Mirror and Shadow Lakes, Waupaca, Wisconsin: An Interpretive Analysis of Water Quality,

Final Report to the Wisconsin Department of Natural Resources

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SUMMARY

Mirror and Shadow Lake are groundwater drainage lakes located in Waupaca, Wisconsin. These lakes reflect cultural eutrophication from surrounding urban development. As early as the 1920's, water issues related to drinking water, fish populations, and algal communities arose. During the 1970's and 80's research projects were conducted to understand and improve conditions in the lakes.

This project was initiated because water quality is still an issue in Mirror Lake. Nutrient concentrations hover in ranges described in previous studies and dissolved oxygen concentrations have not improved. This study was designed to assess current hydrologic and algal conditions, provide assistance/education for the formation of citizen-based lake group, and recommend how conditions can be improved.

Lake water quality is determined by the quality of water that enters and processes that occur within the lake. Water and nutrients enter and leave Mirror and Shadow Lakes from a variety of sources. Water and nutrient components were assessed by evaluating the quantity and chemistry of the surface and groundwater and by surveys of the littoral and shoreland vegetation. Groundwater flow and quality was measured and sampled using small wells around the near shore perimeter. Inflow and outflow streams were measured and monitored using stream flow monitors, pressure transducers, and siphon samplers. In lake conditions were measured with data sondes, Secchi disks, and chemical and biological water analyses. Finally, surface and groundwater components were assembled and coupled with estimates for runoff and nutrients from specific areas, which created the Lake's nutrient budgets. Nutrient budgets are the basis for understanding water quality in Mirror and Shadow lakes because nutrient budgets account for how much water and nutrients enter and leave the lakes over a year.

Dissolved oxygen concentrations in Mirror Lake were below concentrations that can support a warm water fish community. Materials that use up oxygen including metals and nutrients from surface water runoff and groundwater inflow cause heavy weed growth and large chemical and biological oxygen demand in the depths of the lake. Even when Mirror Lake overturned the oxygen throughout the water column was less than 3 mg/L. This occurred in the fall and had the lake not been aerated, Mirror Lake would have likely experienced winterkill of fish. In addition, Mirror Lake does not overturn annually which causes oxygen in the lake to continue to be consumed without replenishment for a full year. Aeration should continue to be used to address oxygen problems in the lake, however, because of the amount of phosphorus in solution in the bottom lake layer, fully mixing the lake is unwanted. Instead, aeration is recommended in the upper layers of the lake in the fall to maximize oxygen levels prior to ice over.

Dissolved oxygen concentrations in Shadow Lake were great enough to support a warm water fish community. The lake mixed seasonally and added enough oxygen to the system to avoid fish winterkill problems. During stratified times of the year the majority of the lake water had sufficient concentrations of oxygen. Up to now, Shadow Lake has been able to handle the load of nutrients and metals added to the lake due to the marl formation in the lake. However, despite the marl, nutrient concentrations can continue to increase. Efforts should be made to reduce the phosphorus and sediment loads to the lake.

Algal communities were dominated by Cyanobacteria (blue-green algae), Chlorophyta (green algae), and Ochrophyta (diatoms and golden-brown algae). The genus *Oscillatoria* was the dominant taxon in nearly every sample. Samples from Mirror and Shadow Lakes contained 66 and 58 algal taxa from 6 algal divisions, respectively. Seasonal algal patterns were similar but more pronounced in Shadow Lake. Algal blooms, most likely stimulated by phosphorus in surface runoff, will likely continue.

The quality of the groundwater flowing into the lakes reflects impacts from the urban environment where the groundwater originates. High concentrations of chloride were measured in most wells and elevated phosphorus and ammonium were present in the groundwater entering the north end of Mirror Lake and the inflows and outflow to and from Shadow Lake. Additional assessment should be conducted to evaluate the sources and conditions associated with the groundwater entering Mirror Lake.

Urban lakes receive large amounts of nutrient input and house many lake property owners. Urban lakes have significantly more impervious surface than lakes surrounded by natural vegetation and therefore receive more runoff of water, sediments, and nutrients. Therefore implementations of best management practices are recommended to control the effects of cultural eutrophication, such as nuisance algal blooms. Many in-lake treatments can be performed to accommodate the desires of lake users, but it is best to understand that these treatments are palliative. At some point in the future these problems will arise again and in order to truly manage eutrophication of lakes, management must be done at a watershed level.

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TABLE OF CONTENTS

SUMMARY .... **I**

ACKNOWLEDGEMENTS .... **III**

TABLE OF CONTENTS .... **IV**

LIST OF TABLES .... **VI**

LIST OF FIGURES .... **VII**

INTRODUCTION **1**

PHYSICAL CHARACTERISTICS AND DEVELOPEMENT 1
- *Setting* *1*
- *Lake Morphology* *1*
  - Mirror Lake 1
  - Shadow Lake 1
- *Geology* *1*

CULTURAL DEVELOPMENT 2

STUDY GOALS AND OBJECTIVES: **4**

METHODS **5**

SAMPLING STRATEGY 5
LAKE MEASUREMENTS 5
INFLOW/OUTFLOW MEASUREMENTS 5
- *Sampling Procedures* *5*
- *Flow Measurement* *6*

GROUNDWATER MEASUREMENTS 7
- *Groundwater* *7*

QUALITY CONTROL 8
METADATA 8

RESULTS AND DISCUSSION **9**

LAKE HYDROLOGY – WHERE THE WATER IS COMING FROM 9
- *Precipitation* *9*
- *Surface Watersheds* *9*
- *Groundwater Watersheds* *11*

SURFACE WATER QUALITY 13
- *Mid Lake Measurements* *13*
  - Dissolved Oxygen and Temperature 13
  - pH 18
  - Alkalinity and Hardness 20
  - Conductivity 20
  - Chloride 22
  - Potassium and Sodium 22
  - Sulfate 22
  - Water Clarity 22
  - Chlorophyll *a* 24
  - Algal Community 24
  - Nitrogen 33
  - Total Nitrogen to Total Phosphorus Ratio 35
  - Phosphorus 36

INFLOW/OUTFLOW WATER QUALITY 38
- *Total Suspended Solids* *39*
- *Nitrogen* *39*
- *Phosphorus* *40*

Chloride *41*
Chemical Oxygen Demand *41*
GROUNDWATER 41
Groundwater Inflow and Outflow *41*
Temperature *43*
Conductivity *45*
Chloride *46*
Nitrogen *48*
Reactive Phosphorus *49*
COMPUTER MODELING 51
SIMULATING LAND USE IMPACTS ON PHOSPHORUS TRANSFER *51*
Simulation Approaches *51*
Pervious/Impervious/Storm Simulation Method 52
Notes 53
THE BIG PICTURE 54
CITIZEN EDUCATION 56

CONCULSIONS AND RECOMENDATIONS 57

Mirror/Shadow Lake Work Plan *60*

WORKS CITED 61

APPENDICES 62

LIST OF TABLES

Table 1. Analytical methods used at WEAL for water quality analysis samples and corresponding detection limits. 6
Table 2. Types and percent of impervious surfaces within the Mirror and Shadow Lake watersheds. 10
Table 3. Descriptive levels of hardness found in Wisconsin lakes. Hardness range for Mirror and Shadow Lakes is highlighted. 20
Table 4. Measurements of turbidity, color, and water clarity during overturn in Mirror and Shadow Lakes, Waupaca, WI. 23
Table 5. Description of water clarity based on Secchi depth measurements in Wisconsin…………..23
Table 6. Algae found in Mirror Lake, Waupaca, WI………………………………………………..27
Table 7. Algae found in Shadow Lake, Waupaca, WI……………………………………………….28
Table 8. Dominant Algal Taxa in Mirror and Shadow Lakes, Waupaca, WI………………………...29
Table 9. Algal Abundance, by Division, in Mirror and Shadow Lakes, Waupaca, WI……………...29
Table 10. Concentrations of nitrogen in Mirror Lake throughout the year. 34
Table 11. Nitrogen concentrations in Shadow Lake throughout the year. 35
Table 12. Total nitrogen to total phosphorus ratios in Mirror and Shadow Lakes, Waupaca, WI. .. 35
Table 13. Concentrations of soluble reactive phosphorus and total phosphorus in mid lake samples collected from Mirror Lake, Waupaca, WI. 37
Table 14. Concentrations of soluble reactive phosphorus and total phosphorus in mid lake samples collected from Shadow Lake, Waupaca, WI. 37
Table 15. Chemical analysis of samples collected from Mirror and Shadow Lake inflows and outflows during baseflow conditions (July 2003). 40
Table 16. Average concentrations of chemicals collected from Mirror and Shadow Lake inflows during event conditions. (March-August 2003) 40
Table 17. Phosphorus load estimates for Mirror and Shadow Lakes. 52

