the amount of calcium carbonate that is suspended in lake water is to compare the differences in calcium concentrations found in both filtered and unfiltered samples. For a summary comparison and discussion of calcium concentrations found in filtered versus unfiltered samples, see Appendix I - Calcium Carbonate Equilibrium.

**Results of Equilibrium Chemistry Modeling**

Sampling, laboratory analysis and equilibrium chemistry modeling conducted for the Ground Water and Surface Water Interaction Study (Appendix G) provided an independent measure of the status of calcium carbonate in Siisebakwet Lake water. Detailed chemical analyses were performed on lake samples collected in October 1998, May 1999, July 1999 and October 1999. A summary of results for both calcium carbonate (CaCO₃) and dolomite (Ca-Mg)CO₃, is provided in Table 14 - Summary of Calcium Carbonate and Dolomite Saturation Index Values. A saturation index of 0 indicates the lake is at saturation with respect to an individual constituent such as calcium carbonate. Positive values indicate the lake is over-saturated and negative values indicate the lake is under-saturated with respect to the individual constituent. It is assumed that each index calculation includes some amount of error so, when the index values are close to zero, it is difficult to know for sure whether the solution is under- or over-saturated.

**Table 14 - Summary of Calcium Carbonate and Dolomite Saturation Index Values**

<table>
<thead>
<tr>
<th>DATE</th>
<th>SITE 101</th>
<th>SITE 410</th>
<th>SITE 14</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LAKE</td>
<td>GROUND WATER AT</td>
<td>NNW STREAM INLET</td>
</tr>
<tr>
<td>October 1998</td>
<td>0.0/-0.5</td>
<td>-0.5/-1.5</td>
<td>-0.5/-1.7</td>
</tr>
<tr>
<td>May 1999</td>
<td>0.3/0.2</td>
<td>-0.1/-0.5</td>
<td>-0.5/-1.5</td>
</tr>
<tr>
<td>July 1999</td>
<td>0.54/0.85</td>
<td>0.22/0.01</td>
<td>-0.28/-1.01</td>
</tr>
<tr>
<td>October 1999</td>
<td>0.0/-0.4</td>
<td>0.0/-0.4</td>
<td>-0.3/-1.1</td>
</tr>
</tbody>
</table>
Other minerals also precipitate out of Siseebakwet Lake water at times although the amounts of these other minerals precipitated are probably small compared to calcium carbonate. Examples of these other minerals include magnesite (MgCO$_3$) which had a saturation index of 0.31 and huntite (CaMg$_3$(CO$_3$)$_4$) with saturation index of 1.48 both at Siseebakwet Lake site 101 in July 1999.

Rhodochrosite (MnCO$_3$) is also known to precipitate in other Minnesota lakes. Dean and Megard (1993) indicate that it commonly precipitates "at times of overturn" when anoxic [very low dissolved oxygen], manganese (Mn) rich water near the bottom of the lake mix with carbonate rich surface waters, "as well as throughout most of the periods of summer and winter stratification. Coatings or concretions of very dark gray to black minerals observed on rocks and sediments in shallow water in Siseebakwet Lake are consistent with precipitation of rhodochrosite. For example, on September 10, 1998, approximately 60 ft. from the southeast shoreline, black staining on fine-grained lake-bottom sediments was observed in about three feet of water. The sediments had a sulfur-like odor. This odor in this type of setting is indicative of reducing (low oxygen) conditions. In all likelihood, oxygen-poor, manganese-rich ground water was entering the lake bottom in this area and precipitating out manganese in minerals such as rhodochrosite in these sediments as it encountered the (relatively) oxygen-rich lake water.

Field observations in September 1998 included lake-bottom sediments near the surface water outlet that appeared to be stained a deep blue-green color. These stains may represent precipitation of azurite, a blue copper carbonate mineral or malachite, a green copper carbonate mineral. Both of these minerals contain hydroxide (OH) groups in their chemical structure. More OH groups are available in solution as the lake water increases in pH. It would not be surprising to have water that has a relatively high pH and a relatively high dissolved oxygen content near the surface water outlet at times because water in this area can be heavily influenced by photosynthesis as it moves through the lake toward the outlet yet may have the least amount of fresh ground water mixing with it. The surface water outlet is most likely the area least influenced by fresh ground water based on field measurements and area flow patterns: they suggest that the lake is probably losing water to the ground water system in that area. For the most part, the ground water has a lower pH and a lower dissolved oxygen concentration than the lake water.

In September 1998, Red to orange-brown staining of sediments was observed at both the surface water inlet and the surface water outlet in September 1998. The color of these stains suggests precipitation of iron-oxide. Iron oxide often precipitates when water with lower dissolved oxygen mixes with water containing higher dissolved oxygen much in the way that manganese precipitation occurs.

In summary, chemical modeling of the analyses indicates that, at the time of sample collection, Siseebakwet Lake was typically saturated or over-saturated with calcium carbonate on all four sampling dates. The lake appears to have been over-saturated in both calcium carbonate and dolomite on the May and July sampling dates. The NNW inlet stream appears to have been under-saturated with respect to both calcium carbonate and dolomite on all sampling dates.

The very shallow ground water sampling point, site 410, appears to have been very near saturation or under-saturated with respect to both calcium carbonate and dolomite on all sampling dates except for July when it appears to have been over-saturated with respect to calcium carbonate. Site 410 was sampled by pushing a sampling probe intake to a depth just a few feet below the lake bottom.

During the peak of the summer growing season, near-shore plants such as trees and shrubs can withdraw and transpire large quantities of ground water. During July, there is a possibility that the increased evapo-transpiration and associated shallow ground water withdrawals from near-shore plants locally altered or even reversed the (normal) direction of flow between surface water and
ground water temporarily. This is the reason that three of the four ground water sampling events were conducted in fall or spring as opposed to summer. Heavy rainfall in July, which would be expected to raise the lake level sooner than ground water levels, could have also shifted the balance in favor of lake water flowing toward the subsurface. These phenomena could have created a mixture of ground water and surface water at the site 410 sampling intake point and may explain why the saturation index is more similar to lake water than the values for other months.

For a more detailed discussion about calcium carbonate equilibrium chemistry and comparisons of calcium concentrations among filtered and non-filtered samples, see Appendix I - Calcium Carbonate Equilibrium.

CHEMICAL EQUILIBRIUM MODELING METHODS AND ACCURACY OF SATURATION INDICES. The Chemical Equilibrium Model, PHREEQE, was used to calculate saturation indices for all samples; the calculations included adjustments for actual water temperatures as measured in the field. Because field alkalinity titration values did not seem to compare well with laboratory data for other analytes from the October 1998 and May 1999 data sets, laboratory alkalinity titrations were added to allow a check for or comparison to field alkalinity titrations for the July and October 1999 data sets. Estimated alkalinity values, where used for the saturation index calculations, can be seen in the row labeled "Calc Alk (CaCo3)" on Table 26.

Based on this experience, it is suggested that any future similar project include a preliminary study to test for solution stability and acceptable holding times. It may be that, if the solution is over-saturated with calcium carbonate or has some other type of unusual chemical or biochemical characteristics, shorter holding times, a modified titration method or special preservation techniques may be necessary to obtain the most accurate saturation indices.

Various sources of information indicate that even the most sophisticated computerized calculations do not adequately address exceptions that might result in a misleading saturation index value. APHA, AWWA and WPCF (1998, pp. 2-30) cautions: "For this reason, do not consider saturation indices as absolutes. Rather, view them as guides to the behavior of CaCO₃ in aqueous systems and supplement them, wherever possible, with experimentally derived information." Wetzel (1983) notes that "large amounts of inorganic carbon can exist as carbonate [CO₃²⁻] and CaCO₃ in metastable conditions … [and that] … "appreciable CaCO₃ occurs in stable colloidal form in hard-water lakes." These factors and others can make accurate and meaningful calculation of the degree of CaCO₃ saturation difficult in a lake like Siseebakwet Lake.

ADDITIONAL OPTIONS FOR EVALUATING CALCIUM CARBONATE SATURATION INDICES. There are a variety of additional options to estimate or assess whether or not a lake or other water body may be saturated or supersaturated with respect to calcium carbonate. For information about additional methods to evaluate calcium carbonate equilibrium, see Alternate Methods for Evaluating the Degree of Calcium Carbonate Saturation beginning on page 183 in Appendix I - Calcium Carbonate Equilibrium.

CHLOROPHYLL a

Chlorophyll a concentrations provide an estimate of the amount of algal production in a lake. Chlorophyll a concentrations from 10 – 20 µg/L are frequently perceived as a mild algal bloom, while concentrations greater than 30 µg/L may be perceived as a severe nuisance (Heiskary and Walker, 1988). Chlorophyll a concentrations found in the near-surface epilimnion (0 – 2 m zone), the shallow epilimnion (an arbitrarily selected zone between 3.5 - 4 m deep) and the thermocline (found between 7.5 and 16.5 m in this study) are shown on the first page of Table 12 - Site 101 Water-Quality Data for Siseebakwet Lake (May – October 1999): Minnesota Department of Health.
Laboratory. The variation in chlorophyll a concentrations in each of these zones by month is shown in Figure 21 - Chlorophyll a (ppb) May - October 1999 at Siseebakwet Lake, Site 101.

Chlorophyll a concentrations in the near-surface epilimnion (0 – 2 m zone) are routinely monitored at numerous lakes in Minnesota. This activity allows development of databases that can be used to establish typical averages and ranges of chlorophyll a concentrations found in the near-surface epilimnion in various ecoregions of the state. It is uncommon for deeper zones to be monitored for chlorophyll a routinely so the additional impact of chlorophyll a concentrations in deeper zones (that are still shallow enough to affect the Secchi disk reading) on Secchi disk measurements is less well documented.

**Figure 21 - Chlorophyll a (ppb) May - October 1999 at Siseebakwet Lake, Site 101**

**THE NEAR-SURFACE EPILIMNION (0 – 2 M ZONE).** During the summer (June – September) of 1999, chlorophyll a concentrations in the 0 – 2 m zone of the epilimnion at site 101, Siseebakwet Lake, rose slightly but steadily from 1.43 µg/L (June) to 3.09 µg/L (September) with an average of 2.13 µg/L. Spring concentrations in the 0 – 2 m zone, 5.75 µg/L in May, and fall concentrations, 3.80 µg/L in October, were both higher than any of the summer concentrations measured in the 0 – 2 m zone. The increase in chlorophyll a concentrations in October may have resulted from an increase in available phosphorus as result of fall mixing. Increased phosphorus in both May and October, the two months with the coolest epilimnion temperatures by at least 6 °C, may have been due to a slowing or cessation of co-precipitation of phosphorus (out of the lake-water solution) with calcium carbonate.

Compared to typical values for the Northern Lakes and Forests (NLF) Ecoregion reference lakes, as shown in Table 10 - Average Summer Water Quality: Siseebakwet Lake (Based on June – September 1999 Epilimnetic Data at Site 101), the Siseebakwet Lake 1999 summer average for the 0 – 2 m zone is low (2.13 versus 4 – 10 µg/L) and the 1999 summer maximum for Siseebakwet Lake is below the low end of the typical NLF Ecoregion summer average range (3.09 versus 4 – 10 µg/L). The 1999 summer
maximum for Siseebakwet Lake is also very low compared to the typical range of maximum values for the NLF Ecoregion: (3.09 versus <15 µg/L).

**THE SHALLOW EPILIMNION (3.5 - 4 M ZONE).** Chlorophyll a was measured in the shallow epilimnion (a depth of about 3.5 – 4 m) in the months of July through October to see if chlorophyll a was present in significant amounts below the 0 – 2 m zone but shallow enough to still impact Secchi disk readings. Chlorophyll a concentrations in the 3.5 – 4 m zone were actually slightly higher than in the 0 – 2 m zone in each of these months except for September. Chlorophyll a concentrations in this zone paralleled those in the 0 - 2 m zone by increasing steadily through the summer and peaking in October. The highest Chlorophyll a concentration in the 3.5 – 4 m zone was 3.81 µg/L in October. Nonetheless, the chlorophyll a concentrations in this zone were still low compared to the typical range of the typical NLF Ecoregion summer average range in the 0 – 2 m zone of the epilimnion (4 – 10 µg/L).

**THE THERMOCLINE.** Chlorophyll a was measured at the thermocline in the months of June through October to see if chlorophyll a was present at this depth in significant amounts. In some clearer lakes, where sunlight can penetrate with adequate intensity to the thermocline, it has been found that the combination of sunlight and temperature at the thermocline can be quite conducive to algal growth. At Siseebakwet Lake in 1999, chlorophyll a concentrations at the thermocline were highest when the sun's rays were most intense (most directly overhead) in June and decreased steadily through October, the study month in which the sun's rays were least intense.

Chlorophyll a concentrations measured at the thermocline were higher than in both the 0 – 2 m zone and the 3.5 – 4 m zone during July and August. In June when only the 0 – 2 m zone and the thermocline were measured, chlorophyll a concentrations were higher at the thermocline. However, chlorophyll a concentrations measured at the thermocline were lower than in both the 0 – 2 m zone and the 3.5 – 4 m zone during the months of September and October. The highest Chlorophyll a concentration measured at the thermocline was 3.27 µg/L in June. The highest dissolved oxygen concentration recorded in the June depth profile was also at the thermocline depth of 7.5 m. Like the two zones above, the concentrations in this zone were low compared to the typical range of the typical NLF Ecoregion summer average range in the 0 – 2 m zone of the epilimnion (4 – 10 µg/L).

**PHYTOPLANKTON COMPOSITION**

All laboratory assessments of lake water from site 101 reported algal abundance (by volume) as “sparse”. This corresponds well with the relatively low chlorophyll a concentrations reported in the previous section. However, data from less formal visual inspection of some August 1999 raw water samples in original sample collection containers differed significantly from the results of the Minnesota Algal Rapid Assessment (laboratory) method. Substantial quantities of relatively large algae colonies were easily visible to the unaided eye in some August samples. Laboratory assessment indicated that blue green algae were dominant (>50%) in all study months except for the July 1999 sample from the 8m depth where blue green algae were assessed at an even 50% of total algae observed. It is not uncommon that blue green algae stand out when the overall algal abundance is sparse.

*Abundance of Phytoplankton by Date, Depth and Algal Groups*

The relative abundance percent of various types of phytoplankton found at different depths throughout the study period at site 101 in Siseebakwet Lake is illustrated in Figure 22 - Phytoplankton Composition Percent by Depth, Type and Month (1999). The actual percentages found can be seen in. Appendix H - Phytoplankton Composition Percent At Site 101 (1999).
The Minnesota Algal Rapid Assessment method was used by Dr. Howard Markus of the MPCA to evaluate the relative abundance of algae in samples collected at site 101 in Siseebakwet Lake from May to October 1999. Since the absolute abundance of algae was reported as “scarce” in all samples, accuracy of the relative abundance percentages is assumed to be lower than in a circumstance where the algal populations are high. It is also believed that, when chlorophyll a concentrations are low, as in this study, blue green algae may be over-represented by the Minnesota Algal Rapid Assessment method. The relative abundance of algal types expressed as a percent of the total of all algae counted, is discussed below.

Blue-Green Algae

Non-nitrogen-fixing blue-green algae were more abundant than nitrogen-fixing algae. In most samples, the blue-green alga, Anacystis, was most abundant. Anacystis was typically found between 35 to 65% of total algae observed and ranged from 15 to 70% of total algae observed.

The nitrogen-fixing alga, Anabaena, was typically found at 15% of total algae observed. However, it was found at only 5% of the total at the lake surface in October and at the thermocline in both August and October. Anabaena peaked at 25% of total at a depth of 4m in July.

Another blue-green algae, Chroococcus, was not reported in the lake surface (0 – 2 m) zone, but was found in the shallow (3.5 – 4m) zone in July 1999 (20% of total algae observed), August (15%) and October (10%) and deeper at the thermocline in September (5%) and October (20%).

Other Algal Groups

More rarely, diatoms or other (non blue-green) algae were found in substantial relative concentrations. Examples of where an individual taxon represented 15% or more of the relative concentration of Phytoplankton are shown in Table 15 - Non Blue-Green Algae in Substantial % Abundance:

<table>
<thead>
<tr>
<th>Algal Group</th>
<th>Taxon</th>
<th>% Abundance</th>
<th>Date</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other Algae</td>
<td>Peridinium</td>
<td>15%</td>
<td>May 12, 1999</td>
<td>0 - 2 m</td>
</tr>
<tr>
<td>Green Algae</td>
<td>Chlamydommar</td>
<td>20%</td>
<td>June 10, 1999</td>
<td>0 - 2 m</td>
</tr>
<tr>
<td>Diatoms</td>
<td>Centric – 1</td>
<td>15%</td>
<td>July 22, 1999</td>
<td>8 m</td>
</tr>
<tr>
<td>Diatoms</td>
<td>Melosina</td>
<td>15%</td>
<td>August 24, 1999</td>
<td>4 m</td>
</tr>
<tr>
<td>Diatoms</td>
<td>Melosina</td>
<td>15%</td>
<td>October 13, 1999</td>
<td>3.5 m</td>
</tr>
</tbody>
</table>
IN THE MPCA LABORATORY. Of special note are previous observations made on August 31, 1999, while inspecting Siseebakwet Lake samples in the original, untreated sample collection containers used to collect samples on August 24. The author saw abundant algal colonies, estimated at roughly 25 – 50 colonies per liter, that were large enough to be easily visible to the naked eye in the laboratory. The abundance of these colonies had appeared even higher in the field at the time of sample collection. In the Minnesota Pollution Control Agency laboratory, long before the formal laboratory analysis, Ed Swain, Ph.D., identified these bacteria colonies as *Gloeotrichia* a nitrogen-fixing blue-green algae. It is noteworthy that this blue-green algae, occurring in spherical colonies, was observed as very abundant in near surface lake water at the same time and location as a high density of white spots or flecks. And it is particularly interesting to note that in a highly detailed study by Thompson et al. (1997) of another oligotrophic marl lake fed by calcium rich ground water, a spherically-shaped blue-green algae, *Synechococcus* was found to be directly responsible for initiation of whiting events (large scale precipitation of calcium carbonate which can appear as a white precipitate). It was indicated in the 1997 report that the spherical shape of *Synechococcus* and the resulting high surface area was one of the important factors in its effectiveness in precipitating calcium carbonate.

Even though *Gloeotrichia* appeared abundant to the naked eye in raw water samples, they not were identified during the formal laboratory analysis of the subsamples prepared with Lugol’s solution and evaluated by the Minnesota Algal Rapid Assessment method. The sample preparation process apparently produced a sample aliquot for analysis that was unrepresentative of the actual lake water.

FIELD OBSERVATIONS. Both the chlorophyll a and phytoplankton data from laboratory analyses suggested relatively low algal concentrations in Siseebakwet Lake water at site 101 from May through October 1999. However, some field observations did not appear to be consistent with laboratory findings. Siseebakwet Lake did appear relatively free of visible concentrations of algae in most of the lake during most of the study. Nonetheless, there were times when certain locations appeared to have very substantial concentrations of algae or some other particulate matter near the surface. In particular, relatively high concentrations of particulates were observed and described in the central, north-central and western portions of the lake in July and August of 1999. As captured in the inset photograph above, the most dense accumulation of particulates observed on the lake surface during the study was near the NNW inlet in August 1999. The particulates in various parts of the lake were sometimes described as yellow-green and sometimes identified as organisms. At other times and locations, observations indicated predominantly white particulates.

Selected excerpts from field notes highlighting these observations, the presence of film-like materials on the surface, white particulates observed near the surface, etc., are included in Appendix J - Field Observations: Phytoplankton, Particulates.

Although unverified, field observations of particulates that varied in color from white to light green were consistent with the possibility that calcium carbonate particulates and some smaller phytoplankton were sorbed or otherwise attached to each other. Calcite is usually white or colorless in pure form and the most predominant forms of algae are generally a shade of green. Phosphorus, a key nutrient for phytoplankton, is known to co-precipitate with calcium carbonate. Therefore, it would not be surprising to see phytoplankton flourishing while in contact with the precipitated calcium carbonate particles where phosphorus has been concentrated. Subsequent discussions in
this text outline a study where very small blue green algae were found to be responsible for promoting the precipitation of calcium carbonate directly on the algae's surface. A summary of the findings of that study can be found in Appendix I in the middle of the section entitled Calcium Carbonate Precipitation beginning on page 169.

If phosphorous concentrated on calcium carbonate precipitate leads to a concentration of algae, then it might also lead to a concentration of life that feeds on the algae. Indeed, on several occasions where high accumulations of potentially algae-rich particulates were seen near the lake surface, large schools of small fish were also observed among the particulates. In addition, the calcium-carbonate-rich ooze found in the sediment trap suspended at depth at buoy #1 at location 26 (see Figure 4 on page 16) was teeming with insect-like organisms.

Whether or not the potential agglomeration of algae (with colors most often ranging from green to blue-green) with calcium carbonate precipitate is an important contributing factor in creating the characteristic whitish green to deep blue-green appearance associated with marl lakes is an interesting question. Unfortunately, determining the answer is beyond the scope of this report.

SURFACE FILMS AND RELATED PHENOMENA. Film-like accumulations of white particulates at the surface were observed at site 101 on August 24, 1999. Similarly, white particulates and surface film were observed at site 101 on October 10, 1999. The surface film and white particulates could represent a very thin but important zone where phytoplankton activity and calcium carbonate precipitation are interrelated. However, film-like material observed there and at various other locations and times on the lake surface in thin layers would not be expected to show up as clearly (as field observations) in analytical results. Near-surface samples for the Lake Assessment Study were collected using an integrated sampler that integrates water sampled from the 0 - 2m depth range. Samples for the Ground Water and Surface Water Interaction Study collected samples from roughly 0.5 m below the surface.

One possibility is that these films were composed of neuston. Neuston are the microscopic components of pleuston. Pleuston are organisms that have adapted to living at the air-water interface including various species of algae and bacteria in addition to macroscopic organisms such as duckweeds and adult insects. "Often populations of epineustonic organisms become so large that light is reflected from the chromatophores and the water appears to be covered with a dry film of varying coloration" (Wetzel, 1983, p. 139).

Areas covered with a translucent film-like material were observed (September 10, 1998) floating on the water surface at the surface-water outlet. Upon touching the film, it broke up and did not come back together as petroleum-based films are known to do. Based on this simple observation, and its appearance, it is assumed that the film is from a non-petroleum organic source.

At times, other areas of the lake, and most definitely, the stream water approaching the NNW inlet (October 12, 1999), just downstream from an extensive backwater, boggy area, exhibited an appearance of having a transparent surface film on top of the water surface. In places, the presence of the film could only be inferred by an unusual reflection of light and the appearance of near-surface flow patterns in eddy currents that could only be explained by multiphase fluid flow by liquids of different viscosities or varying surface tension. Although it is difficult to put the appearance of this phenomena into words, it is believed the existence of the film is evidenced by the fact that, in the early fall of 1999 (e.g., September 15, 1999), there were numerous "sand rafts" (small patches of sand) observed floating on the lake's surface close to the shoreline just northeast of the NNW inlet. At the same times as the surface film was observed in the NNW inlet, there were very high densities of fingerling-sized fish observed in the stream. The density (of occurrence) of these fish was so high that they gave the appearance of completely filling the stream from bank to bank.
Figure 22 - Phytoplankton Composition Percent by Depth, Type and Month (1999)
TRANSPARENCY OF LAKE WATER

Lake water transparency is commonly measured by following an observation protocol to determine the maximum depth to which a Secchi Disk can be lowered below the lake surface and still remain in clear view by the unaided eye. In typical Minnesota lakes, transparency is generally a function of the amount of algae (phytoplankton) in the water. Suspended solids (other than phytoplankton) or color due to dissolved organic material may also reduce water transparency.

Preceding sections of this report summarize current lake conditions, in general, including some of the factors normally considered to affect transparency. This section focuses more directly on factors that affect transparency. The following section, "Trends in Water Quality and Related Factors", examines longer term patterns in lake characteristics.

Overview: What's Happening at Siseebakwet Lake

The total suspended and inorganic solids values found in Siseebakwet Lake in 1999 are relatively low and comparable to reference lake values in this ecoregion; the chlorophyll \( a \) (indicator of algae abundance) and color values are lower than what is typical for the ecoregion. (Table 10). These levels of color and total suspended solids should not limit water transparency in Siseebakwet Lake.

Although Siseebakwet Lake's 1999 Secchi disk transparency summer mean of 9.8 ft. (3.0 m) and range of 7.0 feet (2.1 m) to a 12.8 ft. (3.9 m) are fairly normal for this ecoregion, they are somewhat poorer (shallower readings) than might be expected with such low average values for total suspended solids, total phosphorus, chlorophyll \( a \) and color.

HOW CAN THE TRANSPARENCY DATA BE EXPLAINED? The results presented in the preceding two paragraphs raise some challenging questions about Siseebakwet Lake water transparency. Two of these questions are highlighted directly below to set the stage for subsequent discussion about transparency in this report:

1. Why doesn't Siseebakwet Lake water transparency correlate to total phosphorus and chlorophyll \( a \) concentrations like most other Minnesota lakes?

2. Why does Siseebakwet Lake water transparency appear to be getting worse in the late 1990s (especially 1996 - 1997)?

Some of the possible explanations include the following:

- precipitation of calcium carbonate in the lake water or the inability to perfectly understand and quantify the impact and variability of the precipitate in the water column
- inability to perfectly quantify other suspended inorganic particulates and their impact on transparency
- presence of significant amounts of algae or other particulate material in the shallow zone just below the zone that is normally monitored (0 - 2 meter depth) but shallow enough to affect Secchi disk measurements
- presence of algae, in forms such as large algal colonies, or other organisms that are not quantified perfectly by field sampling or laboratory analysis techniques
- unintentional bias in Secchi disk measurement dates (timing)
• insufficient frequency of monitoring to understand variability and decipher patterns of factors affecting transparency
• natural variation of other factors that are not well understood
• undetected or undecipherable factors
• other factors not considered

Phytoplankton

Blue-green algae were dominant through much of the summer, but, on average, they were measured at relatively low levels (laboratory results quantified total algae as "sparse" at all times and locations for the entire study), and may have contributed to the perceptions of “not quite crystal clear” coloration noted in observers’ subjective comments. Blue-green algae often form visible blooms near the surface of the water; however, this did not seem to be the case during most sample visits in 1999. These scums are most likely to accumulate near the surface during extended hot and calm periods. As explained above in the “Chlorophyll a” and “Phytoplankton Composition” sections and illustrated in Figure 21 - Chlorophyll a (ppb) May - October 1999 at Siseebakwet Lake, Site 101, average algae concentrations appear to have been fairly low most of the time in 1999 and do not appear to be responsible for reducing average Secchi disk transparency to observed values.

Nonetheless, it should be noted that field observations at some locations and times, July and August 1999, and site 101 and lake water near the NNW inlet in particular, indicated that there were more algae present in the near-surface water than indicated by the laboratory quantification of samples. Near-surface accumulations of these algae and the interspersed white particulate matter were probably dense (prevalent) enough to affect transparency at limited locations and times. Although these easily visible accumulations of algae and associated particulates appeared fairly limited in space and time based on very limited observations, that assumption could be inaccurate as measurement of their horizontal and vertical extent and duration was beyond the scope of this investigation.

In some cases, in near-surface lake water, a nitrogen-fixing blue-green algae, *Gloeotrichia*, was observed in the field in abundance as spherical colonies intermixed with numerous white particulates. Examples of field observations like this can be seen on page 187 of Appendix J - Field Observations: Phytoplankton, Particulates, etc. It is noteworthy that in a highly detailed study by Thompson et al. (1997) of another oligotrophic marl lake fed by calcium rich ground water, a spherically-shaped blue-green algae, *Synechococcus* was found to be directly responsible for initiation of whiting events (large scale precipitation of calcium carbonate which can appear as a white precipitate) leading to a drastic reduction in Secchi disk transparencies. A summary of the findings of that study can be found in Appendix I the middle of the section entitled Calcium Carbonate Precipitation beginning on page 169.

Water Color

Color for Siseebakwet Lake, site 101 averaged 6.7 Pt-Co Units for the study and the summer (May – September) mean was 6.3 Pt-Co. These values indicate little to no coloration due to dissolved or incompletely dissolved organic matter. The inlet streams contained significantly more color than the average lake water. The study (June – October 1999) average color value was 40 Pt-Co Units at the WNW inlet stream and 20 Pt-Co Units at the SW inlet stream. Dilution of stream inflow color by ground water and rainfall inputs to the lake and possibly other processes apparently minimize the impact of stream water color on the lake.
The laboratory color analysis described above, focuses only on color derived from dissolved substances. For a discussion about the appearance of Siseebakwet Lake, including observed color changes, please see the section entitled Changes In Observed Water Color Due To Calcium Carbonate Precipitation, beginning on page 176 in Appendix I.

**Suspended Solids**

Total suspended solids (TSS) averaged 1.8 mg/L for the study and the summer (May – September) mean was 1.7 mg/L. When measured, the “shallow zone” (3.5 – 4m deep) between the surface and the thermocline typically had the highest concentration of suspended solids (Figure 23 - Total Suspended Solids (mg/L): May - October 1999 at Siseebakwet Lake Site 101). Additional laboratory analyses allow differentiation between inorganic and organic (primarily algae) fractions of TSS. The summer mean for total suspended inorganic solids was 0.7 mg/L, but in June, August and October the inorganic suspended solids content was low (0.0 – 0.4 mg/L). The highest concentration of organic (assumed to be mostly algae) suspended solids found was 2.0 mg/L in August. There was no detectable suspended organic matter in July and September.

**THE IMPORTANCE OF EFFECTIVE FILTER PORE SIZE.** It is possible that undetected suspended solids, smaller than the minimum particle size counted in the laboratory suspended solids analysis, could affect lake water transparency. Precipitation of calcium carbonate in the lake water is suspected as a possible contributor of suspended solids that may be small enough (in some cases) to avoid accurate detection by the standard suspended solids test.

Suspended solids analyses were conducted at the Minnesota Department of Health laboratory. They routinely use a filter with a 1.5 micron particle retention size for determinations of suspended solids. Kelts and Hsu (1978) discuss the range of sizes observed for calcium carbonate crystals forming as freshwater lake precipitates and present numerous photographs (scanning electron micrographs). They describe crystal sizes in the 15 to 20 micron range as "large". No precipitated calcium carbonate crystals in this size range would be expected to pass through a filter with a 1.5 micron particle retention size. However, they explain that "high supersaturation levels [of calcium carbonate] apparently cause high nucleation rates which favor the formation of micrite" and describe micrite grains as typically ranging in size from 1-4 microns. They also describe (page 314) calcite crystals ..... produced on nearshore macrophytes as having "fine grained sizes of less than 1 micron". Calcium carbonate precipitate crystals that are approximately 1.5 micron size or smaller, if present in Siseebakwet Lake, may possibly pass through the filters used for total suspended solids analysis. If so, and if the bulk of the precipitate crystals were this small, it could possibly explain the low amounts of suspended solids being reported when other evidence indicates more substantial concentrations of precipitate might be present.
Another factor to consider is that some authors, as indicated in Wetzel (1983, p. 206), believe that "appreciable CaCO₃ occurs in stable colloidal form in hard water lakes". The definition of "colloid" in terms of its size varies depending on the source. Colloids have been described as particles less than 10 microns in size by some authors and between 0.003 and 10 microns by others. A graphical comparison of colloid size versus 0.45 micron filter pore size by Gillham et al. (1983) indicates that the largest colloids would still be considerably smaller than 0.45 microns. In any case it is a real possibility that some or even much CaCO₃ in colloidal form could pass through a 0.45 micron filter.