LIST OF FIGURES

Figure 1. 2000 ortho-photo showing location of Mirror and Shadow Lakes in Waupaca and some local landmarks. 1
Figure 2. Surface watershed boundaries and land uses. Mirror and Shadow Lakes, Waupaca, WI 2000 11
Figure 3. Groundwatershed and flow direction associated with Mirror and Shadow Lakes, Waupaca, WI. 12
Figure 4. Shadow and Mirror Lake groundwatershed and associated land use in Waupaca, WI 2000. 12
Figure 5. Schematic showin layering o lakes during stratificaiton 13
Figure 6. Seasonal temperature variation causing the stratification and mixing of many Wisconsin lakes (Shaw et al., 2000). 14
Figure 7. Profile of temperatures in Mirror Lake throughout the year. 15
Figure 8. Profile of dissolved oxygen concentrations in Mirror Lake throughout the year. 16
Figure 9. Profile of temperatures in Shadow Lake throughout the year…………………………...17
Figure 10. Profile of dissolved oxygen concentrations in Shadow Lake throughout the year……….18
Figure 11. Profile of pH in Mirror Lake throughout the year…………………………………………19
Figure 12. Profile of pH in Shadow Lake throughout the year. 19
Figure 13. Profile of conductivity in Mirror Lake throughout the year. 21
Figure 14. Profile of conductivity in Shadow Lake throughout the year. 21
Figure 15. Water clarity measurements in Mirror and Shadow Lakes. 23
Figure 16. Algae in Mirror Lake, Waupaca, WI…………………………………………………….31
Figure 17. Dominant Algal Divisions in Mirror Lake, Waupaca, WI………………………………….31
Figure 18. Algae in Shadow Lake, Waupaca, WI……………………………………………………….32
Figure 19. Dominant Algal Divisions in Shadow Lake, Waupaca, WI…………………………………32
Figure 20. Groundwater flow conditions in Mirror Lake Waupaca, WI Summer 2003. 43
Figure 21. Groundwater flow conditions in Shadow Lake Waupaca, WI Summer 2003. 43
Figure 22. Groundwater temperatures measured from mini-piezometers in Mirror Lake Waupaca, WI Summer 2003. 44
Figure 23. Groundwater temperatures measured from mini piezometers in Shadow Lake Waupaca, WI Summer 2003. 45
Figure 24. Conductance of groundwater entering Mirror Lake Waupaca, WI Summer 2003. 45
Figure 25. Conductance of groundwater entering Shadow Lake Waupaca, WI Summer 2003. 46
Figure 26. Chloride concentrations in groundwater entering Mirror Lake Waupaca,WI 46
Figure 27. Chloride concentrations in groundwater entering Shadow Lake Waupaca, WI 47
Figure 28. Ammonium concentrations in groundwater entering Miror Lake Waupaca, WI. 47
Figure 29. Ammonium concentrations in groundwater entering Shadow Lake Waupaca, WI 48
Figure 30. Soluble reactive phosphorus concentrations in groundwater entering Mirror Lake Waupaca,WI. 48
Figure 31. Soluble reactive phosphorus concentrations in groundwater entering Shadow Lake Waupaca, WI 2003. 49
Figure 32. Primary sources of water to Mirror and Shadow Lakes. 54
Figure 33. Shadow and Mirror Lake nutrient budget from the various sources of inflow and outflow ……………………………………………………………………………………………55

INTRODUCTION

PHYSICAL CHARACTERISTICS AND DEVELOPEMENT

Setting

Mirror and Shadow Lakes are located in Waupaca County, WI. The lakes are surrounded by the city of Waupaca, which has a population of approximately 6000 residents. The city of Stevens Point lies 30 miles to Waupaca's northwest and Green Bay 60 miles to Waupaca's northeast. The Tomorrow or Waupaca River flows one mile north of the lakes and the Crystal River flows one quarter mile to the south. Roads surround both the lakes and residential development occurs along the majority of the land adjacent to Mirror the Lakes. South Park, a city park, is located on the west side of the lakes and provides public access to the lakes, a boat landing, a swimming beach, picnic areas, and washroom facilities. The City of Waupaca has a municipal well located on the east shore of Mirror Lake and Lakeside Memorial Park cemetery perches on the northwestern shore of Shadow Lake.

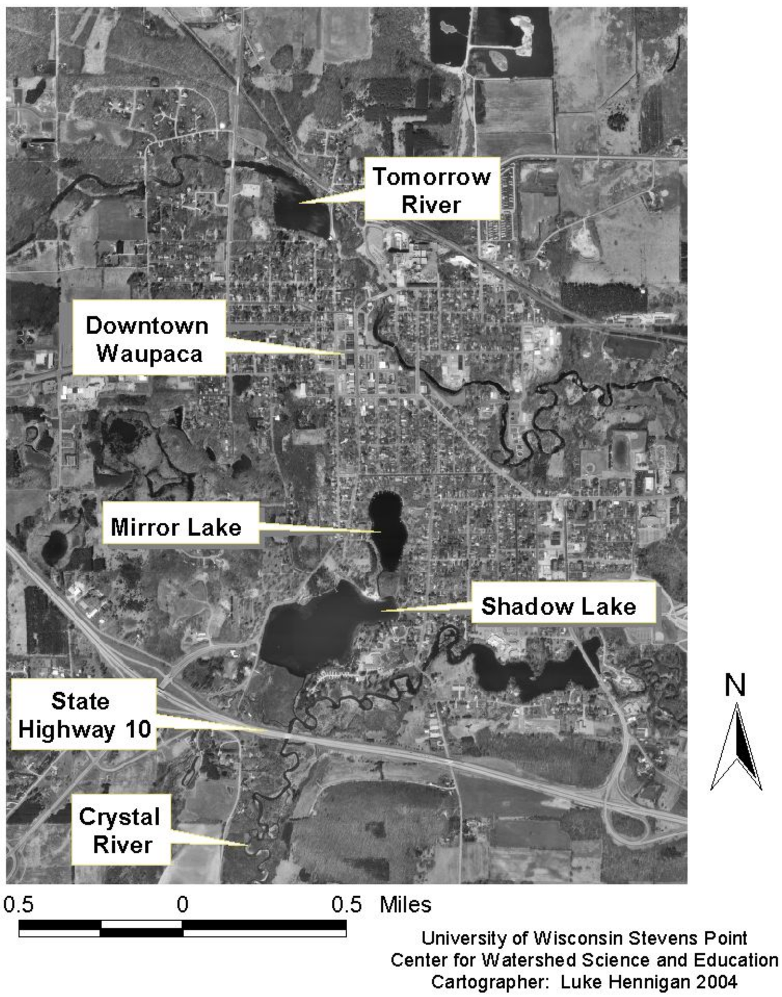

Figure 1. 2000 ortho-photo showing location of Mirror and Shadow Lakes in Waupaca and some local landmarks.

Lake Morphology

<u>Mirror Lake</u>

Mirror Lake is an oblong groundwater drainage lake residing in a Kettle pothole, which is a bowl like depression (Figure 1). Mirror Lake covers 13 acres, has a maximum depth of 43 feet, and an average depth of 25 feet. The *littoral zone* (area where rooted aquatic plants grow) is small because of the steep lake bed that quickly descends to greater depths. A renovated channel on the southern shore drains Mirror Lake's water to Shadow Lake.

<u>Shadow Lake</u>

Shadow Lake is a 43 acre drainage lake with a maximum depth of 41 feet and an average depth of 17 feet. Hills exist on Shadow Lake's northern expanse and slope into wetlands along the southern shore. Shadow Lake has a dredged channel that outflows to the Crystal River.

Geology

Possin (1973) found that Mirror and Shadow Lake's basins were formed in the outwash plain of the receding Green Bay Lobe of the Cary ice sheet that developed in Pleistocene glaciations about 12-14,000 years ago. As this ice sheet melted or wasted back northward large blocks of ice separated from the main glacier and remained in the newly laid glacial sediment. Deposited ice melted within the sediment and formed glacial lakes, often called "kettle lakes" because of the lakes morphological resemblance. Around Mirror and Shadow Lake, glacial deposits and outwash sediment of medium to coarse grained sand compose the top 50-100 ft of soil and overlay 50 ft of glacial till, which is a variable mixture of soil, pebbles, rocks, and boulders. Underneath lies the parent material composed of crystalline granite bedrock.

The lakes bottoms are composed of outwash that has been overlain with brown fibrous peat and marl sediment that have been formed and deposited by the lakes themselves. Peat occurs along the shores in abundance and especially on the west shore of Mirror Lake. Peat is underlain by a marl layer that extends out into the deeper areas and at the greatest depths a thin layer of organic muck has been deposited on top of the marl (Possin 1973).

CULTURAL DEVELOPMENT

Mirror and Shadow Lake have a long cultural history dating back to pre-settlement when Native Americans used the area for encampment (Garrison and Knauer 1983). In the 1850s, European settlers came to the region and began development. By 1901 streets surrounded Mirror Lake and during the 1920s, water issues developed with Mirror and Shadow Lake's nearby wells and surrounding groundwater as the city strove to obtain more water while maintaining a healthy drinking water network for the growing city. Problems included well clogging due to the regions fine sands and decreased water quality in Mirror Lake that created the need for treatment in order to for Mirror Lake to continue serving as a source of drinking water (Alvord and Burdick, 1921). Mirror Lake's wells are still present on Mirror Lake's shores today, but contribute only to the City's water supply on a much reduced scale. Well number 2 on Mirror Lakes eastern shore is completely out of use. By 1935 nearly all residences were established on Mirror Lake and deterioration of the lake's water quality lead to the failure of Mirror and Shadow Lakes stocked trout fisheries by the mid 1950s (Possin 1973). Alterations in drawings and air photos show that sometime between the 1930s and 50s an outflow was dredged at the south end of Shadow Lake to allow access from the Crystal River. Around the same time, a wetland inflow was channalized on Shadow Lake's northwestern shore to transport stormwater drainage from the city. In the 1960s the land adjacent to the east shore of Shadow Lake was developed as both lakes took up residence in the growing city of Waupaca, WI (Garrison and Knauer 1983).

In the mid 1970s a study of Mirror and Shadow Lakes confirmed that cultural eutrophication was occurring. Consistent with studies elsewhere, runoff from streets, lawns, and rooftops, were found to be adding nutrients and metals to Mirror and Shadow Lakes causing enhanced algal and plant growth and decreased dissolved oxygen concentrations. Data showed that reducing the amount of nutrients and metals in the lakes was necessary and led to the diversion of storm sewers away from the lakes in 1976. Then, in 1978, aluminum sulfate was applied to the lakes to reduce internal phosphorus loading (aluminum forms a precipitate with phosphorus that can reduce its availability to aquatic plants and algae). The storm sewer diversion was estimated to have reduced external phosphorus loading by approximately 58% to 65% for both lakes and aluminum sulfate application reduced in-lake phosphorus concentrations from 90 mg/m^3 in Mirror Lake and 33 mg/m^3 in Shadow Lake to 20 to 25 mg/m^3 in both lakes (Garrison and Knauer 1981). Along with these treatments, Mirror Lake has been aerated to prevent low winter dissolved oxygen concentrations and increase spring oxygen concentrations.

Recently, water quality monitoring has been conducted by Adopt-a-Lake Program participants and Dave Furstenburg's Waupaca Learning Center students. These volunteer participants, the Waupaca Department of Public Works, the City of Waupaca's Lakes District, and the Wisconsin Department of Natural Resources (WDNR) gathered four years of information about each lake. Concern arose with when low dissolved oxygen concentrations were found in Mirror Lake. Participating groups determined that dissolved oxygen was low because of Mirror Lake's depth, narrow vegetative border, wind-sheltered surface, and lack of circulation. In February of 2001, shortly after the discovery of low dissolved oxygen concentrations, Mirror Lake suffered a winter fish kill. Low dissolved oxygen concentrations were blamed for the fish kill and recent monitoring showed low dissolved oxygen concentrations remain in Mirror and Shadow Lakes. Therefore funds were procured for lake studies on both Mirror and Shadow Lakes.

A partnership between the City of Waupaca, Mirror and Shadow Lake Watchers Adopt-A-Lake group, UW-Stevens Point, and the Fox-Wolf Watershed Alliance was formed and a study design was created. In 2002, funds were provided for the study by the WDNR Lake Planning Grant Program, the City of Waupaca, and the University of Wisconsin Stevens Point (UWSP) Center for Watershed Science and Education (CWSE).

STUDY GOALS AND OBJECTIVES:

- Estimate a water budget for Mirror and Shadow Lakes and determine the land areas impacting surface and groundwater feeding the lakes.

- Determine the current quality of the surface water, the inlets and outlets, and the groundwater in Mirror and Shadow Lakes over an annual cycle.

- Describe the algal community during seasonal succession.

- Produce a preliminary nutrient budget and establish relationships between water quality and land use.

- Provide educational opportunities for lake landowners that enhance the understanding of the Lakes and the lakes watersheds. Allow lake landowners to participate in parts of the study and provide workshops on shoreline management practices.

- Summarize results in an understandable format to be used by residents and agency personnel to acquire a better understanding of Shadow and Mirror Lakes. Detail how landowners land use practices may affect water quality in nearby streams and lakes and provide recommendations to assist future lake management decisions.

- Create an updated management and implementation plan for the two lakes and provide data for the update of the county Land and Water Resource Plan.

- Identify data that a citizens group could collect that would be useful for long-term monitoring of the lakes and develop a quality assurance plan for the citizen's collection effort.

- Assess current shoreline management including an updated shoreline land cover and littoral zone map.

- Work with the City of Waupaca Lake District to form an advisory committee to provide pertinent water data and information to assist the Lake District in comprehensive ("smart growth") management to develop any needed changes to ordinances and city plans by providing suggestions for the prioritization of city restoration money.

- Incorporate the Adopt-A-Lake group in the collection of data and outreach components of the study.

METHODS

SAMPLING STRATEGY

Sampling was conducted to provide data from groundwater and surface water that would establish the current water quality conditions. Sampling was done throughout the year during the spring thaw, spring overturn, summer growing season, fall overturn, and winter. Year round sampling allowed the characterization of seasonal variation. Sampling was also done within sampling seasons when conditions drastically changed to determine the effects of events such as precipitation.