**Turbidity**

Turbidity is another indicator of lake water transparency because it measures how light is reflected or scattered by particulates in the water. Turbidity depends on both the concentration of the particulates and properties of individual particles such as size and refractive index. Although measurements for turbidity, suspended solids and Secchi disk transparency are related, each of these measurement types employs a different measurement scheme. Since each of these measurement schemes is affected differently by variations in particulate characteristics, they are not quantitatively equivalent.

When turbidity and total dissolved solids data were initially compared to Secchi disk readings for this study, it seemed somewhat inconsistent that neither turbidity nor total dissolved solids data correlated particularly well with Secchi disk measurements. Secchi disk readings varied considerably throughout the study while the other two parameters showed little variability. An explanation was given above for the total dissolved solids data. An explanation for the turbidity data set, based on similar assumptions, is given below.
Based on other studies of lakes with similar chemistry, it is suspected that there may have been large amounts of colloidal calcium carbonate in Siseebakwet Lake water at times. If true, data from a turbidity meter could be misleading because "The light scattered by a particle and therefore the turbidity of a given suspension depends heavily on the size of the particle in question" (Sigrist-Photometer, 2001). Moreover, according to Sigrist-Photometer, 2001:

\[
\text{Above 0.3 microns, the scattered light increases in proportion to the square of the effective cross-section of the particles. In the case of extremely small particles of less than 0.3 microns, the scattered light intensity increases in proportion to the square of the volume, i.e., raised to the sixth power of the diameter (dipole radiation).}
\]

Figure 24 - Scattered Light Intensity vs. Particle Size illustrates how, the smaller the particle size, the smaller the measured response for scattered light intensity would be on an instrument such as a turbidity meter; this is especially true for particles smaller than about 0.3 microns.

Therefore, even if Siseebakwet Lake had relatively large amounts of very small (less than about 0.3 microns diameter) calcium carbonate particulates in suspension, as was determined in studies of other similar lakes, then, for the most part, these smaller particulates would not be expected to have been detected in either total dissolved solids tests or turbidity meter measurements made during this study. This is apparently the reason why there does not appear to be a strong correlation between Secchi disk transparency and values for total dissolved solids and turbidity.

Summary discussions of laboratory turbidity measurements and then field turbidity measurements are presented below. In both cases, most turbidity measurements at site 101 were quite low and relatively near the method or instrument detection limit. The highest turbidities for site 101 were recorded in the field. Potential explanations for numerical differences between laboratory and field measurements could be due to various factors including differences in instrument accuracies, precision, calibration, operator proficiency, etc. Differences could also be due to the dynamics of the lake such as
potentially rapid changes in turbidity or heterogeneous distributions of turbidity over relatively small areas. Finally, degradation of samples before analysis in the laboratory could explain differences.

LABORATORY TURBIDITY MEASUREMENTS. Although all the laboratory turbidity measurements for this project were very low at site 101, it was highest during July and August at all depths measured as shown in Figure 25 - Laboratory Turbidity (NTU): May - October 1999 at Siseebakwet Lake Site 101. In general, turbidity was highest in the “shallow zone” from about 3.5 to 4 m deep. The laboratory turbidity measurements from this study suggest that, at the time and place of the turbidity measurements, turbidity was too low to have had a significant negative impact on lake water transparency. Nonetheless, it should not be assumed that a laboratory turbidity measurement perfectly represents the turbidity in the lake at the time of sample collection. Laboratory turbidity measurements can be misleading. Furthermore, it should not be assumed that turbidity will correlate perfectly with Secchi Disk transparency measurements.

FIELD TURBIDITY MEASUREMENTS. Field turbidity measurements were made at various locations and depths during the July and August 2001 sampling events. Although significant concentrations of particulates were observed at the lake’s surface and appeared to extend down to the Secchi disk depth at site 101 during the July and August 1999 sampling events (Appendix J - Field Observations: Phytoplankton, Particulates, etc. on page 187), field turbidities measured at site 101 were relatively low except for one measurement of 12.3 NTU measured near the 2 m depth in late August.

In general, for the July and August sampling events, the near-shore measurement locations had higher turbidities than at site 101 which is located far from shore in the deepest part of the lake. This may be because bottom sediments (including precipitated calcium carbonate particulates) in shallower, near-shore areas are regularly agitated and may be re-suspended by wave action. Excluding locations near the surface water inlets, field turbidities measured in July and August, 1999, at sites other than 101 typically ranged from approximately 4.5 to 6.5 NTU.
Measurements on July 22, 2001, at site 101 between 2 to 8 m deep ranged from 2.6 to 3.7 NTU. The highest reading between 2 and 25 m deep was 4.4 NTU at a depth of 10 m. The Secchi disk depth recorded with these measurements at site 101 was 2.1 m (7 ft.), representing the worst transparency measured by MPCA during this study. The two turbidity measurements made at the (comparable) 2 m depth were 2.6 and 3.1 NTU. Turbidity was measured at 100 NTU at the NNW and 267 NTUs at the SW Inlet.

On August 24, 1999, at site 101, field turbidity was 12.3 NTU at a 2.1 m depth and 1.1 NTU at 3 m deep. The 12.3 NTU reading was the only field turbidity measurement at site 101 (significantly above the lake bed) where the field turbidity appeared significantly elevated. Since the turbidity meter has increased sensitivity to larger particles as described above, it is probably no coincidence that the highest near-surface turbidity reading occurred at the same time that large amounts of particulates were visible to the unaided eye at the surface. The Secchi disk depth recorded with these measurements at site 101 was 2.8 m.

During the site 101 depth profiling field measurements beginning at noon on August 24 between the 4 and 12 m depths, the highest turbidity reading was only 2.1 NTU and below that, down to a 29 m depth, all turbidity readings were 0 NTU. When re-visiting site 101 hours later at approximately 5:38 PM the same day, turbidity near the 2 m depth had decreased from 12.3 to 5.5 NTU. In the same time frame, turbidity at the 11 m depth increased from 0.5 to 5.4 NTU. One of many possible explanations for these changes is that some or most of the particulate matter, possibly the largest or heaviest particles located near the 2 m depth around noon had sunk deeper to at least the 11 m depth by 5:38 PM that day.
On August 24, 1999, the field turbidity at site 6, located in Siseebakwet Lake just east of the SW inlet was 43 NTU. Site 6 is so close to the SW inlet that it is probably too strongly influenced by the inlet to be considered as representative of normal lake conditions in terms of turbidity. However, August 24 is the same day that the overall lake surface appeared to have higher densities of algae and other particulate matter near the surface than on any other day of the study.

Secchi Disk Transparency Measurements

A comparison of Secchi Disk transparency measurements from a variety of sources for Siseebakwet Lake 1999 (Table 16 - Comparison of 1999 Secchi Disk Transparency Data Sets) provides some insight on the variability and reliability of measurements due to a variety of factors. Differences in measurements made at different dates and at different locations on the lake are likely to reflect real differences in transparency. However, even when two researchers make simultaneous measurements side by side, some variability is expected due to the subjectivity of the measurement and differences in operator perception. Additional details and plots of each data set are presented below.

Table 16 - Comparison of 1999 Secchi Disk Transparency Data Sets

<table>
<thead>
<tr>
<th>DATA SET</th>
<th>TRANSPARENCY RANGE (FT.)</th>
<th>SUMMER MEAN (FT.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPCA Site 101</td>
<td>7.0 (July 22) – 12.8 (June 10)</td>
<td>9.8</td>
</tr>
<tr>
<td>CLMP Site 101</td>
<td>6.5 (Sept. 1) – 14.5 (June 14 &amp; 23)</td>
<td>10.3</td>
</tr>
<tr>
<td>CLMP Site 203</td>
<td>7.5 (Sept. 2) – 16.0 (Sept. 27)</td>
<td>12.6</td>
</tr>
<tr>
<td>Northern Lakes and Forests Ecoregion: Reference Lakes</td>
<td>8 – 15 (based on 25th to 75th percentile for ecoregion)</td>
<td></td>
</tr>
</tbody>
</table>

MPCA Secchi Disk Measurements at Site 101. MPCA Secchi disk transparency measurements on Siseebakwet Lake at site 101 ranged from a minimum of 7.0 feet (2.1 m) in July to a maximum of 12.8 ft. (3.9 m) in June (Figure 26 - Siseebakwet Lake 1999 MPCA Secchi Disk Transparency at Site 101).
Figure 26 - Siseebakwet Lake 1999 MPCA Secchi Disk Transparency at Site 101

Figure 27 - CLMP Secchi Disk Transparency Measurements at Site 101, 1999
These transparency measures are similar to the expected range of values for reference lakes in the NLF ecoregion: 8 – 15 ft. (Table 10). The Secchi disk transparency summer (June – September) mean was 9.8 ft. (3.0 m).

CLMP SECCHI DISK MEASUREMENTS AT SITE 101. CLMP (Citizens Lake Monitoring Program) Secchi disk data are presented here for comparison purposes; the MPCA data will be used for summer mean and trophic status indicators in this report. CLMP transparency measurements on Siseebakwet Lake at site 101 ranged from a minimum of 6.5 feet (2.0 m) on September 1 to a maximum of 14.5 ft. (4.4 m) in mid June (Figure 27 - CLMP Secchi Disk Transparency Measurements at Site 101, 1999). These transparency measures are also similar to the expected range of values for reference lakes in the NLF ecoregion: 8 – 15 ft. (Table 10).

The Secchi disk transparency summer mean for the CLMP data at site 101 was 10.3 ft. (3.1 m). This indicates a slightly better transparency (more highly transparent water) compared to the MPCA data but the difference in these data sets is small enough that none of the conclusions presented in this report would be changed by considering the CLMP data instead of the MPCA data. The primary reason that the CLMP summer mean indicates a better transparency is that there were four readings averaging 14.25 ft. recorded in June and during the same time period, the MPCA summer mean calculation only includes one measurement of 12.8 ft. (June 10).

CLMP SECCHI DISK MEASUREMENTS AT SITE 203. Secchi disk transparency data were also collected at site 203 (Figure 28) to compare Secchi disk measurements from two different locations on Siseebakwet Lake in 1999. The MPCA data from site 101 will be used for summer mean and trophic status indicators in this report. Site 203 measurements ranged from a minimum of 7.5 ft. (2.3 m) on September 2 to a maximum of 16.0 (4.9 m) ft on September 27. A secondary low of 8.0 ft. (2.4 m) was also measured on August 2. These transparency measurements are also similar to the expected range of values for reference lakes in the NLF ecoregion: 8 – 15 ft. (Table 10). The Secchi disk transparency summer mean for the CLMP data at site 203 was 12.6 ft. (3.8 m)
It is normal and expected that Secchi Disk measurements from a given lake will vary from day to day and even at the same moment at different locations based on variability throughout the lake, unavoidable inaccuracies in the method, normal differences between operators and other factors.

Comparison of the Secchi disk transparency summer means indicates there were more highly transparent lake water conditions in the west-southwestern portion of Siseebakwet Lake at site 203 than at site 101 regardless of which data set (CLMP or MPCA) is used for site 101.

CLMP site 101 transparency data, which included several more monthly measurements than the single MPCA monthly measurements, is more similar to the site 203 data in terms of reflecting short term changes in transparency throughout the study period. CLMP data for both site 101 and 203 show a rapid deterioration in transparencies between early July and the beginning of August with a strong and very rapid improvement between early and mid September. The data set which only includes single monthly measurements made by the MPCA does not have enough data points to clearly define when the rapid changes in transparency occurred.

For information about historical trends in Secchi disk readings at Siseebakwet Lake, see the Transparency discussion beginning on page 109 of the Trends in Water Quality and Related Factors section.
Subjective Measures of Transparency and Related Observations

Along with CLMP transparency measurements, subjective measures of Siseebakwet Lake’s "physical appearance" and "recreational suitability" were made by the CLMP observer. Physical appearance ratings range from "crystal clear" (Class 1) ... to "dense algal blooms, odor, etc." (Class 5) and recreational suitability ratings range from "beautiful, could not be any nicer" (Class 1) ... to "no recreation possible" (Class 5) in this rating system (Heiskary and Wilson, 1988).

From May 6 through October 11, 1999, lake conditions at site 101 were typically characterized as follows:

- **Physical Condition** - "not quite crystal clear – some algae present" (Class 2)
- **Suitability for Recreation** - “very minor aesthetic problems” (Class 2) and sometimes “beautiful, could not be nicer” (Class 1)

However, a substantial number of quite different conditions were observed in July, August, September and October in various, usually limited, locations on the lake or inlet streams. A few example excerpts are included directly below, but the details, including many more significant observations are presented in Appendix J - Field Observations: Phytoplankton, Particulates.

- July: relatively dense concentrations of particulate matter, many bright spots and yellow to olive-green sphere-shaped organisms
- August: high algae levels with limited clarity and/or mild odor apparent (see photo showing oar over water coated with algae).
- September: clear film or oily liquid coating the surface of the water.; numerous “rafts” of sand, up to about one-inch long, were observed floating on the surface of the lake
- October: significant amount of “white specs” were observed

Typical Seasonal Trends in Lake Transparency

The change in the transparency of Siseebakwet Lake over the course of the summer is fairly typical for lakes in Minnesota. Typically, transparency is high in the spring when the water is cool and algae populations are low. Frequently, zooplankton (small crustaceans which feed on algae) populations are high at this time of year also, but will decline later in the summer because of predation by young fish. As the summer proceeds, the waters warm and the algae make use of available nutrients. As the algae become more abundant, the transparency declines. The decrease in the abundance of zooplankton may allow for further increases in the amount of algae. Later in the summer, surface blooms of algae may appear. On a day-to-day basis, transparency may differ between the sites measured, but the overall pattern is normally fairly consistent.

Zooplankton (*Daphnia*)
As discussed in the Transparency of Lake Water section beginning on page 85, there are several interrelated factors that affect transparency. Figure 29 - Relationships Between Transparency and Related Factors: Site 101 Epilimnion - May to October 1999, illustrates how some of these factors correlated with transparency and with each other. MPCA Secchi disk measurements were used for this comparison. Total suspended solids concentrations are not plotted here but, much like the related factor, (laboratory) turbidity, total suspended solids concentrations in the 0 - 2 m depth zone of the epilimnion were relatively low, often near the minimum laboratory reporting limit of 1 mg/L, and showed little variation (1.2 - 2.8 ppm) throughout the study period. Similarly, chlorophyll a, and total phosphorus data were quite low and showed little variation. These facts make it difficult to assess whether reported differences in these criteria throughout the study period were due to real differences in the environmental system or simply due to normal variation in the magnitude of sampling and analytical errors (normal limitations on precision).

It is believed that much of the total suspended solids in Sisebakwet Lake occur in the form of colloidal calcium carbonate precipitate comprised of particulates so small that conventional methods for measuring suspended solids and turbidity fail to quantify them. It was explained in the Suspended Solids section on page 87 that many or most of these particulates may have passed through the 1.5 micron effective pore-size filters used for the total suspended solids analyses. In the
Turbidity section on page 88, it was explained that many or most of these particulates may have been too small to be detected even semi-quantitatively by the turbidity meter. If these assumptions are correct, strong correlation between reported total suspended solids, turbidity and Secchi disk transparency would not be expected in Siseebakwet Lake.

CORRELATION BETWEEN TRANSPARENCY AND RELATED FACTORS. There does not appear to be a particularly strong correlation between transparency and related factors in this 1999 epilimnion data. Since there was not a high degree of variability observed in these data sets, any actual correlation might be expected to appear fairly subtle. There does appear to be some correlation between total phosphorus and transparency, however, the correlation is the opposite of what is normally expected. Worsened transparency would normally be expected in response to elevated phosphorus concentrations because phosphorus encourages the growth of phytoplankton. However, as shown in Figure 29, transparency is actually better at the beginning and end of the study when phosphorus levels were slightly higher. During the middle of the study, June 10 through September 15, total phosphorus concentrations were slightly lower but transparency was at its worst of the study period.

The combination of higher lake-water temperatures and relatively high solar insolation during this (June 10 September 15) period normally encourages increased phytoplankton growth. Therefore one might assume that increased consumption of phosphorus by phytoplankton explains the lowering of phosphorus during the middle of the sampling period. But Chlorophyll a, used as an indicator of phytoplankton productivity, instead decreased about 4 ppb from May to June and from June through October it slowly rose from about 2 ppb to only about 4 ppb. Therefore, phytoplankton growth does not appear to explain the pattern of total phosphorus concentrations or to have been a substantial factor in Secchi disk transparency changes. There is, however, another explanation for the seasonal patterns in total phosphorus and Secchi disk transparency.

CO-PRECIPITATION OF CALCIUM CARBONATE AND PHOSPHORUS. A probable explanation for these data is that calcium carbonate precipitation increased during the middle of the sampling period as rising water temperatures and increased phytoplankton photosynthesis drove the process of calcium carbonate precipitation. Increased calcium carbonate precipitation would not only worsen transparency by "clouding" the water with calcium carbonate particulates but could also reduce phosphorus concentrations by co-precipitation of phosphorus (out of the lake water solution). Phytoplankton growth may have been limited because co-precipitation of phosphorus reduced the available supply of this critical, growth limiting nutrient. Total dissolved solids and turbidity apparently did not correlate well with Secchi disk transparency because of the technical limitations on detecting very small, colloidal-sized particles as explained above.

A CLOSER LOOK AT TRANSPARENCY RELATED FACTORS. Figure 30 - Reciprocal Transparency vs. Related Factors: Site 101 Epilimnion - May to October 1999 is presented to provide an alternate view of this data set. The transparency values are shown as the absolute value of reciprocal transparency (1/transparency) multiplied by 100 and turbidity has been multiplied by 3. These transformations were made to allow a clearer graphical comparison among these transparency-related factors. In this view it is easier to see that the trends for reciprocal transparency and total phosphorus are opposite from at least July through October. Because an exact concentration was not available for phosphorus in June, it is unknown whether the apparent trends in these two variables paralleled each other between May and June or whether the pattern of opposite trends began in June or July.
This view suggests a possible correlation between laboratory turbidity and reciprocal Secchi disk transparency. However, the danger in multiplying the turbidity by 3 in this view is that it makes barely measurable differences in turbidity appear to be substantial differences. Therefore it may be over-interpretation of the data to draw any conclusions about the relationship between reciprocal transparency and turbidity.

SEASONAL TRENDS IN TRANSPARENCY-RELATED FACTORS. Chlorophyll a and reciprocal transparency are expected to exhibit a strong positive correlation with each other in typical Minnesota lakes. Therefore it is interesting to note that both are decreasing between May and June but trending in opposite directions between July and October. Based on direct visual observation during field work on the sampling dates, the lake appeared mostly gray or blue-gray on the May and June sampling dates. However, on the sampling dates in July and especially in August, the lake exhibited deep shades of green and substantial accumulations of particulates were observed in parts of the lake. Total (unfiltered) calcium concentrations were higher in June (89 ppm as CaCO3) and July (82 ppm) compared to August (74 ppm) and September (75 ppm).

These data may indicate that, sometime in late June or early July, large scale precipitation of calcium carbonate began, increasing reciprocal transparency by clouding the water with (possibly) small-sized calcium carbonate particulates and reducing total phosphorus as it co-precipitated along with the calcium carbonate. Given that July 22 marks the date of the lowest total phosphorus concentration measured in the 0 - 2 m depth zone (0.007 ppm) and also the highest (worst) reciprocal transparency measurement, it may represent the closest sampling date to a peak of calcium carbonate precipitation in the site 101 area. The complete CLMP Secchi disk transparency data set for site 101 (Figure 27) indicates that significantly poorer transparencies were observed between about mid July to mid
in September and that very substantially poorer transparencies were observed between about July 22 until the beginning of September.

Although CLMP Secchi disk transparencies at site 203 (Figure 28) were also at their worst between mid July to mid September, transparency actually improved at site 203 in mid to late August.

SETTLING OF CALCIUM CARBONATE PARTICULATES. Based on data from site 101, calcium carbonate precipitation and, photosynthesis, believed to drive the calcium carbonate precipitation process, may have begun to slow by late August (August 24 sampling date) allowing total phosphorus concentrations to begin to rise again. However, (possibly) because the very small-sized calcium carbonate particulates can take a long time to settle out and sink to deeper waters, reciprocal transparency was still recovering to the June level through October.

July 22, 1999, field measurements at site 101 appear to be consistent with this assumption as they indicated that turbidity increased steadily at successive one-meter depth intervals from 2.6 - 3.1 NTU at the 2 m depth to 3.7 NTU at a depth of 6 m.

Field turbidity measurements made at site 101 on August 24, 1999, were dissimilar, with a reading of 12.3 NTU at a depth of 2.1 meters and much lower values without a clear trend below that point. However, readings made later in the day at site 101 at the same depths indicated either rapidly changing conditions or difficulties in obtaining meaningful measurements. For example, the reading at the 1.9 meter depth five hours later, yielded a value of 5.5 NTU compared the 12.3 NTU value measured at 2.1 meters earlier. Since these turbidity measurements probably were not sensitive to very small particulates, as explained above, the turbidity trends observed may primarily represent the larger particulates.

The lake still exhibited an olive green color in September but there appeared to be considerably less particulates at the lake surface. The laboratory turbidity data trends, if significant, indicate that turbidity in the 0 - 2 m depth zone was elevated during the period described above as having the maximum amount of calcium carbonate precipitation. The recovery of turbidity in the 0 - 2 m depth zone to its minimum sooner than reciprocal transparency may indicate that much of the particulates had settled to below 2 m but were still shallow enough to affect Secchi disk measurements.

COMPARING SISEEBAKWET LAKE TO OTHER LAKES. The following section about trophic status discusses a system commonly used to evaluate, compare and categorize lakes based on statistical norms and typical relationships among total phosphorus concentration, chlorophyll a concentration and Secchi disk transparency. In particular, this system was not designed to accommodate the impact of substantial amounts of suspended particulates on lake transparency nor was it designed to accommodate phenomena such as co-precipitation of phosphorus with large scale calcium carbonate whiting events. In light of the data and discussion presented above, organizations taking an active role in managing and protecting Siseebakwet Lake and its watershed may want to consider using a supplementary or alternate approach to evaluating the status of the lake that is more tailored to its marl-lake "personality". Since Siseebakwet Lake understandably does not reflect the typical relationships among total phosphorus concentration, chlorophyll a concentration and Secchi disk transparency found in ordinary (non-marl) lakes, a supplementary or alternate approach to monitoring the lake’s status over time may be more useful.

Megard (1999) describes how a combination of Secchi disk readings and laboratory analyses combined with statistical analysis can be used to identify the relative optical importance of phytoplankton, inorganic particles and dissolved organic carbon in determining the transparency of a specific lake. This information helps to clarify which substances are most responsible for causing changes of light attenuation and for affecting visual perceptions of water quality. This type of
analysis may help those interested in monitoring and protecting the lake to decide which monitoring parameters and what monitoring techniques would be most beneficial. In turn, this could help interested parties focus their efforts on the type of monitoring that will provide the most useful information for Siseebakwet Lake.

**TROPHIC STATUS**

One means to evaluate trophic status a lake and to interpret the relationship between total phosphorus, chlorophyll a and Secchi disk readings is Carlson’s Trophic State Index (TSI) (Carlson 1977). This index was developed from the interrelationships of summer Secchi disk transparency and the concentrations of surface water chlorophyll a and total phosphorus. TSI values are calculated as follows:

- Total phosphorus TSI (TSIP) = 14.42 ln (TP) + 4.15
- Chlorophyll a TSI (TSIC) = 9.81 ln (Chl-a) + 30.6
- Secchi disk TSI (TSIS) = 60 - 14.41 ln (SD)

Total phosphorus (TP) and chlorophyll a are in µg/L and Secchi disk transparency is in meters. TSI values range from 0 (ultra-oligotrophic) to 100 (hypereutrophic). In this index, each increase of ten units represents a doubling of algal biomass.

**TROPHIC VARIABLES AVERAGES.** Average values for the trophic variables in Siseebakwet Lake and respective TSIs are listed in Table 17 - Trophic Status Indicators for Siseebakwet Lake 1999 and displayed on bar graphs in Figure 31 - Carlson’s Trophic State Index for Siseebakwet Lake. Based on these values, Siseebakwet Lake is oligotrophic but may be close to being a mesotrophic lake. The mean TSI of 39 ranks Siseebakwet Lake at the 75 th percentile relative to 1,223 other lakes in the NLF ecoregion. This implies that relative to lakes in the NLF, only 25 percent had a lower mean TSI value. The individual TSI value for Secchi (TSIS = 44) does not agree especially well with the individual TP (TSIP = 34) and chlorophyll a (TSIC = 38) TSI values. For example, the TP TSI value is more indicative of an oligotrophic lake but the Secchi TSI value is more consistent with that of a somewhat mesotrophic lake. This implies that Secchi transparency cannot be relied upon to provide a good estimation of trophic status for Siseebakwet Lake.

**Table 17 - Trophic Status Indicators for Siseebakwet Lake 1999**

<table>
<thead>
<tr>
<th></th>
<th>CARLSON’S TSI</th>
<th>PERCENTILE FOR NLF ECOREGION</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>35</td>
<td>90 th</td>
</tr>
<tr>
<td>Chl a</td>
<td>38</td>
<td>80 th</td>
</tr>
<tr>
<td>Secchi</td>
<td>44</td>
<td>50 th</td>
</tr>
<tr>
<td>Mean (All) TSI</td>
<td>39</td>
<td>75 th</td>
</tr>
</tbody>
</table>

1 Relative to approximately 1,223 assessed lakes in the North Lakes and Forests Ecoregion, whereby the lower the trophic state (TSI), the higher the percentile ranking (100 percent level implies lowest TP or deepest Secchi disk for that ecoregion).
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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NLF Ecoregion Range: ............................................. Siseebakwet Lake: ●

*Figure 31 - Carlson’s Trophic State Index for Siseebakwet Lake*
SISEEBAKWET LAKE CHARACTERISTICS VS. TYPICAL NLF ECOREGION VALUES. The summer mean of measurements for Secchi, alkalinity, total suspended solids (TSS), total suspended inorganic solids and turbidity, were within the typical range of expected values for the NLF reference lakes. Measurements of TP, chlorophyll a, total Kjeldahl nitrogen and color were below the typical range of expected values for the NLF ecoregion. Siseebakwet Lake values for pH, chloride, specific conductance and the ratio of total nitrogen to total phosphorus were above the typical range of expected values for the NLF ecoregion. The color value of 6.3 Pt-Co units indicates clear water and little influence from “bog staining,” which is more common in lakes which have a lot of wetlands in their watershed.

SUSPENDED VS. DISSOLVED CONTENT IN THE LAKE WATER. The TSS and total suspended inorganic solids values are low as is typical in the NLF ecoregion (Table 10 on page 52). These two parameters measure the amount of suspended materials in the water. TSS includes both organic matter, such as algae, and inorganic matter, such as suspended soil or clay particles. The values for total suspended inorganic solids do not include algae or other suspended organic matter. In contrast to these measurements of suspended matter, several parameters that reflect the dissolved inorganic content of the lake water, namely conductivity, chloride and alkalinity, are relatively high for this ecoregion.

TRENDS IN WATER QUALITY AND RELATED FACTORS

In this section, historical data for Siseebakwet Lake from a variety of sources are compared in an attempt to evaluate possible trends in factors that affect the long term quality of the lake. The MPCA respects the work of other environmental investigators but knows considerably less about the comparability and reliability of data generated for some of these reports compared to projects where the MPCA is directly involved. Nonetheless, it is valuable to look at a variety of data sets over time to see if they can collectively provide insight to trends in water quality and related factors. When evaluating the data sets presented below, we suggest that readers be cautious and use their own judgement especially where data sets from different sources are compared.

EXTERNAL SOURCES OF INFORMATION

NATIONAL BIOCENTRIC, INC. (1972). In 1972, National Biocentric, Inc. (1972) conducted studies of Midwestern lakes and streams that included several lakes in Itasca County in 1972. They described Siseebakwet Lake (referred to as “Sugar Lake”) as

“… one of the strikingly clear water lakes in Itasca County. Secchi disk readings of greater than 20 feet were observed. …. Some pressure is already observed as illustrated by higher phosphate, ammonia and coliform readings along the south shore and in the north west corner. These higher readings may suggest that the homes in this area do not have adequate septic tanks and drain fields or may be suggestive of higher applications of lawn fertilizer. It is particularly interesting to observe the temperature and oxygen profile in Sugar Lake. … we did not observe a decline in oxygen level associated with the decline in temperature at 25 feet.”
They sampled at six locations around the lake, none of which were particularly close to the middle or to the deepest part of the lake. Their location “B”, described as “North east” is probably most equivalent to site 101 for comparative purposes.

WHITEFORD (1985). The Whiteford report features 1984 data including eight measurements between June 13 and September 29 and one measurement on October 13 at three lake locations, the two lake inlets and the outlet. The in-lake locations were designated NE, SW and NW. Measurements reported by Whiteford at location ‘NE”, roughly 0.4 miles northeast of the center of the lake, are probably the most equivalent to site 101 for comparative purposes. The data set includes pH, total phosphorus, chlorophyll a, Secchi disk transparency, temperature and dissolved oxygen. Whiteford also references 1980 Secchi disk transparency data from a report by Eastlund (1981) (now unavailable) and 1983 and 1985 data, apparently collected by Whiteford, that help fill a data gap for these years.

MINNESOTA DEPARTMENT OF NATURAL RESOURCES. Several years of (limited) historical data sets were provided by the Minnesota Department of Natural Resources, Ecological Services.