LAKE MEASUREMENTS

Mid lake measurements were taken at the deepest point of each lake. Deep points were marked and relocated using a global positioning system. Sampling at each deep point used a *Hydrolab* Model 4600 data sonde to collect temperature, dissolved oxygen, conductivity, and pH data throughout the entire depth of the lake. Mid lake measurements were taken in November 2002; February, April, June, July, and Aug 2003. Depending on the time of year, the lake water samples were collected either through the use of an integrated bailer or an alpha bottle. Depths of the lake layers were determined by data sonde temperature recordings and depending on the time of sampling all or some of the lake's layers were sampled. When the lake was layered, deep water samples were acquired with an alpha bottle. Samples were transferred to two 60 mL polypropylene bottles that contained sulfuric acid (H_2SO_4). One 60 mL bottle was unfiltered and the other was field filtered through a 0.45 micron membrane filter. During the growing season the upper layers were sampled for total phosphorus and chlorophyll *a* while bottom layers were sampled for only total phosphorus. Chlorophyll *a* samples were transferred to an unpreserved 1000 mL bottle and then filtered with 934 AH glass fiber filter. The filter pad was folded and placed in aluminum foil and sealed in a *Fischer* whirl pack for delivery on ice to the state-certified UW-Stevens Point Water and Environmental Analysis Lab (WEAL).

ALGAL COLLECTION AND ANALYSIS

For each sampling date, two to three algal samples were taken. Sampling included a mid-lake volumetric sample, a combined near-shore plankton tow, and a shoreline grab sample. Each sample was split and half was counted immediately while the other half was preserved with Lugol's Iodine. All organisms in random samples were counted using a Sedgewick-Rafter counting cell and an Olympus Inverted Microscope until 100 of the most common organism were tallied. Identification was to genus using standard taxonomic references for characteristic algal groups.

INFLOW/OUTFLOW MEASUREMENTS

Sampling Procedures

During runoff events (heavy rainfall or snowmelt), the inflows and outflows of Mirror and Shadow Lakes were sampled and analyzed for nitrate, nitrite, ammonia, total Kjedahl-N, total and reactive phosphorus, chloride, total suspended solids, and chemical oxygen demand. Water samples were collected from each site using siphon samplers or the grab method. Water was transferred to three polypropylene bottles, one 500 mL unfiltered unpreserved sample, one 60 mL H_2SO_4 preserved unfiltered sample, and one 60 mL H_2SO_4 preserved filtered sample. Grab samples were collected by placing a capped bottle into the stream, facing the lid downstream, lowering it to the mid depth of the flowing water, and then opening the bottle.

Baseflow samples were taken during periods of low flow when precipitation had not donated to the system recently. Sampling during periods of no precipitation allowed for the analysis of groundwater feeding the stream sites. Baseflow samples were collected once on July 24th, 2003 and were analyzed for nitrate, nitrite, ammonia, total Kjedahl-N, total and reactive phosphorus, chloride, and total suspended solids. The same bottling and filtering procedures were used for event flow and baseflow sampling.

ANALYSES	METHOD	METHOD DETECTION LIMIT
Alkalinity	Titrimetric 2320 B	4 mg/L
Chloride	Automated Ferricyanide 4500 C1 E	0.2 mg/L
Chlorophyll *a*	Spectrometric 10200 H	0.1 mg/L
Conductivity (in lab)	Conductivity Bridge 2510 B	1 umho
Hardness, Calcium	Titrimetric 3500 Ca D	4 mg/L
Hardness, Total	Titrimetric 2340 C	4 mg/L
Nitrogen, Ammonium	Automated Salicylate 4500-NH_3 G	0.01 mg/L
Nitrogen, Nitrate + Nitrite	Automated Cadmium Reduction 4500 NO_3	0.021 mg/L
Nitrogen, Total Kjeldahl	Block Digester; Auto Salicylate 4500-NH3 G	0.08 mg/L
Phosphorus, Soluble Reactive	Automated Colorimetric 4500 P F	0.003 mg/L
Phosphorus, Total	Block Digester, Automated 4500 P F	0.012 mg/L
Potassium	ICP 3120B	270 ug/L
Sodium	ICP 3120B	0.2 mg/L
Sulfur (SO4)	ICP 3120B	26 ug/L
Total Suspended Solids	Glass Fiber 103-105C 2540D	1 mg/L

Table 1. Analytical methods used at WEAL for water quality analysis samples and corresponding detection limits.

Flow Measurement

Flow measurements were taken with a Marsh McBirney Model 2000 portable current meter. Measurements were taken by measuring the width of the inflow or outflow's defined stream edges. Stream width was recorded and divided into 10 to 20 equal units. The Marsh McBirney current meter was used at each unit's midpoint to determine the velocity and depth of the stream at each section. Velocity was measured at 60% of stream depth. Total discharge was calculated by multiplying the velocity and cross sectional area for each width unit [Discharge= Width (X ft) x Depth (X ft) x Velocity (X $^{ft}/_{sec}$)] and then summing all calculated discharges [Total Discharge=Σ(Discharge of section 1,2,3,4…)].

Along with discharge readings, a *Solinst Level Logger* pressure transducer was installed in the wetland stream to determine the stream's stage. The loggers were set in an "event" mode, which triggered the logger to collect data when there was an increase in stage (increase in pressure). In event mode, the pressure transducer collected pressure and temperature readings at set intervals, which varied from 15 to 30 minutes. The unit was installed at locations and with procedures to minimize damage of equipment and ensure quality of recorded data. The two pressure transducers for Mirror and Shadow Lake were installed: in the wetland stream running in Shadow Lake from the west side and barometric pressure was measured outside the Waupaca Learning Center.

The data stored in the pressure transducers was downloaded onto a laptop in the *Level Logger* program. The data was calibrated using the barometric pressure data to adjust for changes in the atmospheric barometric pressure. Data was then stored in a Microsoft Excel spreadsheet and combined with discharge data to develop a rating curve. Information was used in estimating loads of water and nutrient budgets.

GROUNDWATER MEASUREMENTS

Groundwater

In June 2003, Mirror and Shadow Lake's groundwater hydraulic head, temperature, and conductivity were measured using mini-piezometers (small temporary wells) every 200 feet around the perimeter of Mirror and Shadow Lake. Thirty-one sites were measured on Mirror Lake and 49 sites on Shadow Lake. Locations were marked with a global positioning system, described, and marked on orthophotos. Groundwater flow was determined (inflow/no flow/outflow) and samples for chemical analysis were collected to determine inflowing groundwater quality at these locations.

The mini piezometers were constructed from lengths of quarter-inch diameter 5-foot polypropylene tubing. One end of the tubing was formed with heat and a brass cast into a point. A small diameter ball-point sewing needle was used to form 3 inches of screen where water could enter. A 1 mL-pipet tip was attached to the front end for easier installation into the sediment.

In the field, a metal insertion rod was inserted into the tube and a steel tile probe initiated the hole before the mini piezometer was inserted into the ground. Mini pieaometers were inserted approximately 1.5 ft into the lake sediment in a depth of approximately 18 inches of water. At this depth, the mini piezometers passed the interstitial zone where water chemistry is changed by soil biota. Once the metal insertion rod was removed, a 60 cc syringe was used to draw up the groundwater. If no water could be drawn, then the well had to be developed. Wells were developed by injecting two to three full syringes of water until the well was purged. Injected water was removed and samples of the groundwater were taken. If the well could not be developed in this manner then no measurements could be taken and the site was marked as a site of no communication.

At each sampling location measurements were recorded in inches for installation depth, tube length above sediment, surface water level, static head (level of groundwater in tube compared to lake water height), slug height (length of tube above static head), and Hvorslev position. Static head indicates whether groundwater was entering or leaving the lake. If the static head was above the surface of the lake water, then groundwater was inflowing. If the static head was below the surface water, outflow was occurring, recharging the groundwater. If neither inflow nor outflow occurred, the site was considered static. Falling head tests were used to determine hydraulic conductivity which when combined with static head, can be used to estimate the velocity of groundwater flow. Falling head tests timed the fall of the water back to a black o-ring placed at 37% of the slug height. This procedure was repeated three times and the average was used in calculations (Hvorslev, 1951). The hydraulic conductivity (ease with which water moves depending on the porosity, grain size distributions, and soil conditions) was determined for each site by dividing the coefficient of hydraulic conductivity (related to the dimensions of the mini piezometer) by the average falling head time. The hydraulic conductivity multiplied by the hydraulic gradient (static head measurement minus the surface water level divided by the installation depth) gives the velocity or seepage rate of the groundwater.