PHOSPHORUS

Historical phosphorus data for Sisebakwet Lake are shown in Table 18 - Historical Surface Phosphorus Data (1954 - 1999). It is believed that all of these data sets represent phosphorus concentrations found in samples collected near the lake surface. These data sets are somewhat difficult to evaluate for trends due to several factors that limit comparability. Little is known about sampling and laboratory analysis methodologies in some cases. Sampling locations vary from year to year or are unknown, some values are annual averages, some are single measurements. In some cases, summer averages were available but, to keep the comparison simple, only annual averages are shown in the table. In this context, "annual average" means the average of all data available for the calendar year. The reader is cautioned not to over-interpret any potential trend implied by Table 18 as some of these data may have uncertainty and errors associated with them that may be similar in magnitude to the differences between numbers shown in the table.
## Table 18 - Historical Surface Phosphorus Data (1954 - 1999)

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>SITE</th>
<th>DATA SET TYPE</th>
<th>DATE</th>
<th>TOTAL PHOSPHORUS (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNR (in Itasca SWCD, 1992)</td>
<td>Unknown</td>
<td>unknown</td>
<td>1954</td>
<td>10</td>
</tr>
<tr>
<td>National Biocentric (1972)</td>
<td>B - Northeast</td>
<td>annual average</td>
<td>1972</td>
<td>(74)*</td>
</tr>
<tr>
<td>STORET Data Base</td>
<td>101</td>
<td>single measurement</td>
<td>1981</td>
<td>10</td>
</tr>
<tr>
<td>Whiteford 1985</td>
<td>NE</td>
<td>annual average</td>
<td>1984</td>
<td>23</td>
</tr>
<tr>
<td>DNR Ecol. Svs.(2000b)</td>
<td>101</td>
<td>single measurement</td>
<td>1984</td>
<td>10</td>
</tr>
<tr>
<td>Itasca SWCD (1992)</td>
<td>101</td>
<td>annual average</td>
<td>1992</td>
<td>8</td>
</tr>
<tr>
<td>DNR Ecol. Svs.(2000b)</td>
<td>101</td>
<td>single measurement</td>
<td>1994</td>
<td>14</td>
</tr>
<tr>
<td>MPCA (1999 Data)</td>
<td>101</td>
<td>annual average</td>
<td>1999</td>
<td>10</td>
</tr>
</tbody>
</table>

* Reported as available phosphate, filtered (please see report text for more details.)

**INTERPRETATION.** Based on the limited data in Table 18, it is difficult to verify a clear temporal trend in phosphorus concentrations. However, it is possible that the relatively low 1954 concentration may indicate low phosphorus associated with limited development of the lakeshore. Higher annual averages found in 1972 and 1984 may indicate phosphorus problems that came with increased lakeshore development. The low phosphorus concentrations in the 1990s could possibly reflect efforts by the lake owners association and individual residents to limit nutrient loading to the lake by improving or replacing septic systems, implementing better near-shore land use practices, etc.

In more recent years (1992, 1998 and 1999) when sampling has concentrated on site 101 (away from shore), the annual average phosphorus concentrations have been relatively low. In fact, all total phosphorus concentrations and averages shown in the table for site 101 are quite low and only range from 8 - 14 µg/L. This suggests that in deeper parts of the lake, near-surface water located away from the shorelines may maintain relatively low phosphorus concentrations over time. However, since the other data sets in this table are not truly comparable or necessarily representative of the lake as a whole, it is difficult to draw any firm conclusions about long term trends in phosphorus for the lake as a whole or in all parts of Siseebakwet Lake. Phosphorus concentrations can vary considerably throughout a lake, especially in shallow, near-shore areas where possible phosphorus sources such as septic tank effluent, lawn fertilizers, etc., may have a substantial local impact. Areas where substantial numbers of water fowl congregate, such as along the northeast shoreline just northwest of the outlet, could also be significant sources of phosphorus.

Collection and analysis of a few mid-lake samples timed to span the summer months is generally considered sufficient to provide a reasonably accurate measure of the bulk phosphorus concentration in general circulation in a lake. However, indications of the heterogeneity of total phosphorus concentrations around Siseebakwet Lake are evident in the contrast between the low phosphorus concentrations found in the epilimnion at site 101, the higher phosphorus concentrations found at depth in October 1999 and the strikingly higher phosphorus concentrations found at the surface water inlets (210 µg/L at the SW inlet and 233 µg/L at the WNW inlet) and outlet (61 µg/L) in October 1998 during a study by Itasca Soil and Water Conservation District (Watkins and Reed, 1999). These contrasts reinforce the point that a small number of epilimnion total phosphorus samples per year at site 101 alone may not well represent the overall distribution or impact of phosphorus on Siseebakwet Lake.
Transient increases in phosphorus over time may also be due to conditions which periodically free phosphorus stored in the bottom sediments and return it to various portions of the lake. Transient decreases in phosphorus could be due to co-precipitation of phosphorus as calcium carbonate is precipitated out of lake water and settles until it is incorporated into the bottom sediments.

Not including the 1954 data about which little is known by the MPCA, the earliest known annual averages, in 1972 and 1984, were also the highest, but we know the least about how reliable the data are from those years. One of the 1972 samples collected on May 23, 1972, from the northeast portion of Siseebakwet Lake, had a concentration of 150 µg/L (“available phosphate, filtered”). The other two samples were reported at concentrations of 25 µg/L (July 1) and 47 µg/L (September 6). Of the nine samples collected for the 1984 annual average data set by Whiteford (1985) the concentrations ranged from 7 to 50 µg/L total phosphorus.

CHLOROPHYLL a

Historical chlorophyll a data for Siseebakwet Lake are shown in Table 19 - Historical Surface Chlorophyll a Data (1981 - 1999). It is believed that all of these data sets represent chlorophyll a concentrations found in samples collected near the lake surface. It is known that the 1992, 1998 and 1999 data sets are corrected for Pheophytin; it has been assumed that the other data sets have also been corrected for Pheophytin. Most samples are believed to have been collected as an integrated sample representing the 0 - 2 m depth range.

**Table 19 - Historical Surface Chlorophyll a Data (1981 - 1999)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Site</th>
<th>Date</th>
<th>Data Set Type</th>
<th>Chlorophyll a (µg/L)</th>
<th>Summer Range (June - Sept.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STORET Data Base</td>
<td>101</td>
<td>17-Aug-81</td>
<td>single measurement</td>
<td>2.11</td>
<td>----</td>
</tr>
<tr>
<td>Whiteford (1985)</td>
<td></td>
<td>1984</td>
<td>summer average</td>
<td>1.55</td>
<td>0.60 - 2.40</td>
</tr>
<tr>
<td>Itasca SWCD (1992)</td>
<td>101</td>
<td>1992</td>
<td>summer average</td>
<td>1.18</td>
<td>0.6 - 2.5</td>
</tr>
<tr>
<td>DNR Ecol. Svs. (2000b)</td>
<td>101</td>
<td>08-Aug-94</td>
<td>single measurement</td>
<td>4.1</td>
<td>----</td>
</tr>
<tr>
<td>Itasca SWCD (1998)</td>
<td>101</td>
<td>1998</td>
<td>summer average</td>
<td>0.94</td>
<td>0.25 – 1.56</td>
</tr>
<tr>
<td>MPCA (1999 Data)</td>
<td>101</td>
<td>1999</td>
<td>summer average</td>
<td>2.13</td>
<td>1.43 – 3.09</td>
</tr>
</tbody>
</table>

INTERPRETATION. The concentrations of chlorophyll a found in these historical data sets are too similar to indicate a clear trend over time. There is no significant trend. The four average values for chlorophyll a from 1984 – 1999 are all within about 1 µg/L of each other. The highest individual summer concentrations listed in Table 19 are 4.1 µg/L on August 8, 1994 and 3.09 µg/L on September 15, 1999. However, higher concentrations of chlorophyll a were found outside of the summer (June – September) sampling season. Whiteford (1985) found 4.32 µg/L chlorophyll a on October 13, 1984 and 5.75 µg/L was found on May 12, 1999, in this study. Watkins and Reed (1999) found 3.12 µg/L on November 13, 1998.
It is worth repeating here that, during this 1999 study, especially in late August, some portions of the lake, including the area at site 101 appeared to have visibly high concentrations of algae-like material in the lake water but the analytical technique used to quantify this algae sample resulted in a quantification of “sparse”. The matching chlorophyll $a$ analysis of this sample yielded a concentration of only $2.47 \mu g/L$ chlorophyll $a$. The discrepancy between field observations and laboratory analyses could be due to the fact that field observations were mostly based on lake surface observations and the laboratory analyses for near-surface samples were performed on composite samples that represented a depth range between 0 - 1 m. However, in some cases, grab samples collected in shallow water beneath the water surface at site 101 and visual observations of the water column against the background of a Secchi disk lowered to about a 1m depth appeared similarly clouded with phytoplankton and other particulates.

MISCELLANEOUS PARAMETERS

Historical data for specific conductance, total dissolved solids, pH, calcium, alkalinity and total Kjeldahl nitrogen are presented in Table 20 - Historical Data for Miscellaneous Parameters. The historical record of these data is too sparse to draw any firm conclusions about long term trends. However, the data suggest that there might possibly be a trend of increasing specific conductance which would imply an increase in total dissolved solids. Alkalinity and total Kjeldahl nitrogen concentrations appear to be slightly higher in recent years compared to earlier years.
<table>
<thead>
<tr>
<th>SOURCE</th>
<th>SITE</th>
<th>DATE</th>
<th>DATA SET TYPE</th>
<th>SPEC. COND.</th>
<th>TDS</th>
<th>PH</th>
<th>Calcium (as Ca^{2+})</th>
<th>ALKALINITY (MG/L)</th>
<th>TOTAL KJEL. NIT.</th>
<th>TOTAL KJEL. NIT.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNR Ecol. Svs.2000b</td>
<td>101</td>
<td>28-Jul-75</td>
<td>single measurement</td>
<td>150</td>
<td>7.70L</td>
<td>8.3F</td>
<td>115L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STORET Data Base</td>
<td>101</td>
<td>17-Aug-81</td>
<td>single measurement</td>
<td>150</td>
<td>8.5F</td>
<td>125F</td>
<td>8.3F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whiteford (1985)</td>
<td>NE</td>
<td>1984</td>
<td>summer avg. (June – Sept.)</td>
<td>110L</td>
<td>8.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DNR Ecol. Svs.2000b</td>
<td>101</td>
<td>05-Sep-84</td>
<td>single measurement</td>
<td>260</td>
<td>8.58L</td>
<td>129L</td>
<td>8.08L (6.8 – 8.8)</td>
<td>19.91</td>
<td>129</td>
<td>321</td>
</tr>
<tr>
<td>DNR Ecol. Svs.2000b</td>
<td>101</td>
<td>15-Aug-88</td>
<td>single measurement</td>
<td>260</td>
<td>8.58L</td>
<td>129L</td>
<td>8.08L (6.8 – 8.8)</td>
<td>19.91</td>
<td>129</td>
<td>321</td>
</tr>
<tr>
<td>Itasca SWCD (1992)</td>
<td>101</td>
<td>4-May-92</td>
<td>single measurement</td>
<td>236</td>
<td>8.5</td>
<td>125F</td>
<td>321</td>
<td>326.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DNR Ecol. Svs.2000b</td>
<td>101</td>
<td>08-Aug-94</td>
<td>single measurement</td>
<td>236</td>
<td>8.58L</td>
<td>129L</td>
<td>8.08L (6.8 – 8.8)</td>
<td>19.91</td>
<td>129</td>
<td>321</td>
</tr>
</tbody>
</table>

1- Specific Conductance
2- Total Dissolved Solids (mg/L)
3- Total Kjeldahl Nitrogen
4- Four readings May13 - June 16, plus one reading on August 13.
TRENDS IN CLMP Secchi Disk Database

Secchi Disk readings in the MPCA CLMP database include measurements from 13 different years between 1974 through 1999. Only one measurement was available from 1974 (14 ft. deep on August 7). All the rest of the readings are from the time period 1988 – 1999 during which readings were recorded each year. Secchi Disk summer means are calculated based on readings from June – September and then plotted to assess trends in lake transparency. Deeper Secchi disk readings, indicated by larger negative numbers on plots in this report, indicate better lake water transparency.

TREND IN 1988 – 1999 CLMP DATA. Summer mean Secchi disk readings at Siseebakwet Lake (compiled from both sites 101 and 203) for 1998 and 1999 were 10.8 and 11.5 ft. respectively. These recent means are slightly less (deep) than the long term summer mean of 12.5 ft. for the time period from 1988 – 1999 (Figure 32 - Summer Mean CLMP Secchi Disk Values, Siseebakwet Lake, Various Sampling Locations, 1988 - 1999).

Four other years on record before 1998 had Secchi disk summer means less (deep) than the long term average.: 1988, 1991, 1996, and 1997. All of these years all had summer means that were lower than or equal to means in 1998 and 1999. Two of those years had lower summer means than both 1998 and 1999. The lowest Secchi Disk summer means on record were in 1996 (10.2 ft.) and 1997 (6.9 ft.).

It should be noted that numerous distinct CLMP measurement sites have been used to collect Secchi disk Transparency data over the years on Siseebakwet Lake. The locations of the fourteen unique CLMP sites are shown in Figure 44 within Appendix K - Trends in Water Quality And Related Factors. This is not unusual, however, the variability expected due to locational differences should be kept in mind when evaluating trends in Secchi disk transparency data over time. Appendix K also includes a table that indicates what years particular sites were used for Secchi disk transparency measurements. An additional potential source of bias in the CLMP data set is examined below.

ASSESSMENT OF MONITORING BIAS. In evaluating whether there has been an actual change in lake transparency over the years 1974 - 1999, it was noticed that there may have been an unintentional (monitoring schedule) bias in the Secchi disk summer mean determinations during the four years with the lowest summer means. Secchi Disk readings in the CLMP database for the three years with the lowest values, 1997 (mean = 6.9 ft.), 1996 (mean = 10.2 ft.), and 1991 (mean = 11.2 ft.) did not include any readings before July. For the fourth of these years, 1988 (mean = 11.5 ft.) the earliest reading was taken on June 30.

In contrast, the four years with the highest (deepest) Secchi Disk summer means recorded were 1989 (15.9 ft.), 1990 (16.0 ft.), 1992 (14.8 ft.) and 1993 (14.8 ft.). In 1989, June values as high as 23.5 ft. (June 10) and 20.5 ft. (June 24) were measured in contrast to values later in the summer as low as 10.0 ft. on July 31 and August 3. It would appear that these June values contributed significantly to a higher (deeper) summer mean for 1989. There was only one June reading (June 25: 22ft.) for 1990, but there were three early July readings (July 1-12) ranging from 24 – 30 ft. deep that also contributed to a relatively high (deep) summer mean. During 1992, there were many readings in June between 20 and 25 ft. In 1993, there were also numerous June readings; all were between 18 and 21 ft.
Since higher (deeper) Secchi disk readings are typically recorded in June, the data from the four years with the lowest (least deep) Secchi disk summer means, 1997, 1996, 1991 and 1988, could be biased toward the months that typically have the higher (deeper) Secchi disk readings. If readings had been recorded for June in those four years, the summer means might have been higher (deeper).

To test the hypothesis that the 1988 – 1999 CLMP Secchi disk data set was exhibiting a trend of worsening transparencies primarily because of bias due to when the readings were made, all the data were reorganized by month and re-evaluated. The new evaluation provided a relatively clear answer. Plots for the years 1988 – 1999 for June, July, August and September all showed the same thing. There has been a trend of worsening transparency for each of the four months between 1988 and 1999. Figure 33 - August Mean CLMP Secchi Disk Readings 1988 - 1999, Siseebakwet Lake, Various Locations and Figure 34 - September Mean CLMP Secchi Disk Readings 1988 – 1999, Siseebakwet Lake, Various Locations are presented as examples of monthly evaluations. Trend lines shown on these plots were automatically calculated within Microsoft Excel’s charting program. The equation of the trend line and an $r^2$ value is provided on each graph. The variable “$r$” was also calculated within the charting program; “$r$” is the correlation coefficient and it indicates how well the dependent variable (the Secchi disk transparency) is “determined” or “explained” by the independent variable (the measurement date). A higher $r^2$ value (ranging from 0 to 1) indicates it is more likely the transparency values are explained by the sampling date, i.e., that the apparent trend in transparency changes according to date is real.
Figure 33 - August Mean CLMP Secchi Disk Readings 1988 - 1999, Siseebakwet Lake, Various Locations

Figure 34 - September Mean CLMP Secchi Disk Readings 1988 – 1999, Siseebakwet Lake, Various Locations
Trends in Secchi Disk Data from Various Sources: 1972 - 1999

In an effort to evaluate Secchi disk transparency trends over a longer period of time, Secchi disk data from a several sources of information have been collected and presented in Figure 35 - Historical Secchi Disk Measurements Trend from Various Sources. The data used to create this table can be found in Table 34 - Data Used for Secchi Disk Transparency History Plot (located in Appendix K - Trends in Water Quality And Related Factors on page 189). Although the MPCA is less familiar with quality control aspects of Secchi disk data from outside of the CLMP program, it is useful to look for consistency in trends in this broader data set. Nonetheless, this mixed data set, which includes data for which the MPCA has very limited documentation, should be used with caution.

The term “annual average” is used here to describe data sets where an average was reported for a given year without specifying the sampling months or when an average is known to include months outside of the range June – September, the months used to calculate a summer average. Most likely, all “annual average” measurements occurred between May and October. The sole data set that was known to include winter measurements was excluded intentionally; it contained only winter measurements.

WHITEFORD (1985). Whiteford reports 1984 data and references 1980 Secchi disk transparency data from a report by Eastlund (1981) (now unavailable). Secchi disk transparency values for 1983 and 1985, apparently collected by Whiteford (1985, page 26), are also included. From the context in Whiteford (1985) it is not completely clear whether these are summer means (June – September average) or average readings from some other time period. However, based on the 1984 measurements included in the Whiteford report, the 1984 average data appears to be the average of all data collected that year which included eight measurements between June 13 and September 29 and one measurement on October 13. Selected data from the Whiteford report are summarized below in Table 21.

Although it is unclear what location(s) is represented by the 1980, 1983 and 1985 data points, Whiteford’s reference to these data helps fill the data gap between the years of 1980 and 1985. 1984 Secchi Disk measurements reported by Whiteford (1985) at location ‘NE”, roughly 0.4 miles northeast of the center of the lake, ranged from 3.10 m to 5.10 m from June to September and the single reading in October was 4.85 m. This location, “NE”, is probably the most equivalent to site 101 for comparative purposes. Secchi disk measurements were recorded for three other locations by Whiteford, but the readings were very similar at all locations.

**Table 21 - Historical Annual Average Secchi Disk Readings from Whiteford (1985)**

<table>
<thead>
<tr>
<th>YEAR</th>
<th>AVERAGE SECCHI DISK DEPTH(m)</th>
<th>AVERAGE SECCHI DISK DEPTH (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>5.10</td>
<td>16.7</td>
</tr>
<tr>
<td>1983</td>
<td>4.35</td>
<td>14.3</td>
</tr>
<tr>
<td>1984</td>
<td>4.20</td>
<td>13.8</td>
</tr>
<tr>
<td>1985</td>
<td>4.18</td>
<td>13.7</td>
</tr>
</tbody>
</table>

INTERPRETATION. Like the 1988 to 1999 data set described earlier, the broader data set spanning 1972 through 1999 also appears to indicate a trend of worsening Secchi disk transparency over time. The trend line in Figure 35 was generated automatically by Microsoft Excel’s charting program. If the three single measurements had been omitted, the trend line would indicate a sharper rate of worsening in Secchi disk transparency in Siseebakwet Lake as more weight would be given to data from 1972 and 1980.
Figure 35 - Historical Secchi Disk Measurements Trend from Various Sources

\[ y = 0.203x - 31.237 \]
What's Causing the Trend in Transparency?

Has there been a change or recent trend in one of the factors that might explain an apparent trend in Secchi disk transparency readings? Could a subtle change in annual temperatures, rainfall or some other factor be responsible for an apparent trend in Secchi disk transparency readings? Could the relatively recent removal of beaver dams upstream from the NNW inlet cause enough additional nutrients or particulates to enter the lake to significantly affect trends in Secchi disk measurements at site 101?

The long-term trend of worsening transparency (Figure 35) appears to be significant and real. It is not a clear and simple trend that features consecutively worsening transparencies each year. The record shows somewhat better years chronologically interspersed with somewhat worse years. Nonetheless, the available data indicate a long-term trend of worsening transparency.

Based on information available at this time, we cannot clearly assign responsibility for the trend of worsening lake transparency to a specific cause or set of causes.

We know lake-water transparency can be reduced by staining (coloring) of water or by "clouding" of water by suspended particulate organic matter such as algae, or suspended particulate inorganic matter such as calcium carbonate precipitate or other fine inorganic sediments. However, we cannot definitively say what mechanism or mechanisms have caused the long-term trend of worsening transparency. Measurements of color, chlorophyll $a$, total suspended solids and turbidity at site 101 were all relatively low at the times sampled in 1999 and, for the most part, in most other recent years when recorded. The apparent discrepancy between the trend of worsening transparency and measurements that indicate that transparency should currently be nearly optimal suggests that the (conventional) methods used to measure color, total suspended solids, chlorophyll $a$ and turbidity do not perfectly represent all factors that affect transparency.

ALGAE AND CHLOROPHYLL $a$. At times in 1999, field observations suggested there may have been a substantially higher concentration of chlorophyll-bearing material in the lake water than was measured in the laboratories. Under-representation of this material in laboratory results may partially explain why transparency values were lower than expected once or twice but would not appear to explain discrepancies at times where no algae were observed in the field. The fact that chlorophyll $a$ concentrations were found to sometimes be higher below the normal monitoring depth of 0-2 m suggests that the impact of chlorophyll $a$ below 2 m on transparency may have been under-represented historically. However, since the chlorophyll $a$ concentrations measured below 2 m but shallow enough to affect transparency measurements were still quite low, this would not appear to be a big factor as far as accounting for impacts on transparency. If there are future studies, it may be worthwhile to further investigate the importance of chlorophyll $a$ below 2 m.

CALCIUM CARBONATE PRECIPITATE. While measurements of color (staining), chlorophyll $a$, total suspended solids and turbidity were indicating very good conditions for transparency, several lines of evidence also indicated that a substantial amount of calcium carbonate was precipitating in the lake water during the study period. This suggests the possibility that the presence of calcium carbonate precipitate and its potential impact on lake water transparency may not have been well represented by measurements such as total suspended solids and turbidity (as is normally assumed).

It appears that precipitation of calcium carbonate in Siseebakwet Lake water may play an important role in the lake's transparency. The frequency, duration and rate of precipitation of calcium carbonate is governed by a somewhat complex set of processes (see Table 32 - Summary of Factors Affecting Sedimentation and Precipitation of Calcium Carbonate) that are difficult to evaluate. The intermittent deep blue-green color observed at the lake's surface is probably caused by the presence of calcium carbonate precipitate in the water. The color and intensity varies
substantially with the amount of sunlight and with the angle of the viewer to the sun unlike the more consistent appearance of algae. It would seem that if there is enough calcium carbonate particulate matter (or other reflective substance) present to change Siseebakwet Lake's observed color from gray to blue-green as observed, then there would be enough to impact the lake water's transparency.

Based on analysis of a single lake bottom sediment core, there doesn't appear to have been any substantial changes in calcium carbonate accumulation in recent times. On the other hand, we cannot rule out the possibility that subtle or undetected changes in parameters we studied or changes in other unmonitored parameters have affected transparency beyond what might be considered normal random variation.

It should also be noted that marl lakes have an unusually complex set of transparency-related factors to consider. In addition to the fact that calcium carbonate precipitate can potentially worsen transparency by clouding the water, co-precipitation of phosphorus and organic matter with calcium carbonate precipitation can actually lead to improved transparency. Co-precipitation of phosphorus with calcium carbonate is reasonably well documented in the literature. Otsuki and Wetzel (1972) state "High concentrations of phosphate ion precipitate with carbonates by simple coprecipitation as the pH of marl lake water is increased. High pH microenvironments associated with photosynthesis probably induce phosphate-carbonate precipitation ...". Co-precipitation of organic matter with calcium carbonate is apparently less studied. However, Otsuki and Wetzel (1974) explain that

> Experimental work by (Otsuki and Wetzel (1973) demonstrated a marked adsorption of yellow organic acids, the major component of dissolved humic materials, to precipitating CaCO₃ [calcium carbonate]. From 1.8 to 13.6 mg of yellow organic acids were associated with each gram of CaCO₃ at concentration range from 0.54 to 5.37 mg per liter ...

Co-precipitation of organic matter with calcium carbonate could potentially reduce water coloring (e.g., brown, organic acid staining). If any nutrient-rich organic compounds were also adsorbed to precipitating CaCO₃, then the supply of organic nutrients available to the food chain might also be reduced. This assumes that the precipitate gets buried under lake bottom sediments or at least travels to a deep enough part of the lake to effectively be removed from the food chain. Since adsorption of nutrients on CaCO₃ precipitate would also result in a concentration of nutrients around the particulates while still suspended, it could be an important factor in nutrient availability in a lake like Siseebakwet which is not nutrient rich.

CLIMATE. A series of graphs were constructed and included in Appendix K to compare historical temperature and precipitation records (Appendix D - Climatic Data) to Siseebakwet Lake transparency measurements. Preliminary analysis of the historical plots did not reveal a strong, obvious correlation between climatic variation and lake transparency. However, this could be due to insufficient detailed, long term Secchi disk monitoring records and does not mean that there is no correlation between climatic factors and transparency. As more years of monitoring are recorded, it would be prudent to re-evaluate the relationship between climate and transparency.

It should be noted, however, that the study period, the time interval during which samples were collected for this investigation, was a particularly warm and wet period compared to historical records. It can also be said, in general, that the years leading up to the study period were considerably warmer and wetter than the long term averages for these climatic factors. Please see Appendix D - Climatic Data for details.

It is worth repeating here that, unlike most common "salts" or mineral precipitates, the solubility of calcium carbonate decreases with increasing temperature. Therefore, if all else could be assumed to be equal, a period of warmer climate might possibly increase the duration, frequency or rate of calcium carbonate precipitation in Siseebakwet Lake. In turn, the increased precipitation, (even though it might lower total phosphorus and dissolved organic matter concentrations through co-precipitation), might cloud the lake water with calcium carbonate particulate matter and worsen transparency.
FUTURE STUDIES. Recommendations for future studies were made at the beginning of this document under the section entitled "Summary and Recommendations".

TROPHIC STATUS

A comparison of trophic status indicators from three studies during the 1990s is presented below in Table 22 - Trends in Trophic Status Indexes for Siseebakwet Lake. The trophic status of Siseebakwet Lake for 1999 was discussed earlier, in detail, at the end of the 1999 Lake Conditions section. The derivation of the trophic status indexes and their abbreviations were also explained above. The 1984 values for TSIP, TSIC and TSIS are averages of trophic status indexes calculated for each of the eight sampling events between June 13 and September 29 (only the October values were omitted) for location NE by Whiteford (1985). The TSI (mean) value was calculated by averaging these three index averages. The 1992 and 1998 values are from investigations performed by the Itasca Soil and Water Conservation District (Reed and Watkins, 1992; and Watkins and Reed, 1999).

Table 22 - Trends in Trophic Status Indexes for Siseebakwet Lake

<table>
<thead>
<tr>
<th>YEAR</th>
<th>TSIP</th>
<th>TSIC</th>
<th>TSIS</th>
<th>TSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>48</td>
<td>41</td>
<td>40</td>
<td>43</td>
</tr>
<tr>
<td>1992</td>
<td>34</td>
<td>32</td>
<td>36</td>
<td>34</td>
</tr>
<tr>
<td>1998</td>
<td>40</td>
<td>31</td>
<td>42</td>
<td>38</td>
</tr>
<tr>
<td>1999</td>
<td>35</td>
<td>38</td>
<td>44</td>
<td>39</td>
</tr>
</tbody>
</table>

INTERPRETATION. During the time period 1984 – 1999, the trophic status index (TSI) has ranged from 34 to 43. There was substantial reduction of the index indicating improvement in lake conditions from middle of the range Mesotrophic conditions to clearly Oligotrophic between 1984 and 1992.

Since 1992, the index has increased steadily from 34 to 39 suggesting a possible deterioration in lake conditions. This change in the index suggests that, during this time period, Siseebakwet Lake has nearly bridged the gap between clearly being an oligotrophic lake (TSI ≤ 35) and becoming a mesotrophic lake (40 ≤ TSI ≤ 50) based on the Carlson’s Trophic State Index shown in Figure 31 - Carlson’s Trophic State Index for Siseebakwet Lake on page 102. However, this apparent trend should not be over interpreted as clearly, in Siseebakwet Lake, the interrelationships between the parameters that make up the TSI do not match the assumptions of the TSI model well. A set of equal values for TSIP, TSIC and TSIS would perfectly match the model assumptions.


For the three Trophic Status Index data sets from the 1990s, the most obvious departure from a classic set of index values is the significant difference between the chlorophyll a index (TSIC) and the Secchi Disk Transparency index (TSIS). The 1984 data set is different in that TSIS and TSIC correlate well and the Secchi disk transparency index (TSIS) is the lowest of the three index values instead of the highest. In the 1984 data set, the total phosphorus index, TSIP, suggests considerably worse lake conditions than indicated by the other two indexes. In contrast, based on the assumptions of the Carlson’s Trophic State Index, Secchi disk transparency was worse (less transparent) for all three years in the 1990s than would be expected based on chlorophyll a and total phosphorus index values.

MODELING AND PHOSPHORUS LOADING

Numerous complex mathematical models are available for estimating nutrient and water budgets for lakes. These models can be used to relate the flow of water and nutrients from a lake's watershed to observed conditions in the
lake. Alternatively, they may be used for estimating changes in the quality of the lake as a result of altering nutrient inputs to the lake (e.g., changing land uses in the watershed) or altering the flow of amount of water that enters the lake. To analyze the in-lake water quality of Siseebakwet Lake, the models MINLEAP (Wilson and Walker, 1989) and Reckhow and Simpson (Reckhow and Simpson, 1980) were used. The "Minnesota Lake Eutrophication Analysis Procedures" (MINLEAP), was developed by MPCA staff based on an analysis of data collected from the ecoregion reference lakes. It is intended to be used as a screening tool for estimating lake conditions with minimal input data and is described in greater detail in Wilson and Walker (1989). Reckhow and Simpson is a spreadsheet model which estimates phosphorus loading to the lake based on phosphorus and runoff coefficients.

MINLEAP. Siseebakwet Lake was modeled using data from 1999 for comparative purposes. MINLEAP predicted an in-lake total phosphorus concentration of 11 (±4) µg/L which is slightly higher but not significantly different from the 1999 observed mean of 8 µg/L. The predicted chlorophyll a concentration of 2.1 µg/L is even closer to observed values. However, there is a notable difference between predicted (4.8) and observed (3.0) Secchi Disk values (Table 23 - MINLEAP Model Results for Siseebakwet Lake).