In addition, the areas of the lake where ice began to melt in late winter were mapped in order to supplement the extent and location of groundwater inflow to the lake.

QUALITY CONTROL

When working in the field and the lab, quality control and quality assurance techniques were used. All analysis not conducted in the field were completed at the state certified Water and Environmental Analysis lab (WEAL) at UWSP.

METADATA

ArcView GIS land coverages of Wisconsin were obtained from the Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data (WISCLAND). ArcView GIS 3.3 software was used with land use, hydrology, road coverage, city municipal structures, and consulting maps for data interpretation. Additional maps were digitized at the university including the local Waupaca storm sewer maps and associated sub-watersheds and the groundwater flow maps.

RESULTS AND DISCUSSION

LAKE HYDROLOGY – WHERE THE WATER IS COMING FROM

Understanding how water gets to and from a lake is important because different sources of water impact the amount of time water stays in a lake, its water quality and chemistry and thus, the aquatic plants and biota in an aquatic system. During snowmelt or a precipitation event water moves across the surface of the landscape towards lower elevations such as wetlands, lakes and rivers, or internally drained areas (where water on the surface reacharges groundwater). The capacity of this landscape to hold water and filter particulates ultimately determines the water quality, habitat, and in-stream erosion. Simply put, the more the landscape can hold water during a storm, the slower the water is delivered to the streams and the greater the ability to filter the runoff.

As water moves across the land surface, soluble and particulate matter are picked up and travel with the flow. Surface water runoff is partially filtered when plants divert and slow water movement causing sediment and associated nutrients to be deposited or absorbed. The best plant filters (buffers) consist of a combination of trees, shrubs, and deeply rooted perennial vegetation. Although some of the land around the lakes contains this type of vegetation, one layer or another is missing from much of the landscape. Bluegrass (sp. *Poa*) is the predominate vegetation, and its short height, flexibility, and shallow rooting depth do not create a good sediment filter (UW-Extention, 1999).

Mirror and Shadow Lakes are receiving water from direct precipitation on the lakes, from surface runoff during rainstorms and snowmelt, and from groundwater inflow. Shadow Lake is also receiving water from Mirror Lake and a wetland channel draining from the northwest. The lakes are loosing water to groundwater and the channel draining to the Crystal River from Shadow Lake.

Precipitation

Precipitation feeds the lakes and their feeder streams directly and via surface runoff and groundwater inflow. About one third of the precipitation that falls infiltrates into the ground to recharge groundwater. The rest of this precipitation is either lost through evapotransporation or makes its way to wetlands, tributaries or the lakes as surface runoff. A combination of interactions between topography, geology, soil, man-made structures, and land use practices influence the water chemistry and regional and local surface water flow. Precipitation records for the last 30 years were acquired from the National Oceanic Atmospheric Association (NOAA); precipitation was shown to average approximately 30 inches per year in the City of Waupaca.

Surface Watersheds

A surface watershed is the land area where runoff from precipitation drains to water bodies before it can infiltrate into the ground. Surface watersheds with large amounts of steeply sloped land, stream inflows to the lake, and a large percent of impervious surface (buildings, roads, compacted soil) deliver additional surface runoff by averting infiltration into the soil and by funneling water directly to the lake. The surface watersheds for Mirror and Shadow Lakes were determined using the high topographic points around the lakes and evaluating maps showing the networks of natural and man-made inflows that feed or divert water to/from the lakes. By the nature of Mirror and Shadow's location within the city, their surface watersheds both include large amounts of impervious surfaces (Table 2).

Table 2. Types and percent of impervious surfaces within the Mirror and Shadow Lake watersheds.

Lake	*Rooftop %*	*Driveway %*	*Sidewalk %*	*Road %*	*Other Impervious %*	***Total Area Imp. %***
Mirror	7.2	0.5	1.7	4.9	3.1	**17.4**
Shadow	6.7	1.4	1.5	15.1	4.6	**29.3**

Alteration of the natural surface watersheds of both Mirror and Shadow Lake have occurred. Due to increased efficiency of local storm water systems, large quantities of water are diverted away from the lakes. Mirror Lake's surface watershed has been reduced to 34 acres with residential development covering approximately 60% of its watershed. The remaining land area includes recreation (14%), transportation (11%), utilities storage, or facilities, woodland (located on the southern edge of the lake) (6.2%), transportation and roadways (4.1%), water and wetlands (2.3%) and about 2% is used by agriculture or is vacant. The dominant land uses in Shadow Lake watershed are residential development encompassing approximately 33% of the watershed. The balance of the water shed includes woodland (20%) (located in the northeastern drainage area), transportation (15.7%), public institutional (15%), recreational facilities such as parks and boat landings (7%), commercial use (3%), water and wetlands (3%), vacant land (2.6%), and 1% is transportation utilities, storage or facilities (Figure 2).

In addition to surface water runoff, three streams/channels deliver or remove surface water to/from Mirror and Shadow Lakes. They include:

- The channel between Mirror Lake to Shadow Lake is located on Mirror Lake's south/southwest side and flows into Shadow Lake near the swimming beach. The approximate width of this channel is 25-35 ft and its length about 300 ft with a depth ranging from 2.5-3.5 ft. The average discharge from Mirror to Shadow Lake is approximately 1.4 ft^3/sec.

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- A large wetland complex drains to Shadow Lake. It enters the lake on its northwest shore. The inflow is a drainage channel that originates 1.5 miles northwest of Shadow Lake where the channel receives drainage from some of Waupaca's residential streets and housing units. The average discharge from the wetland into Shadow Lake is approximately 0.06 ft^3/sec.

- The channel from Shadow Lake to the Crystal River is located on the south/southwest shore of Shadow Lake; it transports water from Shadow Lake to the Crystal River. The outflow was constructed as an access point from Shadow Lake to the Crystal River for access by fisherman, canoeists, and other lake users. The channel is approximately 25-35 ft in width, is approximately 300 ft in length, and has a depth around 2.5-3.5 feet. The average discharge from Crystal Lake is 1.6 ft^3/sec.