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>PREDICTED</th>
<th>OBSERVED&lt;sup&gt;10&lt;/sup&gt; (1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Phosphorus (µg/L)</td>
<td>11 ± 4</td>
<td>8 ± 0.9</td>
</tr>
<tr>
<td>Chlorophyll a (µg/L)</td>
<td>2.2 ± 1.5</td>
<td>2.1 ± 0.5</td>
</tr>
<tr>
<td>% Chlorophyll a &gt;20 µg/L</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>% Chlorophyll a &gt;30 µg/L</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Secchi (meters)</td>
<td>4.8 ± 2.1</td>
<td>3.0 ± 0.4</td>
</tr>
<tr>
<td>Phosphorus loading rate</td>
<td>310 kg/yr.</td>
<td>--</td>
</tr>
<tr>
<td>Phosphorus retention (%)</td>
<td>82%</td>
<td>--</td>
</tr>
<tr>
<td>Phosphorus inflow concentration</td>
<td>61 µg/L</td>
<td>--</td>
</tr>
<tr>
<td>Water load</td>
<td>0.93 m/yr.</td>
<td>--</td>
</tr>
<tr>
<td>Outflow volume</td>
<td>5.09 hm&lt;sup&gt;3&lt;/sup&gt;/yr</td>
<td>--</td>
</tr>
<tr>
<td>&quot;Background Phosphorus&quot;</td>
<td>16.1 µg/L</td>
<td>--</td>
</tr>
<tr>
<td>Residence time</td>
<td>14.2 Years&lt;sup&gt;11&lt;/sup&gt;</td>
<td>--</td>
</tr>
</tbody>
</table>

The phosphorus loading rate based on the MINLEAP model is estimated at 310 kg/yr. Based on simplifying assumptions that do not include ground-water inputs or outputs, the lake appears to retain a high percentage of the phosphorus which enters the lake (about 82 percent). For estimating "Background Phosphorus" the model assumes proportional delivery of phosphorus and CaCO<sub>3</sub> from the watershed. The somewhat high estimated background phosphorus is due to the lake's elevated alkalinity. The model does not consider the potential loss of phosphorus from the epilimnion through co-precipitation with CaCO<sub>3</sub>. The model estimates water residence time (time it would take to fill the lake if it was completely empty) at about 14.2<sup>11</sup> years.

<sup>10</sup> Summer mean value ± the standard error (standard error = standard deviation/square root of the number of measurements).

<sup>11</sup> Note that the hydraulic residence time calculated by a more rigorous analytical method (Water Budget Modeling) that accounts for ground water and surface water interactions (Appendix G - Ground Water and Surface Water Interaction Study) was 6.5 years.
VIGHI AND CHIAUDANI MODEL. A second mathematical model developed by Vighi and Chiaudani (1985) estimated that the in-lake total phosphorus concentration for Siseebakwet Lake would be 16 µg/L. This prediction was a little high compared to the MINLEAP model's predicted 11 µg/L, and the observed concentration of 8 µg/L total phosphorus in 1999. The Vighi and Chiaudani model prediction is based on the morphoedaphic index routinely used in fishery science and predicts background (or more or less natural) phosphorus concentrations based on the lake's alkalinity and mean depth.

RECKHOW-SIMPSON MODEL. The Reckhow-Simpson model was used to estimate the water quality of Siseebakwet Lake. For Reckhow-Simpson modeling, estimates of precipitation, runoff and evaporation for Siseebakwet Lake's watershed were used. Phosphorus loading to the lake was estimated based on land use composition, as provided by the Itasca County SWCD and export coefficients. The Reckhow and Simpson model provides a basis for estimating water and nutrient budgets for Siseebakwet Lake using a combination of runoff and phosphorus export coefficients based on land use in the watershed. Estimates for phosphorus and water loading were made as follows:

1. Phosphorus export coefficients - standard coefficients based on the literature and past experience were used.
2. Precipitation - was estimated based on 1999 water year data and runoff was estimated from statewide isopleth maps.
3. Atmospheric – was estimated at 20-30 kg phosphorus/km².
4. Septic systems – based on number of seasonal and annual residences, standard per capita loading rates, and a high “soil retention” coefficient (80 – 90 %).

Using a range of phosphorus export values and coefficients, the Reckhow-Simpson model predicted a range of in-lake phosphorus concentrations from 11 µg/L (275 kg phosphorus/year) to 18 µg/L (579 kg phosphorus/yr). As shown in Table 24 - Summer-Mean Phosphorus Concentrations & Model Estimates, the "low" end of the Reckhow-Simpson model output range, 11 µg/L, is most similar to the observed phosphorus concentration of 8.3 µg/L. Correspondingly, the "low" end of the phosphorus loading rate predicted by the Reckhow-Simpson model (275 kg phosphorus/year), is closest to the MNLEAP estimated phosphorus loading rate of 310 kg phosphorus/yr. (Table 23).

<table>
<thead>
<tr>
<th>1999 MEAN</th>
<th>MINLEAP</th>
<th>VIGHI - P</th>
<th>RECKHOW-SIMPSON</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 ± 1 µg/L</td>
<td>11 ± 4 µg/L</td>
<td>16 µg/L</td>
<td>11 - 18 µg/L</td>
</tr>
</tbody>
</table>

Based on an overall phosphorus loading rate of about 275 kg phosphorus/yr., the relative contributions are estimated as follows: watershed runoff, 55 - 58 percent; precipitation on the lake, 32 - 36 percent; and septic systems, 8 – 11 percent (Table 25). The validity of these estimates is contingent on the model accurately predicting the in-lake phosphorus concentration of the lake.

Table 24 - Summer-Mean Phosphorus Concentrations & Model Estimates

<table>
<thead>
<tr>
<th>POTENTIAL SOURCE</th>
<th>ESTIMATED RELATIVE CONTRIBUTION (PERCENT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watershed</td>
<td>55 - 58</td>
</tr>
<tr>
<td>Precipitation</td>
<td>32 - 36</td>
</tr>
<tr>
<td>Septic Systems</td>
<td>8 - 11</td>
</tr>
</tbody>
</table>
IMPACTS OF INTERRELATED ENVIRONMENTAL FACTORS ON LAKE TRANSPARENCY

The typical causes of worsened transparency in Minnesota lakes have been described in this report as primarily increased phytoplankton (algae), and secondarily, suspended solids (other than phytoplankton) and color due to dissolved organic material. Phosphorus is typically the key limiting nutrient for phytoplankton growth. The following discussion focuses on how these typically important factors and other environmental factors with special importance at Siseebakwet Lake may interact to affect lake transparency.

RELEASE OF LAKEBED PHOSPHORUS BY LOW OXYGEN GROUND-WATER RECHARGE. Substantial amounts of phosphorus can accumulate on the lakebed and become immobilized by incorporation into the bottom sediments when dissolved oxygen concentrations in adjacent lake water are high enough. However, as dissolved oxygen concentrations decrease, the phosphorus can be released from the bottom sediments and partition back into the lake water solution. Monson (1992) indicates that release of phosphorus is likely to occur when dissolved oxygen concentrations fall below 1 mg/L.

Ground water that has traveled a significant distance is often low in dissolved oxygen because oxygen is normally consumed as ground water travels along its flow path. The dissolved oxygen concentrations measured in the field for three domestic wells located adjacent to Siseebakwet Lake in November 1999 ranged from only 0.20 to 0.72 mg/L. Since a large percentage of annual Siseebakwet Lake recharge comes from ground water passing through its lake bed, changes in the dissolved oxygen content of recharging ground water could be a significant factor in the amount of phosphorus available in the lake water system at a given point in time. Seasonal and annual variations in the relative amount of ground water entering Siseebakwet Lake could also have a significant effect on the concentration of phosphorus in the lake water. A variety of factors, especially climatic factors such as temperature and rainfall, can cause such variations. For reference, historical climate data for the Siseebakwet Lake area can be found in Appendix D - Climatic Data.

The areas of the lake bed that receive ground-water recharge can also potentially change over time. It has often been assumed that, for typical lake settings, most ground-water recharge occurs near the margins of the lake. However, recent studies have shown that significant amounts of ground water can also enter the more central portions of a lake. Short term, seasonal and annual variations in precipitation and other climatic factors can potentially alter the specific lake bed locations (or relative amounts per location) recharged by ground water and also change the total lake bed surface area that is recharged. If the lake bed recharge area temporarily expanded into an area that does not normally receive direct ground-water recharge, the result could possibly be to release phosphorus that has accumulated over a substantial amount of time in lake bed sediments. Such a release could potentially have a significant effect on the concentration of phosphorus in the lake water.

CO-PRECIPITATION OF CALCIUM CARBONATE, PHOSPHORUS AND ORGANIC MATTER. As calcium carbonate precipitates out of lake water, organic compounds, phosphorus and other inorganic compounds can coprecipitate and settle to the lake bed. As the precipitate is incorporated into the lake bed, the phosphorus and organic matter may, in effect, be removed from the lake water system. There may be limited exceptions with benthic organisms using a fraction of the these materials as nutrients before they are buried too deeply. And of course, the preceding paragraphs outlined processes that could potentially mobilize "buried" phosphorus.

This process can have both positive and negative effects on lake water transparency. While the precipitation of calcium carbonate can potentially cloud the lake water and reduce its transparency, the coprecipitation of phosphorus (and to some extent, organic compounds) reduces the availability of important algal nutrients and can result in improved transparency due to reduced algal mass. If the precipitation of calcium carbonate is only temporary and the precipitate settles promptly, the worsening of transparency would only be transient. On the other hand, the partial removal of phosphorus and organic compounds from the circulating lake water system can
be long term or permanent notwithstanding the continual influx of additional phosphorus and organic compounds into the lake.

In Siseebakwet Lake, it is possible that this precipitation process affecting calcium carbonate, organic compounds, phosphorus and other inorganic constituents takes place intermittently, regularly or nearly constantly in some parts of the lake. If this process is always dependent on a substantial amount of photosynthetic activity to drive local pH up high enough to initiate the reaction in Siseebakwet Lake, then the precipitation may take place primarily in the warmer months at times of higher sunlight intensity. In any case, it is likely to be a significant factor in both the summer average transparency and in the temporal and spatial variability of transparencies observed in the lake.

It may be of interest to note that, under some circumstances, phosphorus can actually serve as a sequestering agent to inhibit calcium carbonate precipitation. Phosphorus may never reach high enough concentrations for this to be a factor in most of the lake. However, in-lake phosphorus concentrations may vary considerably near septic systems, near substantial populations of waterfowl, near the stream inlets or near the shoreline after rapid snowmelt events or intense or prolonged rainfall events. If phosphorus-induced inhibition of calcium carbonate precipitation ever becomes significant in some part of Siseebakwet Lake, then the balance among phosphorus (key algal nutrient and sequestering agent for calcium carbonate), phytoplankton (worsens transparency and drives calcium carbonate precipitation) and calcium carbonate precipitation (coprecipitates phosphorus and worsens transparency) may be particularly precarious. The status of a cycle of such closely interrelated physical, chemical and biochemical factors could depend on a very delicate balance and could be difficult to model, understand or control.

RE-SUSPENSION OF LAKE-BOTTOM SEDIMENTS. There are numerous sources of materials and organisms that might potentially impact lake transparency. Some of those discussed earlier include sediments and dissolved constituents that come in through surface water inlets, overland flow, shoreline and bank erosion or ground water. A variety of chemical and biochemical processes that can impact transparency have also been discussed. But when wind and wave action increase there is also the possibility of re-suspending lake bottom sediments or sediments that have fallen to deeper zones and are near the lake bottom.

Depending on the magnitude and configuration of a physical disturbances such as a wave, the chemical make up of the bottom sediments, their particle size, shape, density and other factors, these lake bottom materials can be suspended in substantial quantities and for considerable lengths of time. Very fine, flat or plate-like, low density particulates can take a long time to settle. In some cases, it may be difficult, through casual observation, to distinguish between a "re-suspension event" versus a "whitening event" which is brought about primarily by chemical or biochemical precipitation of calcium carbonate from the open water column of the lake. Spring and fall lake turnover could also bring particulates from deeper zones back to near-surface waters which, in turn, could temporarily impact lake transparency.

GOAL SETTING

Measured in-lake phosphorus concentrations are not particularly high and are less than or equal to the concentrations predicted by the models. Therefore, the emphasis for setting phosphorus-related goals should be placed on maintaining the current, satisfactory phosphorus concentrations. Maintaining low phosphorus concentrations requires ongoing preventative maintenance and watchful diligence to prevent or at least minimize harmful land use practices in the watershed, especially in the lakeshore area. Continue to educate and survey lake area residents about taking care of septic systems, shoreline property and stormwater runoff issues. Emphasize the importance of shoreline cover and how they can maintain or improve it.

Consider using the septic system survey data to create a schedule to automatically send reminder letters to lake residents based on the age of their septic systems. The letter could remind them when it is time for a detailed inspection, maintenance or possible replacement of their septic system.
Due to the long term trend of worsening transparency and the complex (marl lake) nature of Siseebakwet Lake, a goal of consistent, long-term lake monitoring, *customized for Siseebakwet Lake's marl lake characteristics*, is recommended. To better use, understand and communicate about that monitoring data, it would be advantageous for the association to build and maintain their knowledge, or at least awareness of issues related to marl lakes. The following paragraphs provide general suggestions on how to address this goal.

*Marl Lake Concerns*

Data collected for Siseebakwet Lake do not correspond well with the typical pattern of relationships between total phosphorus, chlorophyll $a$ and Secchi disk transparency observed in Minnesota lakes. Most notably, Secchi disk data do not correspond well with total phosphorus or with chlorophyll $a$ values. The factors that control lake water transparency at Siseebakwet Lake are not completely understood. It is believed that frequent or ongoing co-precipitation of phosphorus with calcium carbonate in Siseebakwet Lake may have a significant role in keeping phosphorus concentrations low in the lake water. It is also possible that co-precipitation of dissolved organic matter with calcium carbonate serves to reduce coloring from water staining (e.g., brown, organic acid staining) and might even reduce the supply of organic nutrients available to the food chain. If some change would alter the rate or consistency of calcium carbonate precipitation in the lake, it is difficult to predict how that might affect the phosphorus concentration and other lake characteristics such as algae growth and transparency.

Because of these uncertainties related to Siseebakwet Lake, it is recommended that the lake association also set a goal of keeping up on both information and institutional contacts that will help keep them current on new lake protection and lake monitoring methods and technology. In particular, the association should watch for any information or resources made available for those concerned about marl lakes. Examples of resources available currently include the List of References on page 123 and staff involved with the recent Siseebakwet Lake study at the Itasca Soil and Water Conservation District and the Minnesota Pollution Control Agency.

*Lake Monitoring*

Because there appears to be a long term trend of worsening transparency in Siseebakwet Lake, it would be prudent to set a goal of maintaining a long-term monitoring program that includes basic, traditional measures such as Secchi disk transparency, total phosphorus and possibly chlorophyll $a$. However, because of Siseebakwet Lake's marl-lake characteristics, some of the supplementary monitoring parameters listed below may be even more important to include (for understanding changes in lake transparency) than chlorophyll $a$ or total phosphorus. If future monitoring continues to indicate that total phosphorus and chlorophyll $a$ correlate poorly with Secchi disk transparency, and the monitoring budget is very limited, decision makers may want to consider de-emphasizing these parameters (e.g., scaling back on sampling frequency) and putting more of available financial resources into the supplementary parameters listed below. Total phosphorus monitoring should not be discontinued altogether because it is important to detect any potentially harmful increases of phosphorus to the lake. It would also be wise to set goals to ensure a reasonable degree of ongoing environmental protection for the lake and the watershed and to not allow complacency based on the fact that "today's" phosphorus concentrations look good.

**KEY "SUPPLEMENTARY" PARAMETERS.** Because of Siseebakwet Lake's special marl-lake characteristics, it is important to add supplementary parameters to the lake monitoring plan. Carefully selected supplementary data collected simultaneously with Secchi disk transparency measurements might help, over time, to clarify the cause of changes in transparency. Examples of supplementary parameters that might be useful include the following:

- Specific conductance (depth profile strongly recommended).
- Water temperature (depth profile strongly recommended).
- pH (depth profile strongly recommended).
- Dissolved oxygen (depth profile strongly recommended).
• Visual observations: detailed record and summary of visual observations at the lake surface and in any samples collected at depth for observation purposes. The transfer of grab samples collected for observation purposes into clear glass containers to check water appearance is recommended. Notes should include water clarity, water color, presence of particulates or organisms and description of particulates including their color.

• Alkalinity, unfiltered; with the possible addition of filtered alkalinity so that the difference between the two could be calculated. Suspended particulates could make the unfiltered alkalinity measurement very tricky; filter pore size for filtered alkalinity should be less than 0.45 microns to be effective.

• Total suspended solids, volatile suspended solids and suspended calcium carbonate (mass per liter filtered). All three of these analyses should be based on how much analyte is held back on a filter with an effective pore size of less than 0.45 microns.

• Chloride: a chemically conservative parameter that is apparently relatively high in shallow upgradient ground water compared to lake water, stream inlet water and deeper upgradient ground water.

IMPORTANCE OF MONITORING AT MULTIPLE DEPTHS. Processes that influence lake water transparency may be dependent on stratification of the lake into a warmer upper-water layer and a cooler bottom-water layer. The combined measurement of monitoring parameters in both layers of the lake could help to reveal the processes or mechanisms that control transparency. To the extent that it is practical for each monitoring parameter, it is recommended that at least one field measurement or sample for analysis should be obtained from both of these layers. Collection of a water sample from the deeper layer for visual comparison to the appearance of water near the lake's surface might also provide useful information. Where field meters are used on long cables (e.g., conductance, temperature, pH and dissolved oxygen), measurements should be recorded at 1-meter intervals.

INCREASING THE RESOLUTION OF SUSPENDED SOLIDS AND SUSPENDED CaCO₃ ANALYSES. Even though it has been inferred from this study's data that suspended solids may have a major role in affecting Secchi disk transparency, in general, only small differences were seen in suspended solids analyses. Most of the suspended solids results were near the reporting limit, making resolution of differences or any trends difficult to verify. To address this problem in future monitoring efforts, it is recommended that, on a trial basis, sample volumes for suspended solids analyses be drastically increased to allow better resolution of differences at low concentrations. This approach is also recommended for suspended calcium carbonate. Increasing sample size by a factor of 10 may be a good place to start. The sample size, data requirements and analytical procedures must be coordinated with the participating laboratory in advance of field work.

REFINING THE MONITORING PROGRAM. The list of monitoring parameters should be refined based on any additional knowledge gained by implementing "Recommendations for Further Study" on page 7 or similar work or analyses. In general, the more systematic and more frequent the monitoring activity is, the more likely it will be that a clear understanding of the lake dynamics will be achieved.
REFERENCES


GLOSSARY OF SELECTED LIMNOLOGY TERMS

(Source: the Minnesota Pollution Control Agency Web Site)

**Acid Rain**: Rain or other precipitation with a higher than normal acid range. Caused when polluted air mixes with cloud moisture. High acidity (low pH) can make lakes devoid of fish.

**Algal Bloom**: An unusual or excessive abundance of algae.

**Alkalinity**: Capacity of a lake to neutralize acid.

**Bioaccumulation**: Build-up of toxic substances in fish flesh. Toxic effects may be passed on to humans eating the fish.

**Biomanipulation**: Adjusting the fish species composition in a lake as a restoration technique.

**Chlorophyll-a**: A pigment produced by algae (and other plants). Chlorophyll-a is measured in a water sample and is used as an estimate of the amount (biomass) of algae in water.

**Dimictic**: Lakes which thermally stratify and mix (turnover) once in spring and fall.

**Ecoregion**: Areas of relative homogeneity. EPA ecoregions have been defined for Minnesota based on land use, soils, landform, and potential natural vegetation.

**Ecosystem**: A community of interaction among animals, plants, and microorganisms, and the physical and chemical environment in which they live.

**Epilimnion**: Most lakes form three distinct layers of water during summertime weather. The epilimnion is the upper layer and is characterized by warmer and lighter water.

**Eutrophication**: The aging process by which lakes are fertilized with nutrients. Natural eutrophication will very gradually change the character of a lake. Cultural eutrophication is the accelerated aging of a lake as a result of human activities.

**Eutrophic Lake**: A nutrient-rich lake - usually shallow, "green" and with limited oxygen in the bottom layer of water.

**Fall Turnover**: Cooling surface waters, activated by wind action, sink to mix with lower levels of water. As in spring turnover, all water is now at the same temperature.

**Hypereutrophic**: A very nutrient-rich lake characterized by frequent and severe nuisance algal blooms and low transparency.

**Hypolimnion**: The bottom layer of lake water during the summer months. The water in the hypolimnion is denser and much colder than the water in the upper two layers.

**Lake Management**: A process that involves study, assessment of problems, and decisions on how to maintain a lake as a thriving ecosystem.

**Lake Restoration**: Actions directed toward improving the quality of a lake.

**Lake Stewardship**: An attitude that recognizes the vulnerability of lakes and the need for citizens, both individually and collectively, to assume responsibility for their care.

**Limnetic Community**: The area of open water in a lake providing the habitat for phytoplankton, zooplankton and fish.

**Littoral Community**: The shallow areas around a lake's shoreline, dominated by aquatic plants. The plants produce oxygen and provide food and shelter for animal life.

**Mesotrophic Lake**: Midway in nutrient levels between the eutrophic and oligotrophic lakes.

**Nonpoint Source**: Polluted runoff - nutrients and pollution sources not discharged from a single point: e.g. runoff from agricultural fields or feedlots.

**Oligotrophic Lake**: A relatively nutrient-poor lake, it is clear and deep with bottom waters high in dissolved oxygen.

**pH Scale**: A measure of acidity.
**Phosphorus**: An essential plant nutrient. Excess quantities promote excessive growth of algae and plants in lakes and streams. Total phosphorus refers to the most common form measured in water and includes both dissolved and particulate phosphorus.

**Photosynthesis**: The process by which green plants produce oxygen from sunlight, water and carbon dioxide.

**Phytoplankton**: Algae - the base of the lake's food chain, it also produces oxygen.

**Point Sources**: Specific sources of nutrient or polluted discharge to a lake: e.g. stormwater outlets.

**Polymictic**: A lake which does not thermally stratify in the summer. Tends to mix periodically throughout summer via wind and wave action.

**Profundal Community**: The area below the limnetic zone where light does not penetrate. This area roughly corresponds to the hypolimnion layer of water and is home to organisms that break down or consume organic matter.

**Respiration**: Oxygen consumption.

**Secchi Disk**: A device measuring the depth of light penetration in water.

**Sedimentation**: The addition of soils to lakes, a part of the natural aging process, makes lakes shallower. The process can be greatly accelerated by human activities.

**Spring Turnover**: After ice melts in spring, warming surface water sinks to mix with deeper water. At this time of year, all water is the same temperature.

**Thermocline**: During summertime, the middle layer of lake water. Lying below the epilimnion, this water rapidly loses warmth.

**Trophic Status**: The level of growth or productivity of a lake as measured by phosphorus content, algae abundance, and depth of light penetration.

**Turbidity**: Particles in solution (e.g. soil or algae) which scatter light and reduce transparency.

**Water Density**: Water is most dense at 39 degrees F (4 degrees C) and expands (becomes less dense) at both higher and lower temperatures.

**Watershed**: The surrounding land area that drains into a lake, river or river system.

**Zooplankton**: Microscopic animals.
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### APPENDIX A - HYDROGEOLOGY

Comparison of Local Glacial Geology Units Described in the Literature

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surficial Glaciofluvial Sediments (including glaciolacustrine), mostly stratified drift associated with Glacial Lake Aitkin II cover much of the Mesabi Iron Range area. Generally has lower transmissivities than Glaciofluvial Sediments between the surficial till and the bouldery till. Thickness: generally &lt; 25 ft</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Till, silty, brown, calcareous; contains shale. Widespread thin veneer over upland areas. Does not yield water to wells. Thickness: 0 – 30 ft.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Surficial Till, light- to medium-brown, sandy, silty, and calcareous. (5 – 15% soluble material in HCl). Pebbles: mostly granitic and metamorphic, but include limestone, dolomite and others. Age/Origin: Des Moines Lobe about 12,000 before present.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Surficial Till, silty, brown. Light-to medium-brown sandy, silty and calcareous matrix. Thickness: generally &lt; 25 ft.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sand, sand and gravel. Surficial outwash and valley-train deposits. Occurs chiefly along major streams. May include ice-contact sand and gravel exposed at the surface Thickness: 0 – 45 ft.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Glaciofluvial Sediments</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Glaciofluvial Sediments: grain size varies greatly horizontally.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Thickest and most continuous of the stratified drift units. Thickness: commonly &gt; 50 ft.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Till, sandy, brown with much gravel, cobbles and boulders; non-calcareous. Occurs in moraines or is buried beneath sand, gravel, clay or younger till. Does not yield significant amounts of water to wells. Thickness: 0 - 140 ft.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bouldery Till: gray, yellow, red, orange, or brown sandy, silty, contains abundant cobbles &amp; boulders and is non-calcareous. (Did not show HCL reaction in the field but did show 2.1 to 8.6% soluble material in lab tests). Pebbles are largely granitic and metamorphic rocks. It is the thickest and most widespread of the 4 tills. Colored bouldery till is below gray bouldery till. Age/Origin: Deposited by the Rainy Lobe – a minimum age of 14,000 to 16,000 years before present.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bouldery Till: gray to yellow, red orange or brown; many cobbles and boulders in a sandy, silty matrix and is non-calcareous. Lenses of glaciofluvial deposits are common. Colored (yellow, red orange or brown ) bouldery till below gray bouldery till may be a separate subunit. Thickness: generally &lt; 50 ft.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Till, sandy gray, clayey and calcareous, contains limestone pebbles. Occurs as buried, fairly continuous till sheet. Does not yield water to wells. Thickness: 20 – 90 ft.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Basal Till: dark-gray to dark greenish gray, sandy, silty, calcareous. (5 – 15% soluble material in HCl). Pebbles: mostly granitic and metamorphic, but include limestone and dolomite. Age: probably middle or early Wisconsin but could be pre-Wisconsin</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Basal Till: dark-gray to dark greenish and brownish gray, unsorted sand and gravel with clay and silt; calcareous (5 – 15% soluble material in HCl). Includes some scattered cobbles and boulders. Thickness: ~ 50 - 100 ft.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Buried outwash, calcareous sand and gravel. Thickness: 0 – 112 ft.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Possible Glaciofluvial Sediments ?</strong> Thickness: generally &lt; 30 ft.**</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Bedrock**
RESIDENTIAL DEVELOPMENT HISTORY BY JAN SMITH AND JIM PARSON
(Submitted by Jan Smith, President of the Siseebakwet Lake Association, November 2000)

To the best of our ability, we speculate the following for 1950 and 1998 and have comments about the other years as well.

### Development of Residences in Watershed

<table>
<thead>
<tr>
<th>YEAR</th>
<th>SEASONAL</th>
<th>FULL YEAR</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>15~</td>
<td>4~</td>
<td>19~</td>
</tr>
<tr>
<td>1967</td>
<td>46</td>
<td>3</td>
<td>49</td>
</tr>
<tr>
<td>1984</td>
<td></td>
<td></td>
<td>122*</td>
</tr>
<tr>
<td>1992**</td>
<td>50 (43%)?</td>
<td>67(57%)?</td>
<td>117?</td>
</tr>
<tr>
<td>1998</td>
<td>106 (57%)</td>
<td>79(43%)?</td>
<td>185</td>
</tr>
</tbody>
</table>

1950--This includes 2 resorts (1 full-year resident with 10 cabins and 1 seasonal with 6 cabins--all the 2nd resort dwellings have since been sold to individuals); one of the full-year residents sold to a seasonal family before 1967.

1967--These #'s look correct to Jim whose family built his cabin in 1965.

1984--We think it is odd there were more residences in 1984 than in 1992; we would be guessing to say what the spread is in 1984, but I think the mix would have been more like 70% seasonal and 30% full year.

1992**--I think the 1984 number is more correct than the 1992 number which is not high enough. When we started the lake association in 1991, it seems we had potential of 180 residences (this does include the number of 2nd tier residents and the 20 people who owned townhomes--some of which lived in them full-time); I also think the ratio is skewed and should be reversed. There were not more full time places in 1992 than in 1998.

1998--We are pretty confident about these numbers and they jibe with the 2000 numbers that I sent you on the survey; this number includes only the 20 townhomes that are owned by people (leaving out the remaining 37 that are rented by the lodge on a sporadic basis) and includes 2 Full Year entries for the Lodge--Bobichs & Floyd Hennagir.

* – Reported in 1995 DNR Lake Management Plan (“1 resort with 20 cabins and 102 private homes and cabins”)

** – These are the original numbers received with this submittal, but the numbers shown for 1992 are in question as per the comments included by Jan Smith in the notes for "1992" above. Based on all sources of information, the author judged that more likely actual numbers for 1992 were approximately 103 seasonal residences and 77 full year residences for a total of about 180 residences. These revised numbers totaling 180 were used in Table 5 in the main body of this report.
### Septic System Survey Results

**Siseebakwet Lakes**  
**October 30, 2000**

#### PARTICIPATION

Face-to-face surveys were done with 124 Lake Residents (this includes Siseebakwet & South Sugar)

There are 167 properties on the Siseebakwet Lakes/of which 17 are 2nd tier properties and 1 is Ruttger's

There are 57 townhomes with 20 owners listed in the tax roles

Sugar Lake Lodge has a shared ISTS with 8 cabins pumping to that system (250+ feet from lakeshore) built in 1992

SugarWood 1 has 32 units: 28 septic tanks with drainfields built in 1975 and 4 mound systems installed in the last 2 yrs.