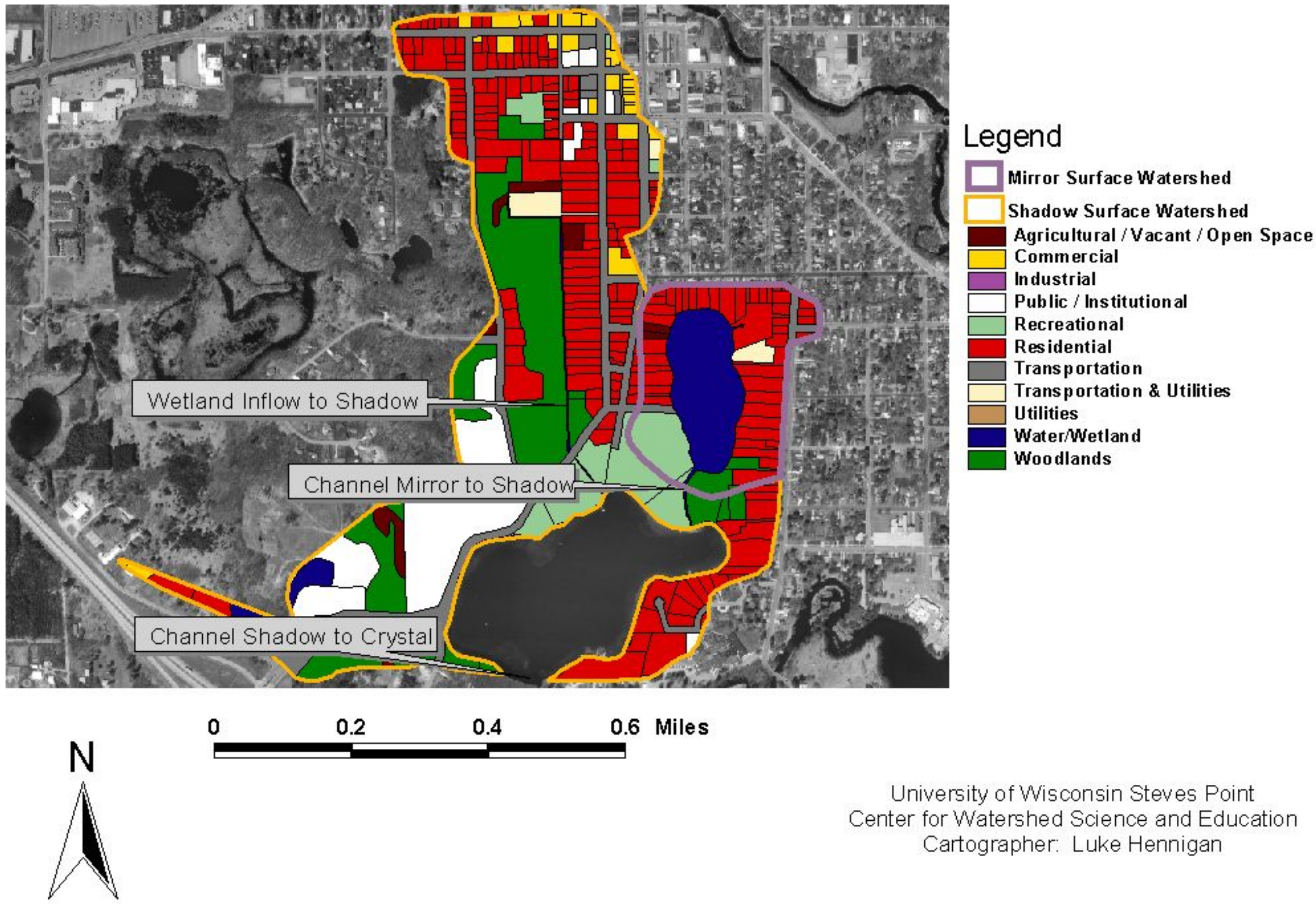

Figure 2. Surface watershed boundaries and land uses. Mirror and Shadow Lakes, Waupaca, WI 2000

Groundwater Watersheds

The groundwater watershed of is the area of land where precipitation infiltrates to the groundwater and moves down gradient to a discharge area like a wetland, stream or lake. Like surface water, groundwater flows according to differences in elevation (head); moving from areas of higher elevation to areas of lower elevation. In this study the direction of flow was determined using a map of the water table with *equipotential lines* that illustrate groundwater table elevations at various locations. The direction of groundwater flow is perpendicular to the equipotential lines (Figure 3). The groundwater watershed for Mirror and Shadow Lakes extends 4-5 miles west of Waupaca and encompasses approximately 3.4 square miles of land area. Approximately 1/3 of this area discharges to Mirror Lake and 2/3 of the area discharges to Shadow Lake (Figure 3).

The primary land uses in the Mirror and Shadow Lake groundwater watershed are residential which comprises 27% of the watershed and forested which makes up 26%. The balance of the watershed land uses are agricultural or vacant (18%), water or wetlands (12%), commercial development (7%), public or institutional facilities (4%), recreational (2%), transportation (2%), and the remaining 2% is used by industries and utilities (Figure 4).

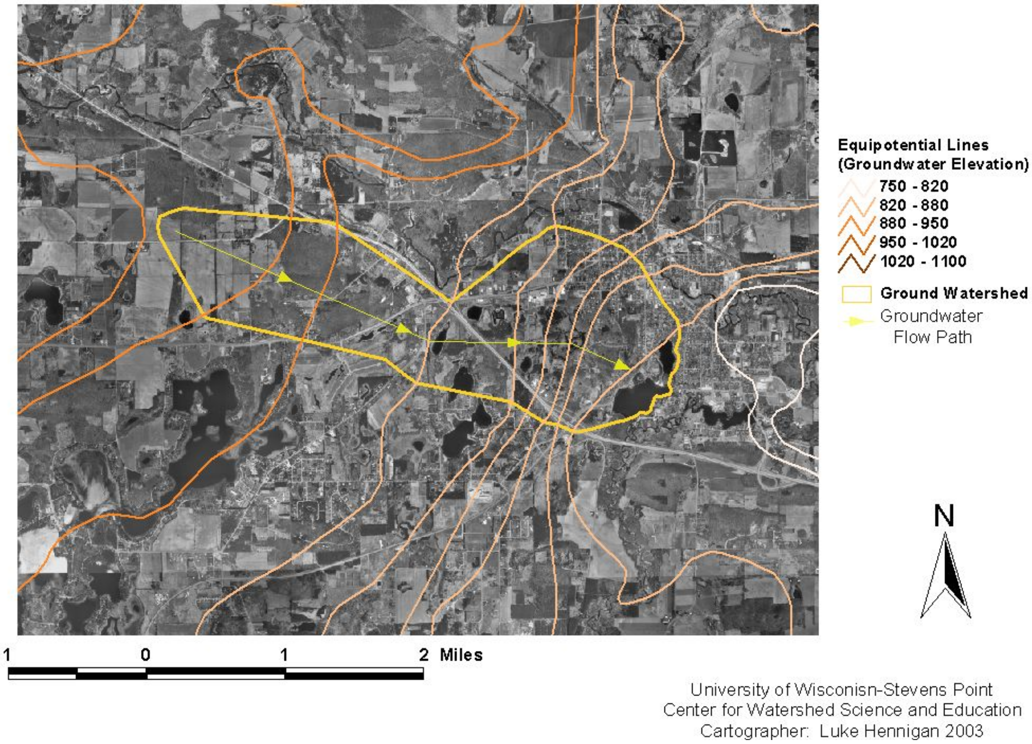

Figure 3. Groundwater watershed and approximate direction of groundwater flow associated with Mirror and Shadow Lakes, Waupaca, WI.