SugarWood 2 has 25 units: septic tanks with drainfields built in 1980

The Lodge/townhomes ARE NOT included below; all are 250+ feet from lakeshore and in the Pokegama watershed

9 properties around the lake have more than one system (total of 20 ISTS’s) reported in total responses

#### TYPE OF DWELLING

<table>
<thead>
<tr>
<th>Type of Dwelling</th>
<th># of Responses</th>
<th>% of Total Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal</td>
<td>58</td>
<td>46.77%</td>
</tr>
<tr>
<td>Year-Round Primary</td>
<td>62</td>
<td>50.00%</td>
</tr>
<tr>
<td>Year-Round not Primary</td>
<td>14</td>
<td>11.29%</td>
</tr>
<tr>
<td>2nd Tier</td>
<td>5</td>
<td>4.03%</td>
</tr>
<tr>
<td><strong>subtotal</strong></td>
<td><strong>139</strong></td>
<td></td>
</tr>
</tbody>
</table>

#### SYSTEM TYPES

<table>
<thead>
<tr>
<th>System Type</th>
<th># of Responses</th>
<th>% of Total Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Septic Tank-drainfield</td>
<td>61</td>
<td>49.19%</td>
</tr>
<tr>
<td>Septic Tank-dry well</td>
<td>22</td>
<td>17.74%</td>
</tr>
<tr>
<td>Septic Tank-dry well with drainfield</td>
<td>31</td>
<td>25.00%</td>
</tr>
<tr>
<td>Shared tank drainfield</td>
<td>1</td>
<td>0.81%</td>
</tr>
<tr>
<td>Cesspool</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>Holding Tank</td>
<td>2</td>
<td>1.61%</td>
</tr>
<tr>
<td>Privy</td>
<td>6</td>
<td>4.84%</td>
</tr>
<tr>
<td>Mound System</td>
<td>7</td>
<td>5.65%</td>
</tr>
<tr>
<td>Don't know</td>
<td>2</td>
<td>1.61%</td>
</tr>
<tr>
<td>Other</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td><strong>subtotal</strong></td>
<td><strong>132</strong></td>
<td></td>
</tr>
</tbody>
</table>

#### SYSTEM AGES (years)

<table>
<thead>
<tr>
<th>Age Range</th>
<th># of Responses</th>
<th>% of Total Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>29</td>
<td>23.39%</td>
</tr>
<tr>
<td>6-10</td>
<td>19</td>
<td>15.32%</td>
</tr>
<tr>
<td>11-15</td>
<td>13</td>
<td>10.48%</td>
</tr>
<tr>
<td>16-20</td>
<td>22</td>
<td>17.74%</td>
</tr>
<tr>
<td>21-25</td>
<td>0</td>
<td>16.13%</td>
</tr>
<tr>
<td>26-30</td>
<td>12</td>
<td>9.68%</td>
</tr>
<tr>
<td>31+ (older than 1966)</td>
<td>15</td>
<td>12.10%</td>
</tr>
<tr>
<td>unknown</td>
<td>2</td>
<td>1.61%</td>
</tr>
<tr>
<td><strong>subtotal</strong></td>
<td><strong>132</strong></td>
<td></td>
</tr>
</tbody>
</table>

#### DISTANCE FROM LAKE

<table>
<thead>
<tr>
<th>Distance</th>
<th># of Responses</th>
<th>% of Total Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>4</td>
<td>3.23%</td>
</tr>
<tr>
<td>51-100</td>
<td>53</td>
<td>42.74%</td>
</tr>
<tr>
<td>101-150</td>
<td>32</td>
<td>25.81%</td>
</tr>
<tr>
<td>151-200</td>
<td>23</td>
<td>18.55%</td>
</tr>
<tr>
<td>201-250</td>
<td>7</td>
<td>5.65%</td>
</tr>
<tr>
<td>251+</td>
<td>14</td>
<td>11.29%</td>
</tr>
<tr>
<td>no response</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td><strong>subtotal</strong></td>
<td><strong>133</strong></td>
<td></td>
</tr>
</tbody>
</table>
### SYSTEM PUMPING

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>More than once per year</td>
<td>6</td>
<td>4.84%</td>
</tr>
<tr>
<td>Every year</td>
<td>8</td>
<td>6.45%</td>
</tr>
<tr>
<td>Every 2 years</td>
<td>53</td>
<td>42.74%</td>
</tr>
<tr>
<td>Every 3 years</td>
<td>16</td>
<td>12.90%</td>
</tr>
<tr>
<td>Every 4 years</td>
<td>13</td>
<td>10.48%</td>
</tr>
<tr>
<td>Every 5 years</td>
<td>14</td>
<td>11.29%</td>
</tr>
<tr>
<td>Every 10 years</td>
<td>3</td>
<td>2.42%</td>
</tr>
<tr>
<td>When problems</td>
<td>2</td>
<td>1.61%</td>
</tr>
<tr>
<td>Never</td>
<td>9</td>
<td>7.26%</td>
</tr>
<tr>
<td>No response</td>
<td>4</td>
<td>3.23%</td>
</tr>
<tr>
<td><strong>subtotal</strong></td>
<td><strong>128</strong></td>
<td></td>
</tr>
</tbody>
</table>

### PROBLEMS

<table>
<thead>
<tr>
<th>Problem</th>
<th>Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeze ups</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>Back ups</td>
<td>4</td>
<td>3.23%</td>
</tr>
<tr>
<td>Inadequate drainage</td>
<td>1</td>
<td>0.81%</td>
</tr>
<tr>
<td>Some - not bad</td>
<td>1</td>
<td>0.81%</td>
</tr>
<tr>
<td>None in the past two years</td>
<td>115</td>
<td>92.74%</td>
</tr>
<tr>
<td>No response</td>
<td>4</td>
<td>3.23%</td>
</tr>
<tr>
<td><strong>subtotal</strong></td>
<td><strong>125</strong></td>
<td></td>
</tr>
</tbody>
</table>

### EVALUATION OF RESPONSES*

- 50.00% of residences are permanent year-round
- 49.19% of systems are Septic/drainfields
- 42.74% of systems still have some form of dry well
- 23.39% of systems are less than 5 years old
- 15.32% of systems are 6-15 years old
- 45.97% of systems are 16+ years old
- 12.10% of systems are older than 1966
- 3.23% of systems are within 50' of the lake (however these are some of the oldest systems on the lake)
- 42.74% of systems are within 51-100' of the lakeshore
- 25.81% of systems are within 101-151' of the lakeshore
- 35.48% of systems are over 150' of the lakeshore (including 4% in the 2nd tier)
- 7.26% of people have never pumped their system
- 77.42% of people pump their systems every 2-5 years
- 92.74% of people reported NO problems with their systems in the last 2 years

*DOES NOT INCLUDE SUGAR LAKE LODGE OR TOWNHOMES
LAKE DEVELOPMENT

Has had, obviously, the most impact on water quality in the resulting runoff from shoreline alterations which remove the ice bank, clearing of lots to make big lawns which removes the vegetation filters, and the construction of access roads. The installation of a hundred or more septic systems, many of which are not illegal, has not enhanced water quality. During WW II, only one permanent family lived on the lake. At that time, there were but a half dozen summer homes on the north side.

ROADS

Until 1962, when Sugar Hills opened, there were no roads on the south, southwest, and southeast shores of the lake, nor were there any roads bordering South Sugar. Roads accessing the lake were a gravel road to the Spade’s property on the east side and one running along the north side as far as Mike Riley’s former property on the west end. The road’s closest proximity to the lake was from the public beach westward.

In preparation for black topping in the sixties, this road was re-contoured and during the “raw stage” before the black top was applied, a good deal of runoff reached the lake during rains via culverts, overpowering the roadside vegetation that until that time, had done a good job of filtering the runoff.

Now that the blacktop is in place and vegetation has returned to the ditches, the problem has lessened. But in the meantime, a good deal of silt entered the lake which has not absorbed it all. In fact, during strong south winds, the silt riles up so on the north side, that one cannot see the lake’s bottom for several hundred feet from shore. And I do not remember any such conditions during the 40s and 50s.

The present roads bordering South Sugar on the south seem to be set back a good distance, so that there seems to be no problem there. The road between the two lakes, runs close to the big lake in spots, but the vegetation filter would seem adequate except for very heavy rains. Most of the east side road is set back a good distance from the lake.

LOGGING

From what I know of the logging operations of the past, they did not significantly affect water quality. There was quite a bit of logging traffic over the ice in the 1890s and the early part of the century, and perhaps oxen and horse droppings there could have had some minor and temporary effect on water quality. Otherwise, the logs left behind would not impact water quality negatively.

FISHING

The fact that we now have lots of black bass in the big lake is, perhaps, a sign of diminished water quality. Although the big and little lakes have always been connected, one seldom caught a black bass in the big lake in the 40s and 50s. But since the 70s, they have proliferated. Normally, bass prefer the weedier, muddier waters.

The walleye population in the medium size range has diminished over the years, but that may be the result of too many fishermen chasing too few fish. The DNR claims that most of Siseebakwet walleyes are planted. So there would seem to be no direct impact on water quality from the changing walleye demographics.

LODGE HISTORY

The golf course used to be a farm which included some animals which were at times near the lake, though that was in the 20s and their long-term impact would have been minimal. During the Otis tenure, the greens were fertilized
but the runoff from that would have been well screened by vegetation before reaching the creek and even it had, the
current goes down stream – towards Pokegama! The original septic tanks accompanying the cabins were set back
from the lake more than the present requirements.

The present ownership fertilizes its greens also, and have added nine more greens and a fairway that comes close to
Sugar brook in spots, but again maintenance of those greens and fairways would impact Pokegama first, if at all,
given the screening of the runoff before it might enter the brook.

The watering of those greens, could feasibly lower the lake levels under extreme conditions, and that could
indirectly impact water quality.

SUGAR HILLS
Opened in 1962, and is about a mile south of South Sugar. The adjacent development, however, resulted in the first
roads on the south and east sides of the lake, and the acceleration of lakeshore development with its attendant
impact on water quality. The activity at the hills itself, though, should have had little, if any, impacts on our water
quality, given its distance from the lakes.

BEAVERS AND DAMS
The beaver dam between the big and little lakes and those between little Siseebakwet and our big lake have
historically served to strain and retain high-water flows into big Siseebakwet. Recent destruction of the dams
between Little Siseebakwet and our big lake has allowed much mud and silt to enter the lake from the west end and
has, I’m sure, done much to diminish our water quality.

The lake has also had a history of “high water” and “low water” advocates tinkering with the mouth of Sugar
Brook, until my father, at the request of the DNR, erected a dam at its mouth, which is now governed by a
committee designated by the lake association.

The above comments are based on what I can recall from have lived on the lake off and on for 70 years, and as a
product of memory are hence subject to error.

John W. Otis
24 November 1999

PROJECT HISTORY

BEGINNING OF PROJECT. September 9, 1998: Initial meeting between MPCA staff and Itasca County SWCD in
Grand Rapids to discuss this project.

INITIAL FIELD WORK. September 10, 1998: Field work at Siseebakwet Lake. Work included miscellaneous field
observations, Secchi disk readings, collection of scrapings from rocks obtained from the lake bottom, collection of
lake plants coated with a white material. Field acid test results indicated the likelihood of calcium carbonate
accumulation on rocks and plants in certain parts of the lake. Based on these field tests, it was preliminarily
assumed that calcium carbonate may be precipitating out in the lake and could potentially be contributing to
apparent changes in lake water transparency.

SAMPLING BEGINS FOR GROUND-WATER – SURFACE-WATER INTERACTION STUDY. October 21, 1998: Field work
included miscellaneous field observations. Field water quality measurements were made at four surface water and
four ground water sampling points. Surface water samples for major ions and oxygen and hydrogen isotopes were
collected and analyzed from the central portion of the lake and the WNW surface water inlet. Four ground water
samples were collected and analyzed for major ions. Two ground water samples were collected and analyzed for
oxygen and hydrogen isotopes. The hydraulic head differential between surface water and shallow ground water
was measured at ten locations.
LAKE ASSESSMENT PROGRAM SAMPLING DATES. Surface-water sampling and measurement of field water-quality parameters for the Siseebakwet Lake, Lake Assessment Program were conducted on the following dates:

- May 12, 1999
- June 10, 1999
- July 22, 1999
- August 24, 1999
- September 15, 1999
- October 13, 1999

GROUND-WATER/SURFACE-WATER INTERACTION SAMPLING DATES. Ground-water and surface-water sampling, measurement of ground-water and surface-water field water-quality parameters, and measurement of piezometric head differences between lake water and very shallow ground water for the Ground-water/Surface-water Interaction study were conducted on the following dates:

- October 21, 1998
- May 13, 1999
- July 21, 1999
- October 11, 1999

RAINFALL SAMPLE COLLECTION. September 25, 1999: A rainfall sample was collected near the southern shoreline near the Don Olson residence for analysis of basic chemistry and hydrogen and oxygen isotopes.

LAKE SEDIMENT CORE SAMPLING. A sample core of lake bottom sediment was collected from Siseebakwet Lake on October 19, 1999, for age dating and chemical analysis.

DOMESTIC WELL SAMPLING. Ground-water samples were collected from three private domestic wells adjacent to Siseebakwet Lake on October 20, 1999. Two of these wells, one shallow and one deeper, are located near the southern shoreline and the third well (shallow) is located near the northwestern shoreline.
APPENDIX D - CLIMATIC DATA

For plots showing the historical relationship between Secchi disk transparency measurements and climatic data, please see Appendix K - Trends in Water Quality And Related Factors.

The following Data sets are presented within this appendix:

TEMPERATURE

Figure 36 - Yearly Average Temperatures In Grand Rapids (1916 - 1999)

PRECIPITATION

Figure 37 - Annual Precipitation at Grand Rapids

Figure 39 - Minnesota Precipitation for Water Year 1998-99

Figure 40 - Precipitation Departure from Normal for Water Year 1998-99
Figure 36 - Yearly Average Temperatures In Grand Rapids (1916 - 1999)

(Forestry Sciences Lab, USWB Site: Midnight to Midnight values)
Figure 37 - Annual Precipitation at Grand Rapids (1916 - 1999)

(Inches of Precipitation at Forestry Sciences Lab)
POKEGAMA DAM, ITASCA COUNTY
AVERAGE ANNUAL PRECIPITATION, 1887 - 1996

Figure 38 - Annual Precipitation (in.) at Pokegama Dam, Itasca County (1887-1996)
Water Year Precipitation
October, 1998 - September, 1999

Figure 39 - Minnesota Precipitation for Water Year 1998-99

values are in inches
Water Year Precipitation Departure from Normal October, 1998 - September, 1999

Figure 40 - Precipitation Departure from Normal for Water Year 1998-99

values are in inches
APPENDIX E - LAKE LEVEL ELEVATION

LAKE LEVEL ELEVATIONS – 1990 – 1999

LAKE LEVEL ELEVATIONS – 1937 – 1999
Sisembakwet Lake  Itasca County (31-0554 00)
RECORDED WATER LEVELS

Figure 41 - Lake Water Level Elevation Measurements (ft.): 1937 - 1999
Figure 42 - Lake Water Level Elevation Measurements (ft.): 1990 - 1999
APPENDIX F – FISHERIES INFORMATION

1995 LAKE MANAGEMENT PLAN EXCERPTS

The following section, Lake Management Plan, was derived from a 1995 document written by Karl Koller with the permission of Chris Kavanaugh, DNR Fisheries Manager, Grand Rapids, Minnesota.
Lake Class 22
Management Priority 7

NA-01570-01

LAKE MANAGEMENT PLAN EXCERPT

<table>
<thead>
<tr>
<th>Region</th>
<th>Area</th>
<th>D.O.W Number</th>
<th>County</th>
<th>D.O.W. Lake Name</th>
<th>Acreage</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>Grand Rapids 210</td>
<td>31-0554</td>
<td>Itasca</td>
<td>Sisebakwet Lake</td>
<td>1360 surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>304 littoral</td>
</tr>
</tbody>
</table>

Long Range Goal:
To maintain the walleye gill net catch rate between the first and third quartile values (4.0 - 9.6/set) for lake class #22. To maintain the northern pike gill net catch rate between the first quartile and the median values (3.0 - 5.0/set).

Operational Plan:
1. Conduct a population assessment in 2001 to assess the status of the fish community and to determine the relative contribution of natural reproduction to the walleye population. Include a water chemistry analysis.

2. Stock Mississippi River strain walleye fingerlings in 1996, 1999 and 2002 at a rate of 1 lb./littoral acre (292 lbs.).

Midrange Objective:
Evaluate the relative contribution of natural reproduction to the walleye population. Monitor the abundance, size structure and growth rates of the walleye and northern pike populations as well as any changes in the rest of the fish community.

Potential Plan:
Conduct a creel survey to determine angling pressure and harvest rates. (Low priority).

Reduce fingerling stocking frequency to once every four years or attempt fry stocking if natural reproduction appears strong in population assessment in 2001. Conduct fall electrofishing for young-of-year walleye in 1999, 2000 and 2001 if the technique is perfected and if time allows.

NARRATIVE: (Historical perspectives - various surveys; past management; social considerations; present limiting factors; survey needs; land acquisition; habitat development and protection; commercial fishery; stocking plans; other management tools; and evaluation plans)
Various Surveys:
Lake Management Plan - 1986
Initial Survey - June 1951
Resurvey - July 1975, August 1984
Smelt Test netting - October 1986, June 1987
Lake Map - June 1951
Walleye Egg Deposition Checks - 1982-83
Whitefish/Tullibee Sportnetting Checks - various years

FOR CENTRAL OFFICE USE ONLY

Entry Date: Year Resurvey:
Stock Species -Size- Number per Acre
Schedule: Year Beginning
Population Manipulation
YES NO Year
Development
YES NO Year
Creel or Use Survey
YES NO Year
Other: Year

Primary Species Management:
Walleye
Secondary Species Management:
Northern pike

Area Supervisor's Signature:
Chris Kavanaugh
Date

Regional Manager's Signature:
Date

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**NARRATIVE:**

Various surveys:
Siseebakwet Lake, also known as Sugar Lake, is in ecological class #22 and is in the Mississippi River Watershed (#7). Lakes in this classification are relatively large (mean = 3,545 acres), deep (mean = 101.6 feet), have a mean littoral area of 38%, have relatively high alkalinity water (mean = 146.8 ppm) and are moderately clear (mean Secchi disc = 9.9 feet). Siseebakwet Lake has a total surface area of 1360 acres, a littoral area of 292 acres and a maximum depth of 105 feet. The total watershed area is 11.2 mi² (7168 acres). The Secchi disc transparency during the August 1994 assessment was 10.5 feet and the total alkalinity was 129.0 ppm. Total phosphorus (0.014 ppm) and Chlorophyll a (4.1 ppb) concentrations are relatively low (August 1994). The Trophic Status Index (TSI) was calculated to be 31 (1991) by the Itasca Co. Soil and Water Conservation District. This qualifies the lake as an oligotrophic lake.

Two lake surveys and six population assessments have been conducted on Siseebakwet Lake over the last forty-five years. Six of these were conducted in the last twenty years. In addition, Siseebakwet Lake was chosen in 1980 to be one of twelve "study lakes" in the Grand Rapids area to be closely evaluated to determine the relative contribution of fry stocking versus natural reproduction to the walleye population. All of the study lakes were to be stocked on a biennial basis with walleye fry at a rate of 1000 fry/surface acre. Assessments were conducted every three to four years and shoreline seining was done weekly during the summer in each of the ten study years.

**Siseebakwet Lake Gill Net Catch Rates**
(Number of fish per net)

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of nets</th>
<th>Northern WALLEYE</th>
<th>Largemouth bass</th>
<th>Yellow perch</th>
<th>Tullibee</th>
</tr>
</thead>
<tbody>
<tr>
<td>1951</td>
<td>12</td>
<td>13.2</td>
<td>1.5</td>
<td>0.0</td>
<td>4.8</td>
</tr>
<tr>
<td>1969</td>
<td>6</td>
<td>17.3</td>
<td>5.3</td>
<td>0.0</td>
<td>15.7</td>
</tr>
<tr>
<td>1975</td>
<td>12</td>
<td>5.1</td>
<td>3.4</td>
<td>0.1</td>
<td>26.5</td>
</tr>
<tr>
<td>1979</td>
<td>5</td>
<td>26.6</td>
<td>8.0</td>
<td>0.0</td>
<td>63.4</td>
</tr>
<tr>
<td>1984</td>
<td>12</td>
<td>3.8</td>
<td>1.8</td>
<td>0.2</td>
<td>86.7</td>
</tr>
<tr>
<td>1988</td>
<td>9</td>
<td>10.7</td>
<td>3.0</td>
<td>0.7</td>
<td>79.9</td>
</tr>
<tr>
<td>1991</td>
<td>9</td>
<td>10.2</td>
<td>1.3</td>
<td>1.1</td>
<td>31.4</td>
</tr>
<tr>
<td>1994</td>
<td>12</td>
<td>11.2</td>
<td>1.7</td>
<td>0.3</td>
<td>16.0</td>
</tr>
</tbody>
</table>
### Past management:
Siseebakwet Lake was stocked with northern pike, walleyes, black crappies, suckers and sunfish in the 1940's and 50's. Since that time, only walleyes and northern pike have been stocked. The stocking history since 1972 is as follows.

<table>
<thead>
<tr>
<th>Year</th>
<th>Species</th>
<th># Stocked</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>Walleye</td>
<td>5,075</td>
<td>Fgl</td>
</tr>
<tr>
<td></td>
<td>Northern pike</td>
<td>28</td>
<td>Fgl</td>
</tr>
<tr>
<td>1973</td>
<td>Walleye</td>
<td>2,000,000</td>
<td>Fry</td>
</tr>
<tr>
<td>1974</td>
<td>Walleye</td>
<td>1,000,000</td>
<td>Fry</td>
</tr>
<tr>
<td>1979</td>
<td>Walleye</td>
<td>3,000,000</td>
<td>Fry</td>
</tr>
<tr>
<td>1981</td>
<td>Walleye</td>
<td>1,500,000</td>
<td>Fry</td>
</tr>
<tr>
<td>1983</td>
<td>Walleye</td>
<td>1,300,000</td>
<td>Fry</td>
</tr>
<tr>
<td>1985</td>
<td>Walleye</td>
<td>1,500,000</td>
<td>Fry</td>
</tr>
<tr>
<td>1986</td>
<td>Walleye</td>
<td>7,123</td>
<td>Fgl</td>
</tr>
<tr>
<td></td>
<td>Walleye</td>
<td>1,095</td>
<td>Yrl</td>
</tr>
<tr>
<td>1987</td>
<td>Walleye</td>
<td>1,300,000</td>
<td>Fry</td>
</tr>
<tr>
<td>1988</td>
<td>Walleye</td>
<td>21,650</td>
<td>Fgl</td>
</tr>
<tr>
<td>1989</td>
<td>Walleye</td>
<td>1,300,000</td>
<td>Fry</td>
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<tr>
<td>1990</td>
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<td>1,138</td>
<td>Yrl</td>
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<td>1991</td>
<td>Walleye</td>
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<tr>
<td>1992</td>
<td>Walleye</td>
<td>4,964</td>
<td>Fgl</td>
</tr>
<tr>
<td>1994</td>
<td>Walleye</td>
<td>1,300,000</td>
<td>Fry</td>
</tr>
<tr>
<td>1996</td>
<td>Walleye</td>
<td>3,823</td>
<td>Fgl</td>
</tr>
<tr>
<td>1999</td>
<td>Walleye</td>
<td>6,475</td>
<td>Fgl</td>
</tr>
</tbody>
</table>

Limited scapnetting for walleye eggs was conducted at four sites in 1982 and 1983. The results are as follows.

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of dips</th>
<th>No. of eggs sampled</th>
<th>No. eggs sampled</th>
<th>Scap net dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982</td>
<td>142</td>
<td>17</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td>80</td>
<td>55</td>
<td>0.69</td>
<td></td>
</tr>
</tbody>
</table>
NARRATIVE:
Past management: (cont’d)
Tullibee netting was not allowed after 1986 because of an apparent decline in tullibee abundance as indicated by low catch rates in personal gill nets.

Present limiting factors:
Because of the clouded stocking history of this lake, it is difficult to determine if natural reproduction is limited in Siseebakwet Lake. The age frequencies and stocking histories from past assessments offer some clues (see the figures entitled 'Number of Walleyes Sampled in Gill Nets by Year Class and the Years in Which Stocking Took Place'). During the 1994 assessment, all of the age-classes sampled were from stocked years. The two strongest year-classes (1992 and 88) were fingerling stocked years suggesting that fingerling stocking may have increased abundance in these years. During the 1991 assessment, the two most abundant age-classes were once again from fingerling stocked years. However, the 1990 and 1984 year-classes also appeared which were non-stocked years proving that some natural reproduction is taking place. Additionally, the distribution of the year-classes resembles the age distribution of a typical non-stocked population. The majority of the walleyes sampled in the 1988 assessment were from the one fingerling stocked year. Year-classes from fry-stocked years were as strong or stronger than non-stocked years. During the 1984 survey, the year with the lowest CPUE, the strongest year class was a fry stocked year. Walleyes were also sampled from three of the four non-stocked year-classes. No fingerlings were stocked in the period examined during this survey. In contrast to the findings of the 1984 survey, the 1979 assessment produced the highest catch rate on record. No fingerlings were stocked in this period either. The two strongest year-classes were fry stocked years, but non-stocked year-classes provided 31.6% of the walleyes that were aged. Aging from the 1975 survey indicates that the majority of the fish were from fry-stocked years. However, five of the seven years were stocked years. Furthermore, the strongest year-class was a non-stocked year. Once again, the distribution resembles a typical distribution which could be the result of natural reproduction. In general, it appears that the abundance of stocked year-classes typically exceed non-stocked years and that abundance of fingerling-stocked years exceed fry-stocked years. However, due to the variability of net catches and year-class strengths, interpretation of these data is difficult. Future assessment of natural reproduction versus fingerling stocking and fry stocking will require a more conservative stocking regime than in past years.

The illegal introduction of smelt is a potential problem because of the close proximity of a population in Pokegama Lake. Natural barriers in Sugar Brook have apparently prevented their movement into Siseebakwet. In addition, the culvert under Co. Rd. 17 was elevated to further prevent their migration. The introduction of smelt could seriously harm the walleye and tullibee populations.

Social considerations:
Siseebakwet Lake shoreline ownership is primarily private and the majority is developed. The 1984 survey states that 100% of the of the shoreline is mixed hardwood and conifers. At that time, there was 1 resort with 20 cabins and 102 private homes and cabins. The golf course located at the resort was upgraded to an 18 hole course recently. There is a county owned public access on the northwest shoreline off Co. Rd. 458.
NARRATIVE:

Survey needs:
A population assessment will be conducted in August 2001. Bony parts should be taken from walleyes and northern pike for age and growth analysis. The age distribution of the sampled walleyes should be closely examined to determine the relative strength of year-classes from stocked versus non-stocked years. Water chemistry samples should be taken at this time. Because of the amount of development, including the recent addition of a golf course that is in close proximity to the lake, total phosphorus and chlorophyll a measurements should be included.

Habitat development and protection:
In 1950, the outlet, Sugar Brook, was cleared of snags and partially dredged resulting in a drop in water level. Rip-rap was then placed at the mouth of the stream to return the lake to its former level. Since this time, there have been several disagreements between lakeshore owners regarding the proper lake level resulting in occasional alterations to the rip-rap dam. Water level measurements taken in 1987, showed the lake was near its historical level. The Division of Waters suggested placing a permanent dam at the outlet, but instead settled on a gauge. The residents have agreed to use the gauge to maintain the water near its historic level.

Northern pike use the inlet on the west shore to access Little Siseebakwet Lake during the spawn. Because it is likely that Little Siseebakwet Lake serves as a nursery area for Siseebakwet, any action that would impede fish movement in the stream should not be allowed.

The resort on the northeast shore of the lake was purchased by Rutgers in the early 1990's. As part of the renovation of the resort, the golf course was upgraded from a 9-hole course to an 18-hole course. One fairway and one green are in close proximity to the lake and to Sugar Brook. Most of the riparian vegetation has been removed in this area. This raises some concerns about the amount of nutrients that reach the lake. It is also likely that much of the rest of the course drains into either the lake or Sugar Brook, (which flows into Pokegama Lake). The Resort is attempting to minimize negative impacts on the lake. Fertilization rates are being kept to a minimum and organic fertilizers are used on the areas near the lake. No insecticides are used and fungicide applications are kept to a minimum. A culvert which drains a small wetland is being raised to increase the holding capacity of the pond. There are also plans to plant some riparian vegetation along the stream. However, nutrient levels in the lake should be monitored in future years. If nutrient levels begin to rise, planting of buffer strips could be recommended. It is possible that Sugar Brook provides some spawning habitat for various species of fish so it too should be protected.

Sugar Lake Lodge is also participating in the DNR bulrush restoration program. In spring of 1996, the DNR will plant 625 ft² of bulrush in front of the resorts property to both improve aesthetics and to reduce erosion.
Habitat development and protection: (cont’d)

In 1992, the DNR accepted a conservation easement on the west shore of Siseebakwet Lake. The one mile of shoreline that this area encompasses contains a large portion of the bulrush found on the lake. This easement should prove very beneficial by protecting this valuable spawning and juvenile habitat for bluegill and largemouth bass. In addition, bulrush provides protection against shoreline erosion and is very efficient at filtering out nutrients from run-off.

In 1994, the Siseebakwet Lake Association and the SWCD investigated complaints of localized submergent vegetation growth on the north shore of the lake, west of the access. It was discovered that a two foot deep ditch had been dug several years earlier that drained a wetland on the north side of Co. Rd. 458. During spring run-off and heavy rain events, run-off from the wetland carries water high in phosphorus and tannins into Siseebakwet. The landowners plan to raise the bottom of the ditch about one foot at the wetland outlet in 1996. This will increase the area of the wetland, resulting in an increase in its holding capacity, which should in turn reduce the frequency of run-off events. In addition, the SWCD is pursuing the possibility of implementing erosion control measures in the ditch to reduce the amount of nutrients and sediment that are entering the lake from erosion.

It was also noted in the above mentioned investigation that there were signs of non-conforming septic systems in the area of increased submergent vegetation. The Lake Association has formed a committee which will attempt to survey the existing systems around the lake and recommend improvements for all non-conforming systems. The Lake Association is also very active in educating any new residents in Best Management Practices for their shoreline.

Commercial Fishery:

There is one mention of rough fish removal in 1963 when 9,771 pounds of bullheads were removed. However, testnetting indicates that rough fish abundance is too low at this time to warrant any commercial fishing.

Stocking plan:

Because walleye year classes have been stronger in stocked years than non-stocked years in recent assessments, walleye stocking will be continued on Siseebakwet Lake. However, because stocking appears to suppress the effects of natural reproduction, and because walleye year class strengths vary naturally, walleye fingerlings will be stocked less frequently. Mississippi River strain walleye fingerlings will be stocked at a rate of 1 pound/ littoral acre (292 pounds) in 1996, 1999, 2002. By having a larger gap between stocked years, evaluation of the success of natural reproduction will be greatly enhanced.

Other Management Tools:

If fall, walleye fingerling electrofishing is determined to be effective, it could be used on Siseebakwet in 1999 - 2001. These data would then supplement the data from the 2001 assessment and aid in the assessment of natural reproduction.
This appendix presents selected data from a preliminary study of Siseebakwet Lake conducted primarily between October 1998 and November 1999. This study was related to but different from the 1999 Lake Assessment Project (LAP) conducted at Siseebakwet Lake. This study focuses more on interactions between ground water and surface water. This work was conducted primarily by Joe Magner and Tim Thurnblad of the Minnesota Pollution Control Agency (MPCA) with the assistance of Don Olson, resident of Siseebakwet Lake, Art Norton, Justin Watkins and Rian Reed of the Itasca County Soil and Water Conservation District and Ed Swain, Will Munson and Steve Heiskary of the MPCA.

The ground water and surface water interaction study was begun partially because Siseebakwet Lake has exhibited some properties that were not easy to explain by traditional assumptions about the interrelationships among phosphorus, chlorophyll a and Secchi disk transparency. Siseebakwet Lake does not fit the pattern normally seen for a Northern Lakes and Forests Ecoregion lake with low suspended solids and little coloring from organic staining. It was believed that more information about the environmental setting of Siseebakwet Lake would be needed to satisfactorily interpret the data from a typical LAP. Due to the special nature of this marl lake, there is also an emphasis on examining ground-water and surface-water interactions and calcium carbonate equilibrium chemistry.

PRELIMINARY DATA

Some of the data and preliminary interpretations have been included in the main body of the preceding report. Tritium results were discussed earlier in the report (Table 3 - Age of Ground Water Adjacent to Siseebakwet Lake Based on Tritium Analysis). More complete data sets for some other parameters are presented here for reference.

Water Chemistry Results

Table 26 - Water Chemistry: Ground Water and Surface Water Interaction Study, 1998-1999 shows the analytical results for lake water, ground water, stream water, rain water and ground water sampled in the Siseebakwet Lake area. Samples collected at site 101 were collected at the same location (site 101) as for the LAP study. These samples were collected through a tube with its opening set at a depth of approximately 0.5 to 1 meter below the lake surface and compare most closely to the 0 - 2 meter integrated sample depth used for collection of the shallowest surface water samples in the LAP study. All standard water chemistry samples for laboratory analysis of ground water, lake water and stream water for this study and all field-alkalinity titrations except for those completed in October 1998 were filtered in the field through 0.45 micron pore size filter paper (Geotech cellulose acetate Geofilter: 142 mm diameter filter with 0.45 micron pore size). October 1998 field alkalinity titrations were not filtered. In addition, the rain-water samples were not filtered.