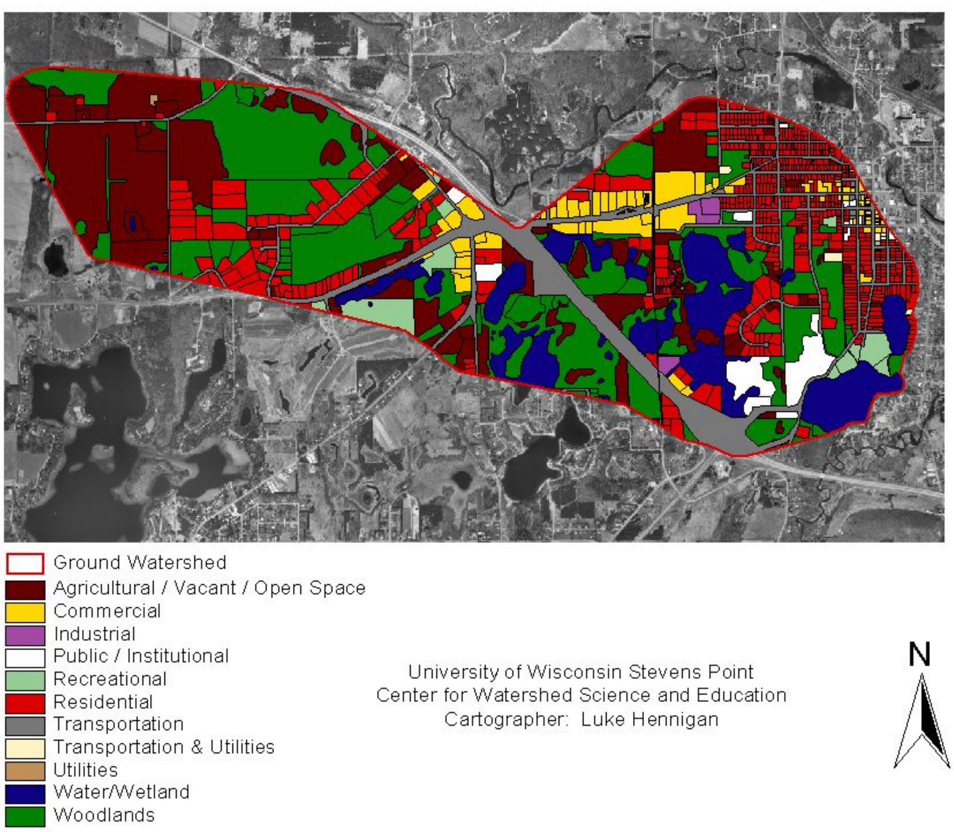

Figure 4. Land use within the Shadow and Mirror Lake groundwater watershed.

SURFACE WATER QUALITY

This study characterized water quality in the lakes, inflow channels, groundwater inflow, and the outflow to Crystal River and summarized those measurements through estimated water (hydrologic) and nutrient budgets. The results are presented first for the lakes, then the streams, then groundwater, and conclude with a nutrient budget summary in part estimated by computer modeling.

Mid Lake Measurements

Dissolved Oxygen and Temperature

Dissolved oxygen is the amount of oxygen contained in water and is key in aquatic ecosystems since many aquatic organisms depend on it for survival. Dissolved oxygen enters lake water by diffusion from the air and photosynthetic activity from plants. Greater wind and wave interaction causes greater diffusion of oxygen into the water and increases the rate at which oxygen is transferred.

A series of interactions between biological material, land use, and near shore land management can lead to reduced dissolved oxygen concentrations. Decaying material in the lake reduces oxygen as decomposers consume material using oxygen to drive their respiration. Nutrients to a lake will increase the oxygen consumption by decomposers because nutrient addition results in increased plant and algal growth. When plant and algal matter die, more oxygen is used by decomposers because of increased food sources. Nutrients come from fertilizers and surface runoff carrying eroding nutrient rich sediment to the lakes during runoff events as well as from groundwater entering the lakes.

Figure 5. Schematic showing layering of lakes during stratification.

Dissolved oxygen concentrations are also affected by water temperature. Cold water can hold more gases than warmer water (Table 3). Temperature variation throughout the year affects how water mixes with the atmosphere because the density of water changes with temperature changes. Water is densest at 39^{o}F (4^{o}C), which causes ice to float and water to mix periodically throughout the year. For example, in a typical year in Wisconsin, lake ice melts in early spring, and the temperature of lake water is similar from top to bottom (Figure 6). The presence of wind causes the lake to uniformly mix because all the water is the same density. Mixing redistributes dissolved oxygen and other dissolved constituents evenly from top to bottom within the lake. This mixing phenomenon is called *overturn*.

As surface water warms in late spring, waters density decreases, keeping the warmer water “floating” above the cooler, denser water (Figure 5). Layers of warm and cooler waters at containing water of differing densities create *layering* or *stratification*. The surface water remains in contact with atmospheric oxygen, while the lower layers are prevented from receiving additions of oxygen. When layering exists for extended periods of time, dissolved oxygen begins to be depleted in the bottom layer, or *hypolimnion*, as decomposers consume oxygen. If enough material decomposes, almost all the oxygen can be used.

During the fall, lake temperatures again begin to become uniform as the season cools the water from the top down (Figure 6). Density becomes more uniform and the lake experiences fall *overturn*. Fall overturn replenishes the water column with dissolved oxygen as water circulates back to the surface where oxygen can diffuse from the air.

In winter, stratification creates colder temperatures at the ice surface than at the lake bottom. During ice cover, temperatures remain relatively stable and there is typically a temperature difference of less than 10°F (Shaw et al., 2000). Without atmospheric contact oxygen is not added to the system and can be depleted throughout the winter although some oxygen may be generated through photosynthesis under the ice if snow is not too deep. Longer periods of decomposition in years of extended snowfall or cold weather can deplete oxygen from much of the water body and may cause winterkills of fish and other species.

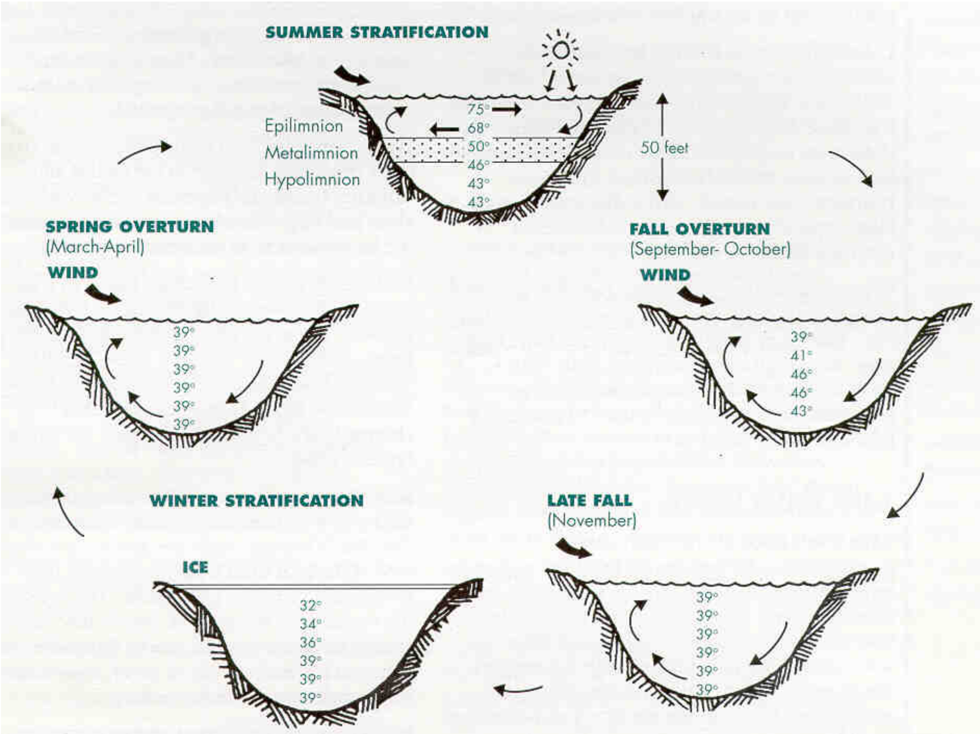

Figure 6. Seasonal temperature variation causing the stratification and mixing of many Wisconsin lakes (Shaw et al., 2000).

Thermal stratification and mixing progressions occur in many of Wisconsin's lakes, but conditions in and around some lakes may preclude full mixing from occurring. In Mirror Lake, a combination of the steep banks around the lake, a small surface area relative to its depth, and steep drop off to the lake bottom often prevents mixing. When mixing does not occur, dissolved oxygen is not replenished in the lower layers. This lack of mixing is one of the factors that may lead to winter fish kills in the lake.

Water sampling during this project confirmed that thermal stratification and mixing were present, indicated by the S-shape curve in temperature profiles (Figure 7). Mirror Lake water temperatures were uniform from top to bottom during the Nov. 2002 sampling, and nearly uniform the following April. Mirror Lake was stratified during the other sampling events. In summer, there was strong thermal stratification with the *hypolimnion* (bottom layer) forming below 18 to 20 ft, the *metalimnion* (transitional middle layer) formed between 8 and 18 ft, and the *epilimnion* (top layer) occupied the upper 8 to10 ft. Temperature ranges varied and provide adequate ranges for both warm and cold water species of fish with temperatures between 8 (46°F) and 27°C (81°F). The February (2/20) and April (4/17) measurements show the lake surface warming with little change in temperature with depth.