Note that none of the samples collected for the Lake Assessment Project as shown in Table 12 - Site 101 Water-Quality Data for Siseebakwet Lake (May – October 1999): Minnesota Department of Health Laboratory and Table 13 - Inlet Streams Water-Quality Data for Siseebakwet Lake (May – Oct. 1999): Minnesota Dept. of Health Laboratory, were filtered.
### Table 26 - Water Chemistry: Ground Water and Surface Water Interaction Study, 1998-1999

(University of Minnesota Hydrogeology Laboratory, St. Paul, Minnesota)

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Lake 101</th>
<th>Lake 101</th>
<th>Lake 101</th>
<th>Lake 101</th>
<th>Groundwater 410</th>
<th>Groundwater 410</th>
<th>Groundwater 410</th>
<th>Groundwater 410</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (ºC)</td>
<td>10.9</td>
<td>9.8</td>
<td>25.8</td>
<td>11.7</td>
<td>10.9</td>
<td>9.6</td>
<td>23.0</td>
<td>13.2</td>
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<td>pH</td>
<td>7.79</td>
<td>8.42</td>
<td>8.42</td>
<td>8.10</td>
<td>6.98</td>
<td>7.60</td>
<td>7.59</td>
<td>7.60</td>
</tr>
<tr>
<td>Cond (µmhos)</td>
<td>270</td>
<td>275</td>
<td>262</td>
<td>245</td>
<td>480</td>
<td>468</td>
<td>492</td>
<td>460</td>
</tr>
<tr>
<td>Redox (mV)</td>
<td>115</td>
<td>182</td>
<td>200</td>
<td>-140</td>
<td>73</td>
<td>-44</td>
<td></td>
<td></td>
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<tr>
<td>D.O. (ppm)</td>
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<td>7.6</td>
<td>8.3</td>
<td>2.0</td>
<td>1.6</td>
<td>2.0</td>
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<td></td>
</tr>
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</table>

#### Cations (ppm)

<table>
<thead>
<tr>
<th>Ca</th>
<th>56.6</th>
<th>34.9</th>
<th>34.0</th>
<th>34.2</th>
<th>80.4</th>
<th>66.4</th>
<th>68.1</th>
<th>67.3</th>
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<tbody>
<tr>
<td>Mg</td>
<td>12.8</td>
<td>12.6</td>
<td>12.7</td>
<td>12.8</td>
<td>20.0</td>
<td>20.2</td>
<td>17.1</td>
<td>20.5</td>
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<td>Na</td>
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<tr>
<td>K</td>
<td>1.47</td>
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<td>1.51</td>
<td>2.63</td>
<td>1.63</td>
<td>2.74</td>
<td>2.57</td>
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<tr>
<td>Al</td>
<td>0.111</td>
<td>0.003</td>
<td>0.074</td>
<td>0.005</td>
<td>0.076</td>
<td>0.007</td>
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</tr>
<tr>
<td>Fe</td>
<td>0.04</td>
<td>&lt;0.02</td>
<td>0.23</td>
<td>&lt;0.02</td>
<td>0.05</td>
<td>0.08</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td>Mn</td>
<td>0.017</td>
<td>&lt;0.001</td>
<td>0.005</td>
<td>0.002</td>
<td>0.048</td>
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<td>0.259</td>
<td>0.242</td>
</tr>
<tr>
<td>Sr</td>
<td>0.112</td>
<td>0.074</td>
<td>0.071</td>
<td>0.072</td>
<td>0.227</td>
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<td>0.188</td>
<td>0.207</td>
</tr>
<tr>
<td>Ba</td>
<td>0.050</td>
<td>0.043</td>
<td>0.041</td>
<td>0.043</td>
<td>0.114</td>
<td>0.125</td>
<td>0.123</td>
<td>0.148</td>
</tr>
<tr>
<td>Si</td>
<td>6.7</td>
<td>5.9</td>
<td>5.2</td>
<td>5.4</td>
<td>11.5</td>
<td>10.6</td>
<td>11.9</td>
<td>11.2</td>
</tr>
</tbody>
</table>

#### Anions (ppm)

| Meas Alk (CaCO3) | 145 | 134 | 136 | 131 | 244 | 242 | 242 | 425 |
| Calc Alk (CaCO3) | 198 | 141 | 302 | 261 |
| Cl  | 1.73 | 2.12 | 1.70 | 2.24 | 0.69 | 0.77 | 0.53 | 2.68 |
| Br  | <0.015 | <0.015 | <0.015 | <0.015 | <0.015 | <0.015 | <0.015 | <0.015 |
| NO2-N | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 |
| NO3-N | <0.005 | <0.005 | <0.005 | 0.008 | <0.005 | <0.005 | 0.005 | 0.012 |
| SO4  | 5.22 | 5.34 | 5.12 | 5.07 | 6.77 | 7.35 | 3.02 | 6.96 |
| PO4-P | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 0.05 | <0.02 |
| total P | 0.05 | <0.02 | 0.04 | <0.02 | 0.06 | <0.02 | 0.08 | 0.04 |
| F   | 0.09 | 0.10 | 0.10 | 0.12 | 0.17 | 0.19 | 0.24 | 0.22 |
Table 26 - Water Chemistry: Ground Water and Surface Water Interaction Study, 1998-1999 (continued)

(University of Minnesota Hydrogeology Laboratory, St. Paul, Minnesota)

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Groundwater 411</th>
<th>Groundwater 415</th>
<th>Groundwater 415</th>
<th>Groundwater 415</th>
<th>Groundwater 415</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (°C)</td>
<td>10.1</td>
<td>11.5</td>
<td>8.4</td>
<td>13.8</td>
<td>10.1</td>
</tr>
<tr>
<td>pH</td>
<td>6.50</td>
<td>6.60</td>
<td>7.42</td>
<td>7.44</td>
<td>7.60</td>
</tr>
<tr>
<td>Cond (µmhos)</td>
<td>590</td>
<td>720</td>
<td>444</td>
<td>515</td>
<td>470</td>
</tr>
<tr>
<td>Redox (mV)</td>
<td>1</td>
<td>1</td>
<td>53</td>
<td>66</td>
<td>5</td>
</tr>
<tr>
<td>D.O. (ppm)</td>
<td>1.9</td>
<td>1.9</td>
<td>&lt;1</td>
<td>1.5</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Cations (ppm)</td>
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<td></td>
<td></td>
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<tr>
<td>Ca</td>
<td>71.4</td>
<td>115.7</td>
<td>66.7</td>
<td>73.8</td>
<td>70.5</td>
</tr>
<tr>
<td>Mg</td>
<td>12.8</td>
<td>25.1</td>
<td>15.1</td>
<td>17.3</td>
<td>16.4</td>
</tr>
<tr>
<td>Na</td>
<td>8.5</td>
<td>11.1</td>
<td>6.10</td>
<td>4.52</td>
<td>7.73</td>
</tr>
<tr>
<td>K</td>
<td>10.8</td>
<td>2.80</td>
<td>0.37</td>
<td>1.40</td>
<td>1.36</td>
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<td>Al</td>
<td>0.387</td>
<td>0.023</td>
<td>0.016</td>
<td>0.015</td>
<td>0.005</td>
</tr>
<tr>
<td>Fe</td>
<td>4.50</td>
<td>0.16</td>
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<td>0.69</td>
<td>1.69</td>
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<tr>
<td>Mn</td>
<td>0.451</td>
<td>0.032</td>
<td>0.004</td>
<td>0.217</td>
<td>0.200</td>
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<tr>
<td>Sr</td>
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<td>0.114</td>
<td>0.067</td>
<td>0.086</td>
<td>0.076</td>
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<tr>
<td>Ba</td>
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<td>0.097</td>
<td>0.028</td>
<td>0.040</td>
<td>0.047</td>
</tr>
<tr>
<td>Si</td>
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<td>10.9</td>
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<td>9.4</td>
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<tr>
<td>Anions (in ppm)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meas Alk (CaCO₃)</td>
<td>201</td>
<td>335</td>
<td>222</td>
<td>275</td>
<td>229</td>
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<tr>
<td>Calc Alk (CaCO₃)</td>
<td>244</td>
<td>373</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl</td>
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<td>24.2</td>
<td>0.98</td>
<td>1.78</td>
<td>2.52</td>
</tr>
<tr>
<td>Br</td>
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<td>0.018</td>
<td>&lt;0.015</td>
<td>&lt;0.015</td>
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<td>NO₂-N</td>
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<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>NO₃-N</td>
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<td>0.115</td>
<td>0.107</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>SO₄</td>
<td>3.14</td>
<td>11.7</td>
<td>8.6</td>
<td>9.5</td>
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<tr>
<td>PO₄-P</td>
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<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>total P</td>
<td>0.05</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
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<tr>
<td>F</td>
<td>0.13</td>
<td>0.09</td>
<td>0.09</td>
<td>0.10</td>
<td>0.10</td>
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</table>
Table 26 - Water Chemistry: Ground Water and Surface Water Interaction Study, 1998-1999 (continued)

(University of Minnesota Hydrogeology Laboratory, St. Paul, Minnesota)

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<thead>
<tr>
<th>Site</th>
<th>SW Inlet</th>
<th>WNW Inlet</th>
<th>WNW Inlet</th>
<th>WNW Inlet</th>
<th>WNW Inlet</th>
<th>Well</th>
<th>Well</th>
<th>Well</th>
</tr>
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<tbody>
<tr>
<td>Name</td>
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<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>466</td>
<td>467</td>
<td>468</td>
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<tr>
<td>Temp (ºC)</td>
<td>7.4</td>
<td>24.0</td>
<td>7.3</td>
<td>7.6</td>
<td>8.1</td>
<td>7.7</td>
<td>8.1</td>
<td>7.7</td>
</tr>
<tr>
<td>pH</td>
<td>8.14</td>
<td>7.20</td>
<td>7.73</td>
<td>7.59</td>
<td>7.60</td>
<td>7.74</td>
<td>7.44</td>
<td>7.10</td>
</tr>
<tr>
<td>Cond (µmhos)</td>
<td>320</td>
<td>250</td>
<td>320</td>
<td>410</td>
<td>410</td>
<td>740</td>
<td>740</td>
<td>740</td>
</tr>
<tr>
<td>Redox (mV)</td>
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<td>172</td>
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<td>-96</td>
<td>-96</td>
<td>-57</td>
<td>-57</td>
<td>-57</td>
</tr>
<tr>
<td>DO (ppm)</td>
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<td>5.2</td>
<td>6.6</td>
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<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
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</table>

**Cations (ppm)**

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<tr>
<th></th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>K</th>
<th>Al</th>
<th>Fe</th>
<th>Mn</th>
<th>Sr</th>
<th>Ba</th>
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<tr>
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<td>43.6</td>
<td>13.4</td>
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<td>0.010</td>
<td>&lt;0.02</td>
<td>0.011</td>
<td>0.082</td>
<td>0.038</td>
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<td>61.8</td>
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<td>3.19</td>
<td>1.73</td>
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<td>0.31</td>
<td>0.069</td>
<td>0.093</td>
<td>0.042</td>
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<td>34.2</td>
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<td>1.86</td>
<td>0.52</td>
<td>0.020</td>
<td>0.15</td>
<td>0.052</td>
<td>0.045</td>
<td>0.032</td>
</tr>
<tr>
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<td>36.2</td>
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<td>2.02</td>
<td>4.68</td>
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<td>0.26</td>
<td>0.034</td>
<td>0.051</td>
<td>0.036</td>
</tr>
<tr>
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<td>49.5</td>
<td>12.1</td>
<td>3.24</td>
<td>1.57</td>
<td>0.006</td>
<td>0.26</td>
<td>0.078</td>
<td>0.073</td>
<td>0.053</td>
</tr>
<tr>
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<td>57.5</td>
<td>16.4</td>
<td>10.6</td>
<td>2.03</td>
<td>0.003</td>
<td>0.33</td>
<td>0.187</td>
<td>0.160</td>
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<td>14.4</td>
<td>2.93</td>
<td>1.25</td>
<td>0.002</td>
<td>4.10</td>
<td>0.221</td>
<td>0.082</td>
<td>0.033</td>
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<tr>
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<td>105.5</td>
<td>29.1</td>
<td>12.3</td>
<td>1.94</td>
<td>&lt;0.002</td>
<td>2.87</td>
<td>0.491</td>
<td>0.148</td>
<td>0.062</td>
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</tbody>
</table>

**Anions (in ppm)**

<table>
<thead>
<tr>
<th></th>
<th>Meas Alk (CaCO$_3$)</th>
<th>Calc Alk (CaCO$_3$)</th>
<th>Cl</th>
<th>Br</th>
<th>NO$_2$-N</th>
<th>NO$_3$-N</th>
<th>SO$_4$</th>
<th>PO$_4$-P</th>
<th>total P</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>157</td>
<td>206</td>
<td>2.41</td>
<td>0.015</td>
<td>&lt;0.005</td>
<td>0.013</td>
<td>6.24</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>168</td>
<td>206</td>
<td>0.78</td>
<td>&lt;0.015</td>
<td>&lt;0.005</td>
<td>0.103</td>
<td>3.79</td>
<td>&lt;0.02</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>109</td>
<td>178</td>
<td>0.73</td>
<td>&lt;0.015</td>
<td>&lt;0.005</td>
<td>0.037</td>
<td>4.01</td>
<td>&lt;0.02</td>
<td>0.04</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>135</td>
<td></td>
<td>3.28</td>
<td>&lt;0.015</td>
<td>&lt;0.005</td>
<td>0.020</td>
<td>1.95</td>
<td>&lt;0.02</td>
<td>0.03</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>162</td>
<td></td>
<td>3.87</td>
<td>&lt;0.015</td>
<td>&lt;0.005</td>
<td>0.046</td>
<td>3.09</td>
<td>&lt;0.02</td>
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</tr>
<tr>
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<td>219</td>
<td></td>
<td>0.70</td>
<td>&lt;0.015</td>
<td>&lt;0.005</td>
<td>0.005</td>
<td>1.87</td>
<td>&lt;0.02</td>
<td>0.08</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>215</td>
<td></td>
<td>1.41</td>
<td>&lt;0.015</td>
<td>&lt;0.005</td>
<td></td>
<td>8.44</td>
<td>&lt;0.02</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>333</td>
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<td>&lt;0.015</td>
<td>&lt;0.005</td>
<td></td>
<td>17.6</td>
<td>&lt;0.02</td>
<td>0.08</td>
<td></td>
</tr>
</tbody>
</table>
The samples labeled as "groundwater" in the "Site Name" row of Table 26 were collected from approximately 0.5 to 2 feet below the lake bed. The basic water chemistry samples were analyzed at or through the University of Minnesota Hydrogeology Laboratory in St. Paul, Minnesota.

Tritium Ground Water Age for Wells Adjacent to Sisebakwet Lake

The three wells listed in Table 26 had well screen open intervals ranging from a minimum of 50 ft. to a maximum of 130 ft. and tritium ages ranging from 9 to 11 years as indicated earlier in Table 3 - Age of Ground Water Adjacent to Sisebakwet Lake Based on Tritium Analysis. For discussion of these results, please refer to the Hydrogeochemistry section which begins on page 37.

Stable Isotope Analyses

The ratios of hydrogen isotopes and of oxygen isotopes in water vary according to the history of the water. For example, as water evaporates from a lake, the ratios of these isotopes in the lake water left behind change leaving an identifiable isotopic signature in the lake water. Similarly, the isotopic makeup of the evaporating water is altered and, when it later falls as precipitation, it has an isotopic signature that is distinct from the lake water and other parts of the hydrologic cycle. Analysis of the stable isotopes of hydrogen and oxygen in water sampled from different parts of the hydrologic cycle can help to quantify the water budget for a water watershed. These isotopic data can also provide valuable insight on mixing of water among the various parts of the hydrologic cycle. The results of the isotopic analyses are presented in Table 27 - Stable Isotope Analyses for Hydrogen and Oxygen.

Water Budget Modeling\textsuperscript{12}

Two models were used to estimate the 1998 water budget. Additionally, to help understand the range of hydraulic residence times (HRT), wet and dry climatic conditions were estimated and used to predict HRT and the relative percentage of ground-water inflow. The more data intense model presented by Krabbenhoft et al. (1990) requires measured inflows and outflows and a best estimate of evaporation. This model then links the measured flux to measured $\delta^{18}O$ values for annual average precipitation, evaporation, surface inflows/outflows and change in lake stage to calculate the subsurface flux. The second model presented by Burns and McDonnell, (1998) compares the $\delta^{18}O$ amplitude (from winter to summer) of a best-fit sine curve for precipitation to the amplitude of a similar curve for the lake $\delta^{18}O$ values. The model assumes a seasonal response and uniform mixing in the watershed and lake.

\textsuperscript{12} The Water Budget Modeling section was prepared by Joe Magner of the Minnesota Pollution Control Agency.
Table 27 - Stable Isotope Analyses for Hydrogen and Oxygen

(The deuterium $^2$H) and oxygen 18 ($^{18}$O) results are expressed as per mil variation from SMOW [Standard mean ocean water])

<table>
<thead>
<tr>
<th>SAMPLE TYPE</th>
<th>SITE</th>
<th>DATE</th>
<th>$^2$H</th>
<th>$^{18}$O</th>
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<td>Lake Water</td>
<td>101</td>
<td>99-05-13</td>
<td>-59</td>
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<tr>
<td>Groundwater</td>
<td>410</td>
<td>99-05-13</td>
<td>-79.6</td>
<td>-11.56</td>
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<td>99-07-21</td>
<td>-56.6</td>
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<td></td>
<td>-11.97</td>
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<td></td>
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<td>-11.12</td>
</tr>
<tr>
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<td>99-10-11</td>
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<tr>
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<td>99-10-11</td>
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</tr>
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<tr>
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<td>-11.25</td>
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<tr>
<td>Replicate</td>
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<td></td>
<td>-29.9</td>
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</tbody>
</table>

Input data for precipitation was obtained from the Pokegama Dam station. Potential evapo-transpiration (PET) was obtained using the Jensen-Haise method where solar radiation was estimated using values from Winter et al. (1998) for Williams Lake. Surface inflows/outflows were measured by the Itasca SWCD. $\delta^{18}$O samples were collected by MPCA staff and values were determined by the University of Waterloo, Waterloo, Canada.

The results indicated an average HRT (in the lake) of six and one-half years with ground water contributing about 43 % of the lake input budget. Precipitation accounted for an additional 35 % of the lake input along with 22 % from surface
inflows. Measured surface-water outflow made up about 42% of the total budget along with 35% PET and 23% lake-water out-seepage to ground water.

It is important to note that budgeting methods that do not account for subsurface flux would assume some ground water input with this data, but would greatly underestimate the percentage and not even account for lake-water out-seepage. This can cause serious errors in estimating HRT.

A wet climate scenario would decrease the ground water input to about 30 to 35% depending on antecedent moisture conditions prior to runoff events. HRT would still remain greater than 6 years. A dry climate scenario would increase the ground water input to about 60 to 65% depending on PET and aquifer storage or relative gradient (hydraulic head differential between ground water sources and surface water receptor) created by previous climatic conditions. Under this scenario HRT would increase to about 7 years.
APPENDIX H - PHYTOPLANKTON COMPOSITION PERCENT AT SITE 101 (1999)

Table 28 - Phytoplankton Composition % Near the Surface (0 - 2m deep)

<table>
<thead>
<tr>
<th>Type</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>0</td>
<td>20</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Other</td>
<td>15</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Yellow-Brown</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Diatoms</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Blue-Green</td>
<td>80</td>
<td>65</td>
<td>80</td>
<td>65</td>
<td>75</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 29 - Phytoplankton Composition % in the Shallow Zone (3.5 – 4 m deep)

<table>
<thead>
<tr>
<th>Type</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Yellow-Brown</td>
<td></td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Diatoms</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Blue-Green</td>
<td>75</td>
<td>80</td>
<td>75</td>
<td>55</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 30 - Phytoplankton Composition % at the Thermocline (7.5 – 16.5 m deep)

<table>
<thead>
<tr>
<th>Type</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>5</td>
<td>15</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Yellow-Brown</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Diatoms</td>
<td>30</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Blue-Green</td>
<td>55</td>
<td>65</td>
<td>90</td>
<td>75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX I - CALCIUM CARBONATE EQUILIBRIUM

WHAT IS A MARL LAKE?

SISEEBAKWET LAKE IS A MARL LAKE. The lake bottom sediment core collected from Siseebakwet Lake contained approximately 52% to 54% calcium carbonate (CaCO3) in the portions that represent modern times. According to the Dictionary of Mining, Mineral, and Related Terms, Second Edition 1996; U.S. Bureau of Mines, U.S. Department Of The Interior, marl is a

A soft, grayish to white, earthy or powdery, usually impure, calcium carbonate precipitated on the bottoms of present-day freshwater lakes and ponds, largely through the chemical action of aquatic plants, or forming deposits that underlie marshes, swamps, and bogs that occupy the sites of former (glacial) lakes. The calcium carbonate may range from 90% to less than 30%.

According to Dean and Megard, 1993:

The sediment in these lakes typically contains more than 30% CaCO3. Such CaCO3 rich sediment is called marl, and lakes that contain marl are often referred to as marl lakes.

Therefore, it appears that it would be appropriate to call Siseebakwet lake a “marl” lake.

WHAT IS THE SOURCE OF MARL?

According to Dean and Megard, 1993,

The major sources of CaCO3 in marl lakes are (1) inorganically precipitated CaCO3, (2) photosynthesis-induced, inorganically precipitated (bio-induced; Dean, 1981) CaCO3, (3) biogenic CaCO3 in the form of remains of calcareous plants and animals, and (4) detrital carbonate minerals derived from carbonate rocks in the drainage basin." …. Biogenic CaCO3, mainly detritus from mollusks and macroscopic calcareous algae (e.g., Chara), may be the dominant source of CaCO3 in the shallow-water (littoral) part of a marl lake, and thick deposits of CaCO3 commonly form a platform or marl bench out from shore to the depth limit of rooted aquatic vegetation. Some of this biogenic CaCO3 may be transported to the deeper (profundal) part of the lake by slumping and turbidity currents, but most CaCO3 in profundal sediments is produced in the surface waters (pelagic zone) by inorganic or bioinduced precipitation (Dean, 1981).

Kelts and Hsu (1978) explain that "In lakes, the calcium ion mainly derives from river or ground water input and sediment refluxing, whereas carbonate ions may also be derived from direct atmospheric equilibria, respiration, and bacterial reduction of organic matter." Substantial amounts of calcium carbonate can build up on the lakebeds of marl lakes over the years. Otsuki and Wetzel, 1974, found that a small lake in southwestern lower Michigan had a calcium carbonate precipitation rate of 446 g per m² per year.
SEDIMENT CORE ANALYSIS

On a rainy, windy and cold October 19, 1999, three attempts at collecting an acceptable lake bottom sediment core from Siseebakwet Lake were attempted. The third attempt was successful. The purpose of collecting the sediment core was to evaluate the history and nature of sediment accumulation in Siseebakwet Lake to determine if there had been any changes over time. In particular, the rate of total sediment accumulation, the rate of calcium carbonate (CaCO₃) accumulation and the percent of CaCO₃ compared to the accumulation of all sediment materials were studied for various times dating back approximately 1000 years. Dates assigned to specific intervals of the core for more recent times are more reliable than for those intervals that represent deposition that occurred many hundreds of years ago. Analysis of lead 210 activity in the sediments at various depths within the core is the key tool that allowed approximate dates to be assigned to individual vertical segments of the core.

SEDIMENT CORE LOCATION LS3 (SUCCESSFUL). The successful sampling location, LS3 (Figure 4 - Monitoring Sites Location Map for Siseebakwet Lake), was roughly about halfway between the center of the lake and the shoreline along an imaginary line extending southwest from the center of the lake (GPS coordinates: 47 09 21.39861 latitude North, 093 40 40.80286 longitude West). The water depth at the sampling point was approximately 61 feet. A piston coring method was used to successfully obtain an “undisturbed” vertical core of lake sediments. The length of the recovered sample core was 0.92 m (3.02 feet). The upper portion of the core had fairly light coloring, the middle portion of the core was darker and the lower portion of the core was again lighter.

SEDIMENT CORE LOCATION LS1. At the first sediment sampling location LS1, about halfway between the center of the lake and the southeastern shore in about 47 feet of water, approximately 4.3 feet of soft sediment was penetrated before striking what appeared to be gravel. The 4.3 feet of soft sediment appeared to be a marl-like material. The sediment sample fizzed readily after adding a small amount of 10 % hydrochloric acid solution suggesting a high CaCO₃ content.

SEDIMENT CORE LOCATION LS2. At sediment sampling location LS2 (GPS coordinates 47 09 16.52984 latitude North, 093 40 33.75639 longitude West ), located roughly 600 feet southeast of LS1 in about 64 feet of water, a minimum of about 4.9 feet of soft sediment was penetrated. A 4.3 foot portion of the soft sediment was recovered. The upper 6 to 8 inches of the material appeared relatively dark; the rest of the 4.3 foot sample was considerably lighter and appeared to have a high marl content. The sediment sample fizzed readily after adding a small amount of 10 % hydrochloric acid solution suggesting a high CaCO₃ content.

ASSUMPTIONS USED FOR INTERPRETATION. The interpretation of sediment core analysis data is necessarily dependent on a number of simplifying assumptions, some of which cannot be verified with the current, limited set of data. One key assumption is that sediment deposition at the core location was sequential in time and that the sediments comprising a given small vertical zone in the core do not include re-mixed sediments from widely-spaced points in time. Based on this initial assumption and others, we assume that the deeper portions of the core represent sediment deposition further back in time. The top of the core is essentially the current lake bottom. The interpretation that we feel is most likely based on available data and previous experience is given below.

TIME TRENDS. In approximately 1880 an upward trend in sediment accumulation began in the area of the sediment core. The rate of increase in the sediment accumulation rate leveled out by about 1920 but the sediment accumulation rate remained higher than in the pre-1880 period. The rate of sediment accumulation was then fairly stable at approximately 0.02 g/cm²/yr from 1900 to about 1960 with a slight increase beginning about 1965 - 1970. Then, about 1970 a relatively sharp increase
in sediment accumulation began. Between about 1970 and 1990, the rate of sediment accumulation doubled to about 0.04 g/cm²/yr. During the time period from 1800 on, changes in the CaCO₃ accumulation rate closely paralleled the overall sediment accumulation rate. Because of this, the percent of the total sediment that was composed of CaCO₃ remained essentially constant from 1800 on.

CALCIUM CARBONATE PERCENT. Quantitative analysis of the dried sediment is reported in three fractions: (1) organic matter, (2) calcium carbonate (CaCO₃) and (3) other inorganic matter. Those fractions can then be reported as a percent of the total sediment found in a particular time-segment of the core. At the sediment core location, the percent of calcium carbonate (CaCO₃) depositing as lake bottom sediment has remained essentially constant between 52% and 54% of the total sediment as far back as at least 1800, and probably earlier. In other words, even though the total amount of sediment accumulating at this location was increasing between 1970 and 1990, the percent of CaCO₃ was not increasing.

Similarly, the proportions of organic and inorganic matter remained constant. Organic matter is the remains of algae, bits of degraded aquatic plants (water lily, pond weed, etc.), leaves blown in from trees, and any eroded top soil. Inorganic matter includes eroded clay-sized mineral subsoil, iron precipitate, silica from diatoms, and the usual minerals associated with plant tissue (calcium, potassium, sodium). All of the sediment this far from shore is extremely fine-grained; large particles such as sand are too dense to be transported so far off shore. The Sediment has a Jell-O-like texture.

EXPLAINING THE TREND. If the actual amount of particulate matter in the lake as a whole changed significantly over time, it would be very unlikely that the fractions (percents) of the three measured components: 1) organic material, (2) calcium carbonate (CaCO₃) and (3) other inorganic material would stay almost exactly the same over time. For instance, if development in the watershed caused an increase in topsoil erosion, it seems unlikely that organic matter, calcium carbonate, and inorganic matter would all happen to increase in exactly the same proportion as loading for the past 200 years. Indeed, it is difficult to conceive of any change in the lake ecosystem that would cause all three fractions to increase exactly in proportion.

How can these results be explained? The results might be better explained by internal redistribution of lake sediments from elsewhere in the lake. More specifically, internal redistribution may have resulted in relatively more sediment being deposited at our sample core location at the expense of sediment being carried away from other parts of the lake. Lake sediment could have been redistributed from one portion of the lake to another by an underwater slope failure or some other more continuous process that could entrain lake bottom sediments to be transported to another lake location. For instance, sediment may have been better retained in shallow water in the past, but now moved preferentially to deeper water.

HOW CERTAIN IS OUR TREND THEORY? Based on the available sediment core information, the preliminary indication is that even though the rate of sediment accumulation has increased at our single sampling point, it appears probable that, on a lake-wide basis, there has not been an increase in sediment accumulation. There has not been an increase in the percent of CaCO₃ compared to total sediment accumulation since at least the year 1800. However, it is important to emphasize that our attempt to interpret this history from a single sediment core sample is open to significant uncertainty and is clearly less reliable than a more expensive study that would generate results from several lake bottom locations that can be compared against each other.
HOW CAN WE BETTER UNDERSTAND THE DEPOSITION HISTORY? Collection and analysis of two additional lake cores or possibly a diatom analysis of the previously collected sediment core may provide a more certain explanation for these trends in sediment accumulation.

EQUILIBRIUM CHEMISTRY INTERPRETATION

Laboratory analysis of the lake-bottom sediment core recovered from a deeper portion of the lake indicated that the calcium carbonate content was about 52 – 54 %. Field testing of rock and plant samples from various shallow parts of the lake, indicated the samples were covered with calcium carbonate. The sediment trap accumulated substantial amounts of calcium carbonate along with very active insect-like organisms in what can be described as an organic scum or ooze-like material. Laboratory analysis of ions in solution coupled with an equilibrium chemistry model indicated that Siseebakwet Lake was saturated with calcium carbonate when sampled.

What controls the saturation and precipitation of calcium carbonate in Siseebakwet Lake and how might these factors affect lake transparency? What other methods are available to evaluate calcium carbonate saturation in a lake?

**Calcium Carbonate On The Lakebed**

Time analysis of the lake-bottom sediment core indicates the calcium carbonate of lake sediments has remained in the 52 – 54 % range since about 1800 at the core location. These results indicate that precipitation of calcium carbonate out of Siseebakwet Lake water has been ongoing and relatively constant for a long time.

Calcium carbonate was found as an encrustation on rocks and plants in shallower waters in various parts of the lake as evidenced by a field test using dilute hydrochloric acid. A rooted, aquatic plant, *Chara*, which is known to process relatively large amounts of calcium carbonate, was observed near the northern shoreline (may occur elsewhere) and, as expected, reacted vigorously with a dilute hydrochloric acid solution.

**Sediment Trap Results**

A sediment trap was deployed from June through September 1999 to qualitatively assess what, if anything, was precipitating out of the lake water. The sediment trap was suspended below the lake surface from a buoy in roughly 45 ft. of water (location #26) about 1/5 of a mile from the southern shore, accumulated significant amounts of calcium carbonate. The sediment trap, a plastic tube with a closure to seal the bottom, was first deployed on June 10, 1999. The sediment was checked, sampled, cleaned and re-deployed on July 22, 1999, August 24, 1999 and September 15, 1999. Each month the sediment trap accumulated a slime or scum that had a relatively high calcium carbonate content as evidenced as evidenced by a field test using dilute hydrochloric acid. Sediment trap observations are summarized in Table 31 - Sediment Trap Results.
Table 31 - Sediment Trap Results

<table>
<thead>
<tr>
<th>COLLECTION DATES (1999)</th>
<th>DESCRIPTION</th>
<th>AMOUNT OF MATERIAL PRESENT</th>
<th>OTHER COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 10</td>
<td>Initial Deployment</td>
<td>New/None</td>
<td></td>
</tr>
<tr>
<td>July 22</td>
<td>The sediment trap was coated with a light-brown slimy material on the outside and the bottom of the inside.</td>
<td>About 1/8” of the brown material accumulated on the bottom plus a lot of particulates, some white, in suspension inside the tube.</td>
<td>The scum scrapings fizzed vigorously with 10% HCL solution suggesting the presence of calcium carbonate.</td>
</tr>
<tr>
<td>August 24</td>
<td>Very similar in color and amount as last month. Scum is light brown with some green tint.</td>
<td>About the same as last month. Some scum inside and outside, plus 1/8” of scum in bottom.</td>
<td>The scum fizzed vigorously with 10% HCL solution. Outlet tube was open so some material could have been lost through the bottom of trap.</td>
</tr>
<tr>
<td>September 15</td>
<td>Thinner, coating of light brown (outside) to tan (inside) slimy material.</td>
<td>Much less than last two months. Very thin coating on outside; ~0.1 mm thick on bottom.</td>
<td>Material on outside of trap was teeming with light green organisms about 1 mm in length.</td>
</tr>
</tbody>
</table>

**Calcium Carbonate Saturation**

A wide variety of factors can affect whether or not calcium carbonate will reach or exceed its saturation point in lake water and whether or not a calcium carbonate crystal will re-dissolve as it travels toward or rests on the lake bed. Some of the primary factors include the pH and temperature of the water plus the concentration of calcium (most typically as Ca\(^{2+}\)) and total inorganic carbon (which can be represented by various species including CO\(_2\), H\(_2\)CO\(_3\), HCO\(_3^\)\(^-\), CO\(_3^{2-}\)) in lake water.

This study produced many forms of evidence that calcium carbonate has (often) been at or above saturation and has (often) been precipitating out of solution in Sisebakwet Lake for an extended period time, for many hundreds of years at a minimum.

**SUMMARY OF EVIDENCE FOR ONGOING SATURATION AND PRECIPITATION OF CACO\(_3\).** Based on many forms of evidence described above (and summarized directly below),

- 52 – 54 % calcium carbonate content in lake bottom sediments,
- calcium carbonate precipitate observed on plants and rock samples collected from various parts of the lake,
- substantial amounts of calcium carbonate captured in sediment trap suspended in lake water
- substantial amounts of calcium carbonate were held back on (apparently because the calcium carbonate had precipitated out of solution) on a 0.45 micron pore size filter when filtering a lake water sample in the field,
equilibrium chemistry modeling indicating that lake water was at or above saturation with respect to calcium carbonate,

there is clearly an overabundance of calcium carbonate available to Siseebakwet Lake water at all times. Even if the lake water is not saturated or supersaturated with calcium carbonate at all locations and depths at a certain point in time, there is always an abundance of calcium carbonate available in the lakebed to bring that water to saturation. In other words, if and when the lake water is well-mixed and in equilibrium with its lakebed, one that has vast quantities of calcium carbonate available, it is saturated with calcium carbonate.

CONDITIONS REPORTED IN SIMILAR LAKES. Some other lakes have been determined to remain over-saturated with respect to calcium carbonate or calcium more or less all the time. Otsuki and Wetzel (1974), through extensive and detailed analysis of a small lake in southwestern lower Michigan, found that the "Ca$^{2+}$ [calcium ion] concentration of all waters we examined contained more than 2 to 4 times the saturation values of Ca$^{2+}$ from the solubility product, even during the summer period".

Dean and Megard (1993) found that "Temperate-zone lakes that have drainage basins in carbonate bedrock or calcareous glacial drift [like Siseebakwet Lake's watershed] commonly have high concentrations (usually more than 1.0 milliequivalent per liter, or epm) of total dissolved alkaline-earth cations, mostly calcium and magnesium, and are saturated with CaCO$_3$ as low-Mg [magnesium] (< 4 mole% Mg) calcite at least during the late summer. The sediment in these lakes typically contains more than 30% CaCO$_3$."
Megard (1993), found that for Elk Lake (in Clearwater County, Minnesota) "The degree of CaCO3 saturation at any depth depends on whether the lake is mixing or stratified …". They explain further that for Elk Lake, in late October 1966, when "summer stratification had almost disappeared and temperatures were near 7 degrees C down to 21 m there was still a weak thermocline. The pH was about 8.0 at all depths above the thermocline, and this water was over-saturated with calcite. However, the water below the thermocline contained little dissolved oxygen, had a pH of less than 7.7, and was under-saturated with calcite."

In contrast they note that "during winter stratification (13 February 1967) all depths below 5 m were oxygen deficient, had pH values of less than 7.7, and were under-saturated with calcite." Mixing conditions were shown to favor over-saturation of calcite:

Later during spring circulation (5 May 1967), all depths were reaerated and oversaturated with calcite. The transition from calcite undersaturation to oversaturation during spring circulation occurred while water temperatures were still only 4 degrees C.

Under fully-stratified, summer conditions, they saw a clear difference between shallow and deep zones of Elk Lake:

During summer stratification (e.g., 11 July and 10 September, 1967; 12 July 1980), the epilimnion (depths above 6 m) is oversaturated with both calcite and dolomite but the hypolimnion (depths below 10 m) is undersaturated.

**Calcium Carbonate Precipitation**

Precipitation of calcium carbonate occurs when and where its components transition from the dissolved phase, as individual ions in solution, into a solid compound in the suspended phase (suspended in the lake water). When in the dissolved phase, the components are represented by individual ions such as calcium ions (Ca2+) and carbonate species, such as bicarbonate ions (HCO3-) and carbonate ions (CO32-) in solution in the lake water.

Under appropriate conditions, these ions can combine and drop out of solution as calcium carbonate in the form of a solid precipitate or particle that is suspended in the lake water. Precipitation of calcium carbonate can be represented by the simplified formula below:

\[
\text{Ca}^{2+} + \text{CO}_3^{2-} \rightarrow \text{CaCO}_3
\]

(simplified formula)

Precipitation of calcium carbonate is most likely to occur when the lake water is saturated or over-saturated with respect to calcium carbonate, but as explained below, other factors can also be important in determining whether precipitation occurs. Of course, under different (opposite) environmental conditions, the reaction described above can work in reverse and cause suspended calcium carbonate or other sources of calcium carbonate in contact with the lake to dissolve into the lake water.
Basic factors that can cause lake water to become saturated, supersaturated, or under-saturated with respect to calcium carbonate have been outlined earlier in this report. Kelts and Hsu (1978) summarize the causes of CaCO₃ supersaturation by stating:

**Two possible mechanisms which can induce supersaturation with respect to calcite are (1) biogenic, through assimilation of carbon dioxide by photosynthesizing plants, and (2) physical-chemical, through seasonal temperature effects on the solubility of carbon dioxide and calcite along with other factors listed in .... [see Table 32 - Summary of Factors Affecting Sedimentation and Precipitation of Calcium Carbonate for some of these factors].**

An increase in water temperature or pH leads to a decrease in the solubility of calcium carbonate; this can cause the lake water to become saturated or supersaturated with respect to calcium carbonate. But what, specifically, might cause saturated or supersaturated lake water to begin to precipitate calcium carbonate?

**HOW PHOTOSYNTHESIS, CO₂, AND pH AFFECT PRECIPITATION OF CaCO₃.** When there is an ample supply of sunshine and essential nutrients such as phosphorus and nitrogen in lake water, algae and other aquatic plants produce chlorophyll through the process of photosynthesis. During photosynthesis, carbon dioxide (CO₂) is assimilated from the surrounding water by the plants. Since removal of carbon dioxide through photosynthesis often occurs faster than it can be replaced (in the lake water column) by the atmosphere or other sources, the lake water pH rises. The rise in pH is especially sharp immediately adjacent to the algae and other plants. This phenomena is believed to be an important factor in initiating precipitation of calcium carbonate.

Otsuki and Wetzel (1972) found that artificially raising the pH of a calcium-rich lake water sample from a pH of 8 to 9 caused nearly total precipitation within 15 minutes. According to Dean and Megard (1993), their studies of primary productivity, carbonate saturation, water chemistry, and sediment-trap samples from Elk Lake in Itasca State Park, Clearwater County, Minnesota, showed that

_Low-Mg calcite precipitates during the summer, triggered by algal photosynthesis. The epilimnion of Elk Lake is always oversaturated with calcite, and the degree of oversaturation increases progressively during the summer. The pH of the epilimnion increases from < 8.0 after spring overturn to almost 9.0 in late summer in response to photosynthetic removal of CO₂ during the summer months. The rate of calcium depletion from the epilimnion is proportional to the increase in pH and the rate of photosynthetic carbon fixation._

Otsuki and Wetzel, 1974, in evaluating a small lake in southwestern lower Michigan, found that

_The agreement between marked decreases in Ca²⁺ [calcium] concentration and total alkalinity and the rapid increase in rates of planktonic productivity suggested the major role of phytoplankton in the initiation of CaCO₃ precipitation in this lake._
Kelts and Hsu (1978) emphasize the following points:

Plant activity controls the overall CO$_2$ budget in a lake. The photosynthesis by algae, for example, uses up large quantities of CO$_2$. Because the exchange equilibrium of atmospheric CO$_2$ with water is a comparatively slow reaction (e.g., Verduin, 1975; Emerson, 1975), carbon dioxide in surface waters during active photosynthesis may become very depleted in eutrophic lakes [Niseebakwet Lake is not eutrophic] within a short time and the waters supersaturated with respect to calcite. Photosynthetic activities of both macrophyta and microphyta can thus induce precipitation of carbonates. Sedimentation rates of the order of meters per hundreds of years may result. Megard (1968) found, for example, that calcium carbonate saturation in some Minnesota lakes is probably controlled entirely by the balance between carbon dioxide consumption during photosynthesis and its release during respiration.

When plants assimilate carbon dioxide (CO$_2$) through photosynthesis, CO$_2$ that might otherwise go to the creation of carbonic acid (H$_2$CO$_3$) is now less available. While this biochemically-induced imbalance exists, less hydrogen ions (H$^+$) are found in solution locally and therefore the pH rises locally. The pH is the negative base 10 log of hydrogen ion {H$^+$} activity in moles per liter. pH can also be described as the negative of the log of the hydronium ion concentration {-log[H$_3$O$^+$]}). The net result is that the rise in pH pushes the equation

$$\text{Ca}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{CaCO}_3$$

(simplified formula)

to the right in favor of precipitating CaCO$_3$.

CHEMISTRY OF PHOTOSYNTHESIS-DRIVEN CALCIUM CARBONATE PRECIPITATION. Carbon dioxide from the atmosphere, ground water, streams and in-lake sources combine with lake water to form carbonic acid. More precisely, an equilibrium (as indicated by the "$\leftrightarrow$" symbol) is established between the right and left halves of the equation shown below:

1. $\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3$

The carbonic acid dissociates into hydrogen and bicarbonate ions:

2. $\text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^-$

Under typical lake conditions, the bicarbonate dissociates into hydrogen and carbonate ions:

3. $\text{HCO}_3^- \leftrightarrow \text{H}^+ + \text{CO}_3^{2-}$

The carbonate ions can combine with calcium ions to form calcium carbonate:

4. $\text{Ca}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{CaCO}_3$ (simplified equation)

How can photosynthesis drive the chemical equilibrium in the direction that causes CaCO$_3$ to precipitate out as solid particles? With ample sunshine and favorable water temperatures, photosynthesis in algae (including cyanobacteria, commonly referred to as blue-green algae) and other
organisms such as macrophytes (larger, rooted plants) can use up a substantial amount of CO₂. As CO₂ is consumed, the process drives the chemical equilibrium to the right as indicated below:

[starting with equation (2) from above]

\[
\begin{align*}
(5) \quad & \text{H}_2\text{CO}_3 \rightleftharpoons \text{H}^+ + \text{HCO}_3^- \rightleftharpoons \text{H}_2\text{O} + \text{CO}_2 \uparrow \quad (\text{consumed through photosynthesis}) \\
\end{align*}
\]

\textit{Photosynthesis}, represented by equation (5), above, causes the pH to rise because it reduces the amount of free H⁺ (as the reaction goes from left to right). Since the solubility of CaCO₃ decreases as pH rises, this reaction tends to make available calcium ions, Ca²⁺, and carbonate ions such as HCO₃⁻, combine as calcium bicarbonate \{Ca(HCO₃)₂\} and come out of solution as CaCO₃ precipitate:

\[
\begin{align*}
(6) \quad & \text{Ca(HCO}_3)_2 \rightleftharpoons \text{H}_2\text{O} + \text{CO}_2 + \text{CaCO}_3 \downarrow \quad (\text{precipitates out of solution as a solid}) \\
\end{align*}
\]

Wetzel (1983, p. 205) explains that "If a solution of calcium bicarbonate [Ca(HCO₃)₂] in equilibrium with CO₂, H₂CO₃ and CO₃²⁻ loses a portion of the CO₂ required to maintain the equilibrium (e.g., CO₂ assimilated by photosynthetic organisms), CaCO₃ will precipitate until the equilibrium is reestablished by the formation of CO₂.

Other materials such as phosphorus, magnesium, iron and dissolved organic matter can co-precipitate out of solution with calcium carbonate.

OTHER FACTORS THAT AFFECT PRECIPITATION OF CaCO₃. A factor believed to be important in initiating the precipitation reaction is the availability of a certain amount or type of particulate to serve as a nucleus or “bridge” for precipitation. Thus, local availability of particulates may be important initially, but, it is possible that, once precipitation begins, the calcium carbonate precipitate itself may serve to sustain and spread the precipitation reaction.

There are numerous additional chemical interactions that can potentially affect calcium carbonate precipitation. APHA, AWWA and WPCF [Standard Methods for the Examination of Water and Wastewater] (1998, pp. 2-30) reference Pytkowicz, 1965, Ferguson and McCarty, 1969, and Merrill and Jorden, 1975, in explaining that "CaCO₃ deposition from over-saturated waters is inhibited by the presence of phosphates (particularly polyphosphates), certain naturally occurring organics and magnesium. These materials can act as sequestering agents or as crystal poisons. Conversely, CaCO₃ deposits have been found in pipes conveying under-saturated water. This apparent contradiction is caused by high pH (relative to the bulk water pH) in the immediate vicinity of certain areas….. A locally over-saturated condition may occur even if the bulk water is under-saturated." The analogy for a lake is that algae, during photosynthesis, create local zones of high pH and other conditions, described below, that encourage precipitation of calcium carbonate.

It is not surprising that interpretation of Secchi disk transparency data dependent on this combination of chemical, biochemical and other processes seems complex at times:

- phosphorus is a crucial nutrient for algae growth which worsens transparency but
- phosphorus can also inhibit precipitation of calcium carbonate which can worsen transparency as it precipitates but
- precipitation of calcium carbonate can also reduce concentrations of phosphorus and certain organic compounds (that could be nutrients) because they tend to co-precipitate out with calcium carbonate
A summary of factors related to precipitation and sedimentation of calcium carbonate is provided in Table 32 - Summary of Factors Affecting Sedimentation and Precipitation of Calcium Carbonate provided by Kelts and Hsu (1978). Examination of most of these factors was beyond the scope of this investigation.

**Table 32 - Summary of Factors Affecting Sedimentation and Precipitation of Calcium Carbonate**

<table>
<thead>
<tr>
<th>Factors Affecting Precipitation</th>
<th>Factors Affecting Sedimentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation index (Temperature, Alkalinity, pCO₂, pH); IAP/Kc*</td>
<td>Aggregation, flocculation, size</td>
</tr>
<tr>
<td>Rate of supersaturation</td>
<td>Ingestion</td>
</tr>
<tr>
<td>Rate of nucleation; seeding</td>
<td>Epilimnion turbulence and residence</td>
</tr>
<tr>
<td>Inhibitors (Mg, phosphate, organic films)</td>
<td>Density and viscosity boundaries</td>
</tr>
<tr>
<td>Mg/Ca molar ratio</td>
<td>Dissolution kinetics</td>
</tr>
<tr>
<td>Ionic strength</td>
<td>Settling rate</td>
</tr>
<tr>
<td>Seeding</td>
<td>Residence time sediment/water interface</td>
</tr>
<tr>
<td></td>
<td>Anaerobic conditions, bacterial activity</td>
</tr>
<tr>
<td></td>
<td>Organic decay</td>
</tr>
</tbody>
</table>

* IAP = ionic activity product = (Ca²⁺)(CO₃⁻²); K_c = equilibrium constant for (Ca²⁺)(CO₃⁻²)

SPECIFIC MECHANISM IDENTIFIED AS KEY TO CaCO₃ WHITING EVENTS. In 1997, Thompson et al. (1997) published a detailed study that focused on understanding the annual "whiting events", caused by calcium carbonate precipitation, that turned a New York State lake a whitish green color and substantially worsened Secchi disk transparency annually. Years of previous, highly detailed, studies on this lake attempted to determine whether inorganic or biogenic factors were responsible for the whiting events. Thompson et al. (1997) discovered and verified that the photosynthetic activity of a specific cyanobacterial picoplankton, *Synechococcus*, was directly responsible for the onset of the annual whiting events. This lake, Fayetteville Green Lake, is similar to Siseebakwet Lake in that it is an oligotrophic marl lake with low phosphorus that is fed by calcium-rich ground water.

Cyanobacteria are also known as blue-green algae because they use photosynthesis to convert nutrients into energy like real algae and, in addition to chlorophyll (green), they also contain a blue pigment. In Thompson et al. (1997), Purcell (1977) explains that "The small size of each *Synechococcus* cell (0.5 microns diameter) and its near-spherical morphology results in a very high surface area-to-volume ratio and a very low Reynolds number" and Beveridge (1988) states that "An envelope of water (10 - 500 nanometers thick around each of these planktonic cells is dominated by the diffusion processes."
Thompson et al. (1997) found that the initiation of the annual whiting event (large-scale precipitation of calcium carbonate) that occurs each year in late May to early June “correlates with exponential growth of the *Synechococcus* population within the lake. *Synechococcus* is the dominant (by ~4 orders of magnitude) autotrophic organism owing to the oligotrophic condition of the lake.” Thompson et al. add that

> Calcite [mineral calcium carbonate] precipitates principally in the microenvironment surrounding *Synechococcus* because of a photosynthetically driven alkalization process and the availability of the cells as nucleation sites.

They further emphasize that their

> field data … provide evidence for a mechanism where dissolved ions interact directly with the surface of *Synechococcus* (a unicellular cyanobacterium) to precipitate carbonate minerals … [and they believe the factors described above] … together with the substantial surface area that arises from the great abundance of micron-sized cells, allow *Synechococcus* to dominate the annual whiting events …

They found that Secchi disk readings worsened from 18 m to only 8 m between May 1 and May 22, 1989 due to two major factors: "the onset of the annual whiting event with the *Synechococcus* bloom and the presence of a spring pollen bloom settling through the upper part of the water column … Secchi disk depth readings decreased until mid- to late July (owing to increased growth of *Synechococcus* and to a subsequent small diatom bloom). Minimum Secchi disk depth was 4.5 m in July and then began to increase again in early September. … During the annual whiting event, light reflected from the lake water is greenish-white as compared to the deep bluish-green seen from late October to early May when light can penetrate to great depth."

The greatest concentrations of *Synechococcus* were found in the lower mixolimnion (8 - 12 m) where there was a steady increase in abundance from May to September, culminating in a seasonal peak of 2.5 x 10^5 cells per ml by 24 September.

The (typically) highest concentrations of whiting (as opposed to re-suspended) calcite and the highest concentration of *Synechococcus* were both found at a depth of 8 m. After September, abundance of *Synechococcus* declined to 7.0x 10^4 cells per ml, a level that remained constant throughout winter. Throughout the year the highest numbers of *Synechococcus* cells were found as a fairly stable population below the seasonal thermocline at a depth of ~6-12 m even during the spring bloom in the surface waters.

Thompson (1997) explains that

> the onset of the annual whiting event in the lake was directly related to the spring *Synechococcus* bloom which was triggered by increased water temperatures and light intensities. This bloom catalyzed the precipitation of calcite in the open water column during the rapid springtime growth of *Synechococcus* at the 4-m depth where there was ~3.3 - 4.0 mg of calcite per liter in the water column.
In contrast to the smaller range in the lower mixolimnion, the concentration of *Synechococcus* in the upper 4 m varied greatly throughout the year. *Concurrent with the onset of a dramatic worsening in Secchi disk transparency beginning in early May and reaching its worst in July, Synechococcus concentrations increased rapidly from early May to early July.*

The advanced scientific methods and technology used in numerous studies by various investigators to discover and verify that *Synechococcus* was responsible for the whiting events were impressive. Thompson (1997) notes the following contributions: They revealed the crucial microenvironment surrounding *Synechococcus* with "pH- or Eh-sensitive fluorescent probes in conjunction with confocal laser microscopy (Lawrence and Caldwell 1990; Caldwell et al. 1992)." Riebesell et al. (1993) showed that "uptake of inorganic carbon by a photosynthetically active cell leads to strong concentration of gradients of CO$_2$, HCO$_3^-$ and CO$_3^{2-}$ in the surrounding milieu. The microenvironment surrounding the cells also has a higher pH due to photosynthesis as well as an elevated calcium level due to the binding of Ca$^{2+}$ to the cell surface layer (Thompson and Ferris 1990; Schultz-Lam et al. 1992), thus this microenvironment promotes the precipitation of [calcium] carbonate."

Thompson (1997) explains through excerpts from earlier articles about the study that, in laboratory simulations, they verified that "the exchange of HCO$_3^-$/OH$^-$ across the *Synechococcus* cell wall created alkaline conditions that promoted epipelic biomineralization of calcite from lake water (Thompson and Ferris 1990; Schultz-Lam et al. 1992)"

A LAKE THAT ONLY HAS WHITING EVENTS EVERY 7 - 10 YEARS. Another recent study points to the growth of a different blue green algae as a possible trigger to whiting events. But this lake clearly does not have major whiting events every year and might eventually reveal some explanation as to what causes long term changes or trends in whiting events. A United States Geological Survey (USGS) study by Hoch and Reddy (1999) of Pyramid Lake in Nevada states concluded that "These results support the theory that the phytoplankton and/or particulates may act as heterogeneous nucleation sites that enhance whiting events in Pyramid Lake." They identified the blue-green algae *Nodularia spumigena* in Pyramid Lake and implied that this may be a key phytoplankton for the precipitation of calcium carbonate.

This study is particularly interesting in that although "some spontaneous precipitation of aragonite occurs annually .... major whiting events occur less frequently (ca. every 7 - 10 years."

Aragonite, a crystalline mineral form of calcium carbonate, has the same chemical formula (CaCO$_3$) as calcite but has a different crystalline structure (orthorhombic), less marked cleavage and a higher specific gravity compared to calcite. Calcite growth is inhibited in Pyramid Lake because of the high magnesium to calcium ion ratio. Based on their study, they state that "Algae associated with late summer blooms have been proposed as nucleation substrates that trigger whiting events, along with increased calcium concentrations and higher water temperatures." They list the possible causes of a "spontaneous precipitation of CaCO$_3$ or whiting event" as including the following:
• Increased temperature raises supersaturation
• Increased Ca²⁺ and alkalinity raise supersaturation
• Algal blooms and other particulates provide mineral nucleation sites

They go on to say that "We know increasing temperature and ionic constituents enhance CaCO₃ nucleation and growth. However, it is much less clear whether phytoplankton act as nucleation "seeds"."

They found that Pyramid Lake is usually supersaturated with respect to aragonite but natural inhibitors such as phosphate and dissolved organic acids suppress nucleation until supersaturation reaches levels as high as 20 times the saturation point, i.e., where the ratio of the aragonite ion activity product to the solubility product is as high as 20.

LONG TERM TRENDS IN CaCO₃ PRECIPITATION. During this study, evidence was obtained that indicates calcium carbonate has been precipitating in and settling to the bottom of Siseebakwet Lake for at least many hundreds of years. Based on a single lake bottom sediment core analysis, there was no indication of a recent change in the rate of precipitation. Nonetheless, we do not have sufficient information to prove there have been no recent changes in the rate of calcium carbonate precipitation.

Has there been a change or recent trend in one of these factors that might explain an apparent trend in Secchi disk transparency readings? Could a subtle change in annual temperatures, rainfall or some other factor be responsible for an apparent trend in Secchi disk transparency readings? Could the relatively recent removal of beaver dams upstream from the NNW inlet cause enough additional nutrients or particulates to enter the lake to significantly affect trends in Secchi disk measurements at site 101?

The long term trend of worsening transparency appears to be significant and real. We cannot clearly assign responsibility for this trend to any specific cause or set of causes based on this study. However, based on the single lake bottom sediment core analysis, there doesn't appear to have been any substantial changes in calcium carbonate accumulation in recent times. On the other hand, we cannot rule out the possibility that subtle, undetected changes in parameters we studied or changes in other unmonitored parameters have affected transparency.

Changes In Observed Water Color Due To Calcium Carbonate Precipitation

For many visitors to Siseebakwet Lake, the most outstanding characteristic related to calcium carbonate precipitation in the lake is the color change that accompanies a "whiting event". The term "whiting event" may come from the white appearance of the large plumes that are observed from the air when large-scale precipitation of calcium carbonate occurs on a lake. Numerous photos in the literature and on the Internet show whiting events that appear as large white swirls "covering" the majority of the surface of lake Michigan. An apparent example of a whiting event in progress on Siseebakwet Lake can be seen in Figure 43 - Aerial View of Probable Whiting Event on Siseebakwet Lake. This image was extracted from a 03 May 1992 U.S. Geological Survey color infra-red digital orthophoto quadrangle and downloaded from a Microsoft TerraServer Web Page at URL:

Although the calcium carbonate particulate plumes appear white in aerial photos, observers located on a lake or lakeshore normally report seeing a turquoise, deep blue-green or whitish-green color.

DEEP BLUE-GREEN APPEARANCE OF LAKE SURFACE. On Siseebakwet Lake, there appears to be times where the lake takes on a deeper blue-green color. The angle of the sun and the angle of the lake surface to the viewer affect the appearance of this lake coloring phenomena. It is widely believed that precipitation of calcium carbonate and the sun’s reflection off the precipitate in the water causes this visual effect.

It was observed on Siseebakwet Lake that the angle of view from the lake, relative to the direction to the sun, was also an important factor in terms of observed water color. During a whiting event, in one direction the lake appeared deep blue-green to the viewer, 90 degrees from that direction, the lake appeared blue-gray. On the other hand, when a portion of the lake appeared green due to an accumulation of algae, the direction of view relative to the sun did not significantly affect the observed color.

SOURCES OF COLOR IN A LAKE. Observed lake water color is primarily determined by the intrinsic color of water (explained below), dissolved chemicals, especially dissolved organic compounds, and particulate matter suspended in the water. In some circumstances, reflected skylight and the color of the lake bottom (in very shallow areas) can also affect the apparent observed color of the lake.

Dissolved organic compounds, if concentrated enough, can impart a yellow to brown or reddish-brown color to lake water. Laboratory tests for water color during this project indicated that dissolved compounds did contribute substantially to the lake water's color. The types of suspended particulates that most commonly have a significant impact on color include phytoplankton and inorganic matter. The phytoplankton typically contribute a green to blue-green hue to the lake through production of chlorophyll. Suspended inorganic matter can be made up of particulates of various colors but, in many circumstances, their size may be more important than their actual color as their size is an important factor in how they scatter light. A special category of suspended matter are colloids which are extremely small particulates that are not in solution but may interact to some degree with other compounds in solution.
THE INTRINSIC COLOR OF PURE WATER. The color of pure water is a faint or pale blue. Pure water appears clear when we are looking through a relatively small thickness of it. The faint blue color becomes evident when we look through a thicker or deeper expanse of water. The intrinsic blue color of water is not due to scattering like the scattering that causes blue sky. According to Braun and Smirnov (1993)

\[ \text{Water owes its intrinsic blueness to selective absorption in the red part of its visible spectrum. The absorbed photons promote transitions to high overtone and combination states of the nuclear motions of the molecule, i.e., to highly excited vibrations. Because the absorption which gives water its color is in the red end of the visible spectrum, one sees blue, the complementary color of red, when observing light that has passed through several meters of water.} \]

Braun and Smirnov (1993) highlight the fact that, "to our knowledge, the intrinsic blueness of water is the only example from nature in which color originates from vibrational transitions. Other materials owe their colors to the interaction of visible light with the electrons of the substances."

COLOR OF LAKE WATER OBSERVED FROM VARIOUS ANGLES. Lakes often appear blue even when we are looking at them and not looking down through the water. Bohren (1987) in Braun and Smirnov (1993) explains that contributions to the observed blue color are made both by reflected skylight and by the intrinsic absorption of water (as described above). Light scattering by suspended matter is required in order that the blue light produced by water's absorption can return to the surface and be observed. Such scattering can also shift the spectrum of the emerging photons toward the green, a color often seen when water laden with suspended particles is observed. Bohren also shows that the relative contribution of reflected skylight and the light scattered back from the depths is strongly dependent on observation angle. This probably explains why the observed color of Siseebakwet Lake appears to change so much according to the observers' location and height above the water's surface.

HOW FINE SUSPENDED PARTICULATES AFFECT LAKE WATER COLOR. Substantial accumulations of algae in lake water can impart a green or blue-green color to the lake. However, very fine inorganic particulates in the water can also cause the lake water to appear green, blue-green or whitish green. It is normally straightforward to assess whether algae are responsible for a big change in water color because large accumulations of algae are easily identified when located on the lake surface and would normally be indicated by laboratory quantification of chlorophyll in lake water. Algae production below the depth of testing, e.g., 0 - 2 m, is more likely to go undetected without sampling for chlorophyll at multiple (deeper) depths.

The wavelength of blue light is very short compared to the rest of the visible spectrum of light. The rest of the visible light spectrum (non-blue) is absorbed rather quickly so that it does not penetrate very far into water. In addition to being able to penetrate further into water, blue light is also scattered more strongly than other light by pure water that is nearly free of particulates. Light with longer wavelengths, such as red light is very weakly scattered and thus is not normally observed being reflected back up from the lake bottom or from particulates. Wetzel (1983) explains that "the observed color of lake water is the result of light being scattered upward from the lake after it has passed through the water of various depths and undergone selective absorption en route."

Both phytoplankton and inorganic particulates, such as clay particles, can add to absorption and scatter of light. To scatter light selectively and strongly, particulates must be approximately the same size as the wavelength of the incoming light. Although moderate to low concentrations of suspended inorganic particulates do not normally have a big impact on color, extremely fine particulates, such as colloidal calcium carbonate, are fine enough to scatter light selectively. The
wavelength of green light, although longer than blue light, is also short compared to the rest of the visible spectrum. Therefore, extremely small particulates, such as colloidal calcium carbonate can selectively scatter light that adds a green or blue and green hue to the lake water. Wetzel (1983) notes that "colloidal CaCO₃, common to hardwater lakes, scatters light in the greens and blues and gives these waters a very characteristic blue-green color.

Calcium Carbonate Balance in the Lake

The availability of excess calcium carbonate on the lakebed tells the story of the calcium carbonate balance in the lake system. The supply of calcium carbonate from any pre-existing sediments in direct contact with the lake combined with the additional calcium carbonate steadily brought into the lake primarily through ground water and surface water has been greater than the supply of calcium carbonate lost to surface-water and ground-water outflow from the lake.

Table 33 - Comparison of Calcium Ion (Ca²⁺) Concentrations shows the distribution of calcium ion (Ca²⁺) concentrations throughout the hydrologic cycle in the study area. Calcium (Ca²⁺) concentrations in the unfiltered lake water samples have been converted from the Minnesota Department of Health laboratory report to be expressed here as ppm Ca²⁺ and not expressed as ppm CaCO₃ as they were earlier in Table 12 - Site 101 Water-Quality Data for Siseebakwet Lake (May – October 1999): Minnesota Department of Health Laboratory. This is done here so that all Ca²⁺ concentrations in Table 33 could be listed in the same units (ppm as Ca²⁺). All data for filtered sample results listed in Table 33 came from the University of Minnesota Hydrogeochemistry Laboratory; more of this data set was presented earlier in Table 26 - Water Chemistry: Ground Water and Surface Water Interaction Study, 1998-1999.

Ground water is represented in Table 33 by the results from a shallow well near the southern shoreline of Siseebakwet Lake because relatively shallow ground water moving toward Siseebakwet Lake from the south is most likely the primary source of ground water recharge to the lake. Based on this sample, ground water, by far, has the highest Ca²⁺ concentrations (105.5 ppm) in the hydrologic cycle in the immediate vicinity of Siseebakwet Lake. The other two wells had Ca²⁺ concentrations of 57.5 ppm (shallow well 466) and 65.5 ppm (deeper well 467).
Table 33 - Comparison of Calcium Ion (Ca\(^{2+}\)) Concentrations

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>FILTERED CONCENTRATION (ppm)</th>
<th>FILTERED CONCENTRATION (ppm)</th>
<th>UNFILTERED CONCENTRATION (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1998</td>
<td>1999</td>
<td>1999</td>
</tr>
<tr>
<td>Rainfall</td>
<td></td>
<td></td>
<td>Sept. 25</td>
</tr>
<tr>
<td>Ground Water(^1)</td>
<td></td>
<td></td>
<td>Oct. 20</td>
</tr>
<tr>
<td>(well 468)</td>
<td></td>
<td></td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>105.5</td>
</tr>
<tr>
<td>Stream Inflow (NNW inlet)</td>
<td>Oct. 20</td>
<td>May - July - Oct.</td>
<td>61.8 - 34.2 - 36.2 - 49.5</td>
</tr>
<tr>
<td>Lake Water (site 101)</td>
<td>Oct. 21</td>
<td>May - July - Oct.</td>
<td>56.6 - 34.9 - 34.0 - 34.2</td>
</tr>
<tr>
<td>Lake Water (site 101)</td>
<td></td>
<td></td>
<td>June through Oct.</td>
</tr>
<tr>
<td>Lake Water (site 101)</td>
<td></td>
<td></td>
<td>July 21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>.34.0</td>
</tr>
<tr>
<td>Lake Water (site 101)</td>
<td></td>
<td></td>
<td>Oct. 11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>.34.2</td>
</tr>
</tbody>
</table>

1 – From shallow well near the southern shoreline of Siseebakwet Lake

Surface water input to the lake is represented in Table 33 by stream inflow from the NNW Inlet because it is the dominant surface water inflow source to Siseebakwet Lake. Much of the time, the SW Inlet’s contribution of stream flow to the lake is very little to negligible. Under high flow conditions, however, the SW Inlet can contribute substantial amounts of water to Siseebakwet Lake. Therefore, it is important to note that the single Ca\(^{2+}\) concentration measured at the SW Inlet was 43.6 ppm compared to 34.2 ppm at the NNW Inlet on the same date (May 13, 1999).

Stream inflow and lake concentrations of Ca\(^{2+}\) from a single sampling event in 1998 (Appendix G - Ground Water and Surface Water Interaction Study) are compared in Table 33 to Ca\(^{2+}\) analyses from sampling on May, July and October 1999 (Appendix G - Ground Water and Surface Water Interaction Study) to highlight that Ca\(^{2+}\) concentrations in the inlet streams and the central part of the lake decreased substantially between October 1998 and the 1999 sampling season. The bottom portion of the table compares filtered and unfiltered concentrations of Ca\(^{2+}\) in samples collected at site 101 approximately 24 hours apart. Logistical constraints resulted in non-simultaneous sampling.

In July 1999, the filtered lake water sample contained approximately 3.6% more Ca\(^{2+}\) than the unfiltered sample. In October 1999, the filtered sample contained approximately 6.7% more Ca\(^{2+}\) than the unfiltered sample. One would expect that, if there were significant amounts of calcium carbonate precipitate in the lake water, the unfiltered sample would instead have more Ca\(^{2+}\). There are many potential explanations why the data do not show more Ca\(^{2+}\) in the unfiltered sample. Some possible explanations include the following:

- changes in the lake’s equilibrium chemistry in the time between sampling events
- normal, expected differences in results reported by two different laboratories due to minor procedural differences and random errors (Minnesota Department of Health Laboratory and the University of Minnesota Hydrogeochemistry Laboratory)
• expected, minor differences in field procedures and random field-related errors from day to day
• time-variable physical factors that are difficult to quantify such as variable mixing of heterogeneous waters through wave action
• time-variable biochemical factors that are difficult to quantify such as the role of algae in affecting lake water pH
• the results may indeed be accurate in indicating that there was not a significant amount of suspended calcium in suspension

Although somewhat obvious, it bears repeating that reduction of much of the uncertainty described above can be eliminated by collecting filtered and unfiltered samples simultaneously and having them analyzed by the same laboratory.

Table 33 shows substantial differences in \( \text{Ca}^{2+} \) concentration at various points in the hydrologic cycle (1999). The ground water that recharges the lake has a considerably higher ion \( \text{Ca}^{2+} \) (105.5 ppm) concentration than the other recharge sources. The concentration of \( \text{Ca}^{2+} \) in filtered stream water (34.2 – 49.5 ppm) is similar to filtered lake water. The concentration of \( \text{Ca}^{2+} \) in rainwater, 1.9 ppm, is very low by comparison.

**CAUSES OF INCREASED PERCENTAGE OF GROUND-WATER RECHARGE TO LAKE.** During periods of lower rainfall, stream flow decreases, and in extended dry periods, streams eventually arrive at a base flow condition where nearly all of the stream flow is supplied by ground water. Therefore, under dry conditions, the ground water component of recharge to the lake would increase relative to both surface water recharge and direct rainfall on the lake. This situation would result in an even more dramatic relative increase in ground water recharge if an extended period of heavy rainfall raises ground-water levels just before onset of an extended dry period.

**CAUSES OF DECREASED PERCENTAGE OF GROUND-WATER RECHARGE TO LAKE.** On the other hand, an extended period of heavy rainfall decreases the relative amount of ground water recharging the lake. Large amounts of rain may fall directly on the lake or reach the lake by near-shore overland flow or through numerous temporary gullies as observed during an especially wet period in 1999. Streams in Siseebakwet Lake’s small watershed can swell quickly during rainstorms and snowmelt events resulting in a substantially greater rate of stream flow into the lake. Ground-water levels and ground-water flow increase in response to a rainfall or snowmelt event but the response is much slower. Infiltration of water through the unsaturated zone to the ground-water table can be very slow. Even after reaching the saturated zone, ground water normally moves many orders of magnitude slower than streams thus delaying ground-water recharge to the lake until a substantially later point in time. Under limited circumstances, the effect of recharge to a confined aquifer that discharges into a lake could actually impact a lake sooner than a water-table aquifer as the equilibration response due to an increased total hydraulic head (due to ground-water recharge) is transmitted much more quickly under confined conditions.

A relative decrease in ground-water recharge to the lake compared to rainfall and surface water recharge to the lake can be even more dramatic if a long dry period resulting in a drop of ground-water levels precedes a large rainfall of snowmelt event.

**DISRUPTION IN THE LAKE’S CHEMICAL EQUILIBRIUM.** The conditions outlined directly above for creating a substantial relative increase or decrease in the relative amount of ground-water recharge to the lake define the situations under which a significant change in the equilibrium chemistry of Siseebakwet Lake may occur.
A higher rate of ground-water recharge to the lake means that relatively more water that is out of equilibrium with a surface-water environment must begin to interact with existing lake water and, ultimately, the atmosphere, to reach a new chemical and physical equilibrium. In all likelihood, it also means that more calcium is coming into the lake than it can keep in solution in the lake's current state of equilibrium. In portions of the lake receiving intensive ground-water recharge, the equilibration response may be to precipitate out some calcium carbonate near the recharge interface (lakebed). The equilibration response takes time so the calcium-rich ground water is likely to disperse to some degree throughout the lake before it reaches equilibrium – if it ever really does reach it. If lake currents are sufficient, the precipitated calcium carbonate could potentially make to any part of the lake and remain suspended of extended periods of time before re-dissolving of depositing on the lake bed.

A relatively lower rate of ground-water recharge to the lake could potentially create the opposite situation where the lake is temporarily under-saturated with calcium carbonate. Fresh rainfall on the lake, for example, would normally increase the shallow water's capacity to hold or dissolve calcium carbonate. If lake currents do not bring calcium carbonate precipitate from earlier times up to the surface waters for a while, then near-surface lake water may be relatively free of calcium carbonate precipitate for some time. As the lake then begins to equilibrate with the excess mineral calcium carbonate on the lakebed or climatic conditions change again, the whole process of calcium carbonate equilibration may continue indefinitely.

CHEMICAL EQUILIBRIUM MODELING METHODS AND ACCURACY OF SATURATION INDICES. The Chemical Equilibrium Model, PHREEQE, was used to calculate saturation indices. Modeling parameters were adjusted for the variability of in-situ water temperatures over the sampling period.

All water samples submitted for equilibrium chemistry model analysis (except for the rain water sample) were filtered in the field through 0.45 micron pore size filters. The October 1998 samples collected for field alkalinity titrations were not filtered; all subsequent samples for field alkalinity titrations were filtered through 0.45 micron pore size filters.

Because field alkalinity titration values did not seem to compare well with laboratory data for other analytes from the October 1998 and May 1999 data sets, laboratory alkalinity titrations were added to supplement field alkalinity titrations for the July and October 1999 data sets. In some cases, an estimated (calculated) alkalinity was used to calculate saturation indices because the field alkalinity did not appear to provide acceptable (anion/cation balance) results when evaluated with other analytes. These calculated alkalinity values are listed in the row entitled "Calc Alk (CaCO3)" in Table 26. All alkalinity values listed in Table 26 as measured, "Meas", represent field alkalinity titrations with the exception of the rain-water sample data and the possible exception of samples collected in May 1999 which may have been titrated subsequent to the sampling event.

In all but one of the nine cases (excluding rain water) where both a measured and a calculated alkalinity value was available, (two lake samples, five shallow ground-water samples and two surface water samples), the laboratory calculated alkalinity values were considerably higher than field alkalinity values. The rain water values were similar: 0.5 (measured in the laboratory) versus 0.36 (calculated). In October 1999, at shallow ground water sampling point 410, a field alkalinity of 425 mg/l was measured versus a laboratory calculated alkalinity of 261 ppm (the units are equivalent in this range). Based on comparisons with previous measurements of alkalinity, specific conductance and other factors, the value of 261 ppm appears to be more realistic and is actually quite consistent with previous data. The 261 ppm value was used for equilibrium chemistry model calculations. In addition, an unfiltered alkalinity value of 251 mg/L was actually used in the model for location 410 for July 1999. The correct (filtered) field alkalinity value was 242 mg/L, a difference of about 3.6%.
Based on this experience, it is suggested that any future similar project include a preliminary study to test for solution stability and acceptable holding times. It may be that, if the solution is over-saturated with calcium carbonate or has some other type of unusual chemical or biochemical characteristics, shorter holding times, a modified titration method or special preservation techniques may be necessary to obtain the most accurate saturation indices. It may also be enlightening to do alkalinity titrations on split samples in the field, one filtered and one unfiltered to compare to alkalinity titrations done later in the laboratory and to get an immediate estimate of the amount of calcium carbonate and similar carbonates (e.g., calcium-magnesium carbonates such as dolomite) that were in suspension at the time of sample collection. If the filtered sample is collected in a system that is essentially closed to the atmosphere, filtered under positive pressure and titrated immediately upon collection, this could yield the most reliable measure of whether or not and how much calcium carbonate and related carbonates are in solution if the lake water solution is unstable as is now suspected.

Alternate Methods for Evaluating the Degree of Calcium Carbonate Saturation

Hem (1989, page 90) describes alternate methods for evaluating calcium carbonate equilibrium. He suggests that, in lieu of computer models, a graphical procedure may be convenient for many interim or preliminary water chemistry studies. Hem lists the following requirements for these alternate methods:

Calculations required to determine whether a particular solution may be in thermodynamic equilibrium with calcite require values for activities of $\text{Ca}^{2+}$, $\text{HCO}_3^-$, and $\text{H}^+$ and solution temperature. Analytical concentrations must be corrected for ionic strength effects and complexing, and equilibrium constants used must be appropriate for the temperature of the system.

The two methods described on page 90 of Hem, 1989, "entail some simplifying assumptions that limit their applicability range to some extent."..... and are "not applicable to all natural waters."

Nomograph for Evaluating Calcium Carbonate Equilibria. The first method employs graphs from Plate 2 found inside the back cover of Hem. This method uses a "Nomograph for evaluating calcite equilibria $T=0$ degrees C to 50 degrees C, and ionic strength (I) from 0.0 to 0.5". The method assumes an equilibrium among dissolved CO$_2$ species (the postulated system upon which the graph is based does not contain a gas phase). This method is fairly easy to employ and is relatively quick as long as you have collected the needed data beforehand. For some types of water, an approximate value for the ionic strength can be estimated from specific conductance. This estimation could be improved if a previous, complete analysis of major and minor ions is available for the water body in question. The saturation index is computed by subtracting the equilibrium pH computed with the nomograph from the pH you measured in the field. A positive saturation index indicates that the water is supersaturated with calcium carbonate; a negative index indicates under-saturated conditions.

What exactly is needed for this technique? In short, good field measurements of pH ($\text{H}^+$), temperature, and specific conductance, an alkalinity titration (to calculate $\text{HCO}_3^-$) (2 or more trials recommended) combined with a preserved sample for a laboratory analysis of calcium will provide most of what you need. If you have a previous complete water analysis for this water body, Hem (1989) Plate 1 provides a method to compute ionic strength of natural waters. Compare the specific conductance of the previous analysis with your current specific conductance as a check on whether
or not the gross chemistry has changed enough to substantially change the ionic strength of the water.

**GRAPHS OF \( \text{CaCO}_3 \) SOLUBILITY VS. PARTIAL PRESSURE OF \( \text{CO}_2 \).** A second method for evaluating calcium carbonate equilibrium discussed by Hem (1989) features a graph of solubility of calcium carbonate (calcite) in terms of calcium concentration in water at 25 degrees C as a function of partial pressure of carbon dioxide (\( \text{CO}_2 \)). The "\( \text{CO}_2 \) content of normal air is 0.03 percent (by volume) or 0.0003 atmosphere." At this partial pressure of \( \text{CO}_2 \), the solubility indicated by the chart for calcium in water in contact with air is about 20 mg/L. This graph is based on laboratory experimental data by Frear and Johnson (1929).

The fact that water samples from Siseebakwet Lake, its inlet streams and adjacent ground water all had calcium values considerably higher than this indicates that at least portions of each of these waters (lake, streams, ground water) spent time in contact with calcium-rich soils or other calcium-rich geologic materials in the subsurface and were exposed to high \( \text{CO}_2 \) concentrations. Hem (1989) notes that "Partial pressures of \( \text{CO}_2 \) in soil air are commonly 10 - 100 times the levels reached in the [surface] atmosphere (Bolt and Bruggenwert, 1978, p.11)."

Hem also mentions that Garrels and Christ (1964) describe the calculations for creating similar graphs for a variety of water temperatures and ionic strengths with a plot of calcium concentration versus partial pressure of carbon dioxide. With the graph for the temperature and ionic strength of the water body in question, one could read the solubility of calcium carbonate directly from the graph and compare it against laboratory analyses to see whether or not the water body is saturated with respect to calcium carbonate. The calculations are based on a simplified, closed system with only water, carbon dioxide gas and calcite. Therefore, Hem cautions, "Natural systems contain other solutes and solids, and this kind of calculation has a somewhat limited practical applicability."

**USING A CARBONATE SATUROMETER FOR REAL-TIME MEASUREMENTS.** Dean and Megard (1973) discuss how they used a "carbonate saturometer" to measure carbonate saturation. They explain that "The degree of oversaturation or undersaturation can be determined simply measuring the pH of the water." 

In the case of Elk Lake and Lake Itasca, they found that calcite was in equilibrium at pH 7.73. An independent calculation using the computer model WATEQ (Truesdell and Jones, 1974, and Plummer and others, 1976) showed that the "surface water of Elk Lake is theoretically saturated with both calcite and dolomite at a pH of about 7.7. This number confirms the validity of the saturometer results (equilibrium pH = 7.73) in this lake and also indicates that any inhibition or kinetic effects are minor in Elk Lake.

**ADDITIONAL EXPERIMENTAL DETERMINATION TECHNIQUES.** Two additional techniques to determine the calcium carbonate saturation index experimentally are discussed in Standard Methods.
The "Saturometry" method documented by Ben-Yaakov and Kaplan (1969), Ben-Yaakov and Kaplan (1971) and Plath et al. (1980) is based on the same principle as the method described directly above by Dean and Megard (1973). This method allows determination of the degree of calcium carbonate saturation without performing a laboratory analysis of all the major and minor ions. In short, the procedure involves measuring what happens when the sample water of interest is allowed to equilibrate with calcium carbonate in a controlled environment. The technique is based on the fact that pH decreases if calcium carbonate precipitates and increases if it dissolves. The water sample is kept in a sealed flask maintained at a constant temperature as it equilibrates with calcium carbonate. The pH change is measured with a pH electrode. The initial pH and calcium values (before equilibrating with calcium carbonate) and the final pH value are used to determine the saturation index of the water sample.

The "Alkalinity Difference Technique" documented by Balzar (1980) allows calculation of the saturation index by equilibrating water of known pH, calcium and alkalinity with calcium carbonate in a sealed, constant-temperature system. As implied by the technique name, the saturation index can be calculated by measuring the change in alkalinity as the sample water equilibrates with calcium carbonate. This method has the advantage of not requiring any assumptions about the identity of the calcium carbonate phase. For example, unlike the "Saturometry" method described above, it would not give erroneous results if the water sample contains a significant amount of non-carbonate alkalinity. On the other hand, it is more difficult to determine when equilibration is achieved while using the "Alkalinity Difference Technique" compared to the "Saturometry" technique.

GRAPHS AND COMPUTER SOFTWARE FOR CALCULATING CaCO₃ Saturation Indices. A table summarizing methods for calculating calcium carbonate saturation indices is presented on page 2-35 of Section 2330, "Calcium Carbonate Saturation", in Standard Methods for the Examination of Water and Waste Water (APHA, AWWA and WPCF, 1998). The table includes eleven different methods including graphs and computer software. The summary indicates the basis of the method, the range of temperature and ionic strength over which it is valid, whether ion pairs and alkalinity of the water are considered and the minimum equipment required. References are also provided to find additional information about each method.
APPENDIX J - FIELD OBSERVATIONS: PHYTOPLANKTON, PARTICULATES, ETC.

(Excerpts from notes are in italics, other text may be paraphrased from notes)

**July 21 – 24, 1999**

**July 21, 1999:** Noon: We observed relatively dense concentrations of particulate matter in surface water near site 101 and took two photographs using a submerged Secchi Disk as a background. However, the surface water looked relatively particulate-free in other parts of the lake. Upon returning to the vicinity of 101 at 2:20 PM ..., we were not able to find such high concentrations of particulates as we encountered earlier.... There are very low particulate concentrations in the lake near the WNW inlet (site 5) compared to site 101 earlier today....

**July 22, 1999:** Lake appears greener than previous visits. Particulate abundance varies throughout lake. At site 101, observed many bright spots & yellow- to olive-green sphere-shaped organisms with pincushion appearance and one snail larva.... Most of the time we spent on the lake between July 20-22, the lake appeared dark green.

**August 1999**

August 20, 1999, at site 101, the lake was characterized as “definite algae; green, yellow or brown color apparent” (Class 3-4) and “swimming and aesthetic enjoyment slightly impaired because of algae levels” (Class 3). Similar conditions were noted on September 1. Slightly worse conditions were observed on August 24: “high algae levels with limited clarity and/or mild odor apparent”.

**August 24, 1999**

“Lake appears gray-green.”

Sites 22, 26, 27: 3:52 – 4:59 PM: greenish tint in water, no to few particulates.
Sites 2 and 29: 4:54 – 5:11 PM: greenish water, fine dark particulates (site 2), dense white particulates (site 29).
Near Sites 10 and 27: 3:30 – 4PM, very little to no particulates observed.
Site 101: 10:35 AM – 12:52 PM: The lake water has relatively dense concentrations of white to light-green particulates. We can see high concentrations of particulates including pincushion-like yellowish-brown organisms [later identified as Gloeotrichia, a blue-green algae], a lot of smaller dark flecks and green particulates, and many groups of 2-6 sphere-like organisms in the 2-liter sample bottles. Site 101: 5:33 PM: greenish water, dense white particulates, large numbers of minnows near the particulates. There is also foam and film-like accumulations of particulates at the surface that were not observed earlier today.

Site 15: 5:46 PM – very high concentrations of yellow-green particulates, even higher than at site 101 were seen here & out to about 200-250 meters from shore (note that Secchi Disk readings taken here were from 8 – 8.5 feet deep and turbidity was measured at 5.0 – 6.5 NTUs.
Site 5: 6:05 PM: (adjacent to WNW Inlet) – extremely high concentrations of yellow-green particulates are seen within 100 feet of the WNW inlet. The water surface appears as one continuous stretch of linear yellow green streaks similar to Langmuir strips. At this time, I also observed waves moving toward the WNW inlet from further out in the lake. As we moved South and away from the shore near site 5, the density of surficial green particulates thinned out but moderately high densities of yellow-green particulates were observed far offshore from site 20 on a line between site 5 and site 13.
Site 6: 6:48 PM, green water, moderately high concentration of yellow-green particulates.
SW Inlet: 7:49 PM, No current observed in stream, very little particulates observed.

Summary of observations of particulates: We saw high concentrations of particulates near the lake surface along the northern and western parts of the lake. We did not see any noticeable amounts of particulates in the eastern and south-central portions of the lake. We saw high concentrations of particulates as far out from the northern shore as site 101.

**September 15, 1999**

On September 15, 1999, the near-surface water at site 101 appeared relatively clear with only a very small amount of suspended material (probably organic) visible. Adjacent to the stream gauge at the
WNW inlet stream, there appeared to be a clear film or oily liquid coating the surface of the water. Just east of the WNW inlet, numerous “rafts” of sand, up to about one-inch long, were observed floating on the surface of the lake.

**October 10 – 13, 1999**

On October 10 and October 13, 1999, a significant amount of “white specs” were observed in near-surface water at site 101. On October 10, the surface of the water at site 101 appeared to be covered with a fairly transparent surface scum or film similar to what had been observed in the WNW inlet stream about a month earlier. The scum or film seemed to have a significantly higher surface tension than the lake water and appeared to be arranged in streaks in some areas near the boat. On October 12, at the WNW inlet sampling location, an oil-like film was observed on the surface of the stream in very slowly moving water. Extremely high densities of minnows were observed at the sampling point and near the stream gauge location a short distance upstream.
HISTORICAL SECCHI DISK MEASUREMENT LOCATIONS AND DATA

Locations of CLMP Secchi disk monitoring sites are shown on the map (next page) in Figure 44 - Citizen Lake Monitoring Program (CLMP) Sampling Points on Siseebakwet Lake. Some other sampling locations are shown on the map in Figure 4 - Monitoring Sites Location Map for Siseebakwet Lake on page 16. Sampling locations are also discussed in the section on Trends in Water Quality and Related Factors beginning on page 103.

Table 34 - Data Used for Secchi Disk Transparency History Plot

<table>
<thead>
<tr>
<th>SOURCE OF DATA</th>
<th>SAMPLE LOCATION</th>
<th>DATA SET TYPE</th>
<th>SECCHI DISK DEPTH (FT.)</th>
<th>DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Biocentric (1972)</td>
<td>Average of A-E</td>
<td>annual mean</td>
<td>18.6</td>
<td>1972</td>
</tr>
<tr>
<td>Whiteford 1985</td>
<td>Unspecified</td>
<td>annual mean</td>
<td>16.7</td>
<td>1980</td>
</tr>
<tr>
<td>Whiteford 1985</td>
<td>Unspecified</td>
<td>annual mean</td>
<td>14.3</td>
<td>1983</td>
</tr>
<tr>
<td>Whiteford 1985</td>
<td>Unspecified</td>
<td>annual mean</td>
<td>13.6</td>
<td>1984</td>
</tr>
<tr>
<td>Whiteford 1985</td>
<td>Unspecified</td>
<td>annual mean</td>
<td>13.7</td>
<td>1985</td>
</tr>
<tr>
<td>DNR Ecol. Svs.2000b (M. Briggs)</td>
<td>Unknown</td>
<td>single measurement</td>
<td>14.0</td>
<td>07/28/75</td>
</tr>
<tr>
<td>CLMP Database</td>
<td>201(most likely)</td>
<td>single measurement</td>
<td>14.0</td>
<td>08/07/74</td>
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<tr>
<td>STORET Database</td>
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<td>07/01/81</td>
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<tr>
<td>CLMP Database</td>
<td>202</td>
<td>summer mean</td>
<td>11.5</td>
<td>1988</td>
</tr>
<tr>
<td>CLMP Database</td>
<td>202, 203</td>
<td>summer mean</td>
<td>16.1</td>
<td>1989</td>
</tr>
<tr>
<td>CLMP Database</td>
<td>203</td>
<td>summer mean</td>
<td>16.1</td>
<td>1990</td>
</tr>
<tr>
<td>CLMP Database</td>
<td>201, 203, 204, 206, 207, 208, 209, 210</td>
<td>summer mean</td>
<td>11.2</td>
<td>1991</td>
</tr>
<tr>
<td>CLMP Database</td>
<td>203, 204, 206, 209, 210, 211</td>
<td>summer mean</td>
<td>14.8</td>
<td>1992</td>
</tr>
<tr>
<td>CLMP Database</td>
<td>203, 204, 206, 209, 210, 211</td>
<td>summer mean</td>
<td>14.8</td>
<td>1993</td>
</tr>
<tr>
<td>CLMP Database</td>
<td>203</td>
<td>summer mean</td>
<td>13.1</td>
<td>1994</td>
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<tr>
<td>CLMP Database</td>
<td>203, 204</td>
<td>summer mean</td>
<td>12.8</td>
<td>1995</td>
</tr>
<tr>
<td>CLMP Database</td>
<td>203</td>
<td>summer mean</td>
<td>10.2</td>
<td>1996</td>
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<tr>
<td>CLMP Database</td>
<td>203</td>
<td>summer mean</td>
<td>6.9</td>
<td>1997</td>
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<tr>
<td>CLMP Database</td>
<td>101, 203</td>
<td>summer mean</td>
<td>10.7</td>
<td>1998</td>
</tr>
<tr>
<td>CLMP Database</td>
<td>101, 303</td>
<td>summer mean</td>
<td>11.5</td>
<td>1999</td>
</tr>
</tbody>
</table>
Figure 44 - Citizen Lake Monitoring Program (CLMP) Sampling Points on Siseebakwet Lake
COMPARISON OF TRENDS IN SECCHI DISK TRANSPARENCY AND CLIMATIC FACTORS

The following tables are presented on subsequent pages in this appendix:

Figure 45 - Secchi Disk Transparency vs. Annual Precipitation 1955 - 1999
Figure 46 - Secchi Disk Transparency vs. Summer Average Precipitation 1955 - 1999
Figure 47 - Secchi Disk Transparency vs. Annual Average Air Temperature: 1955 - 1999
Figure 48 - Secchi Disk Transparency vs. Summer Average Air Temperature: 1955 - 1999

IMPORTANT NOTES ABOUT THE TRANSPARENCY VS. CLIMATIC FACTORS PLOTS. Please note that multipliers were used in the creation of these figures to make trends in each data set on the plots easier to see. The multipliers used on the precipitation or temperature data sets are shown at the top of each figure. In addition, please note that the bottom of the vertical scale on these figures was clipped and starts at a value greater than zero for the the same reason: to make trends in the plots easier to see.

The Secchi disk data used for these plots is described earlier in this appendix in Table 34 - Data Used for Secchi Disk Transparency History Plot. Note that the data set includes summer averages, annual averages (assumed to be mostly summer measurements) and, in some cases, individual summer measurements.

Finally, please note that whereas Secchi disk readings are often presented as negative values on bar chart plots, the Secchi disk readings (depth below lake surface) are presented as positive numbers in the following plots so they can be more easily compared side by side with the climatic data.

These tables were prepared to allow a very basic analysis of the potential historical relationship between Siseebakwet Lake Secchi disk transparency and climatic factors. Further analysis might reveal trends that are not obvious by viewing these simple plots alone. However, what is most needed to perform a useful analysis of this type is a longer, continuous (every year) record of reliable measurements to calculate annual summer mean Secchi disk readings. The need for a longer record is especially important for evaluation if there are time lag factors involved, between a climatic input and a corresponding transparency response.
Figure 45 - Secchi Disk Transparency vs. Annual Precipitation 1955 - 1999
Figure 46 - Secchi Disk Transparency vs. Summer Average Precipitation 1955 - 1999
Figure 47 - Secchi Disk Transparency vs. Annual Average Air Temperature: 1955 - 1999
Figure 48 - Secchi Disk Transparency vs. Summer Average Air Temperature: 1955 - 1999
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