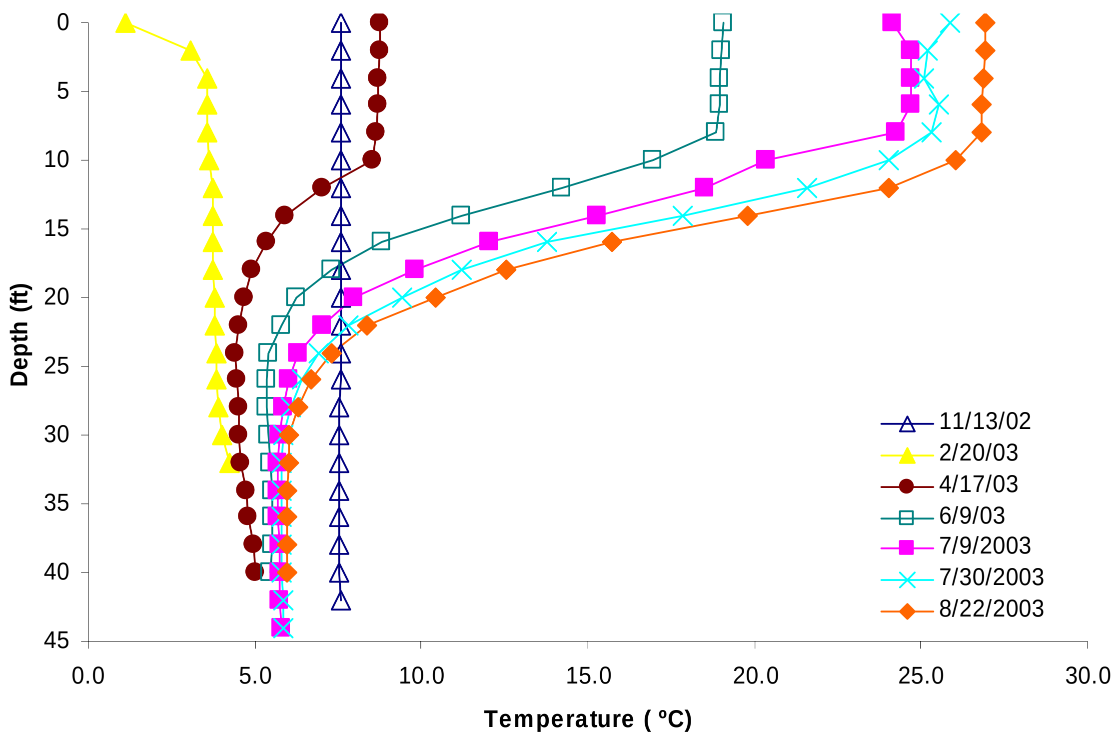

Figure 7. Profile of temperatures in Mirror Lake throughout the year.

Dissolved oxygen concentrations in Mirror Lake vary greatly throughout the year (Figure 8). The upper layer (*epilimnion*) contained plenty of dissolved oxygen throughout the year, but when overturn occurred anoxic (devoid of oxygen) water from the lake bottom is mixed with oxygen in other layers and overall dissolved oxygen levels plummeted. Mixing and transfer from the atmosphere can restore those concentrations in the upper layers providing there is enough time between fall overturn and the formation of ice. Oxygen concentrations in the epi and metalimnion maintained adequate oxygen concentrations for some warm water fish and other biota throughout the year except during fall overturn, when concentrations fell below 5 mg/L, which is needed to sustain most fish species. In February, when ice cover was present the dissolved oxygen concentrations were once again plentiful. Dissolved oxygen concentrations may have been abnormally elevated as the snow cover during the early part of winter was minimal, which allowed for photosynthesis to take place below the ice, this condition adds oxygen to the water from plant respiration. Weak spring mixing did not result in oxygen transfer to replenish the water in the lake bottom (*hypolimnion*). In April the dissolved oxygen profile showed the oxygen was already depleted below 25 ft. The metalimnion, present between 8 and 18 ft, showed spikes in dissolved oxygen during the summer. At this layer of the lake dissolved oxygen spikes are often due to algal blooms, which produce oxygen through photosynthesis. Oxygen concentrations at depths below 20 ft were less than 2 mg/L (anoxic conditions), which are conditions that prevent the reproduction, growth, and survival of cold water biota. Fall sampling suggested substantial oxygen demand within the water that competed with oxygen transfers ability to provide such large amounts of oxygen. High oxygen demand created conditions where mixing was unable to meet the demand of oxygen consuming parameters. Oxygen concentrations remained low throughout and after mixing, reflecting oxygen demanding material (organic matter, iron etc.) in the hypolimnetic water that was removing the oxygen faster than oxygen could be transferred to the water.

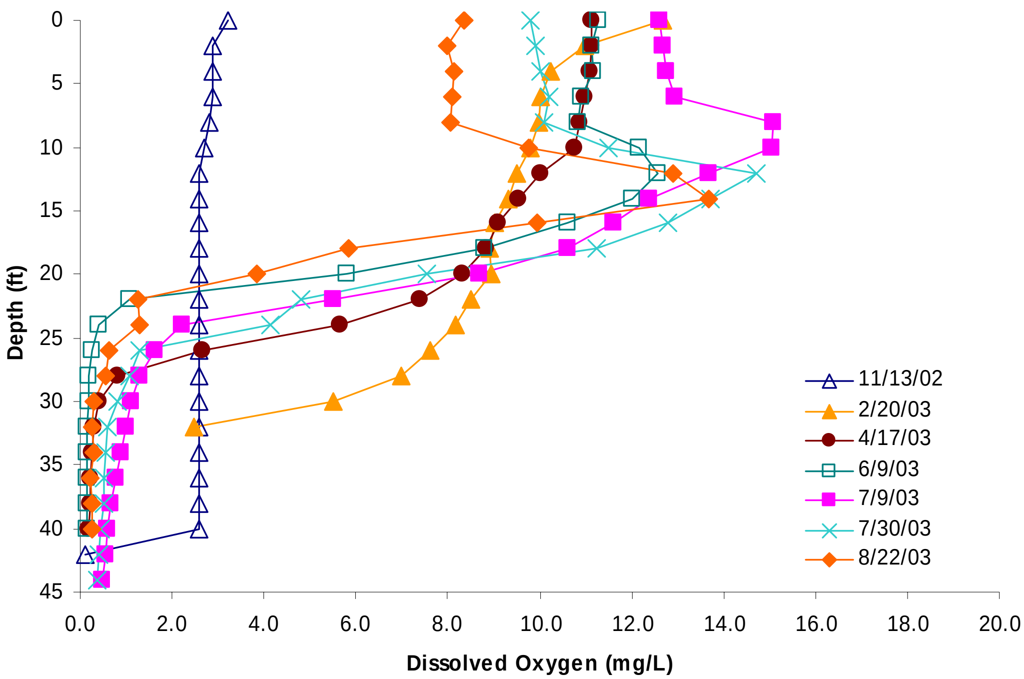

Figure 8. Profile of dissolved oxygen concentrations in Mirror Lake throughout the year.

Shadow Lake undergoes more typical annual cycles of mixing and stratification because of Shadow's large lake surface and moderately sloped and open shorelines. Stratification was present from early June into late July with the hypolimnion forming below 20 to 25 ft, the metalimnion between 8 and 20 ft, and the epilimnion occupying in the upper 8 to 10 ft. Temperatures ranged between 8 and 27^{o}C (46 to 50^{o}F) (Figure 9). Similar to Mirror Lake, the February 2002, data showed extremely cold surface water and spring overturn in April 2003 showed uniform temperatures throughout the upper 20 feet.

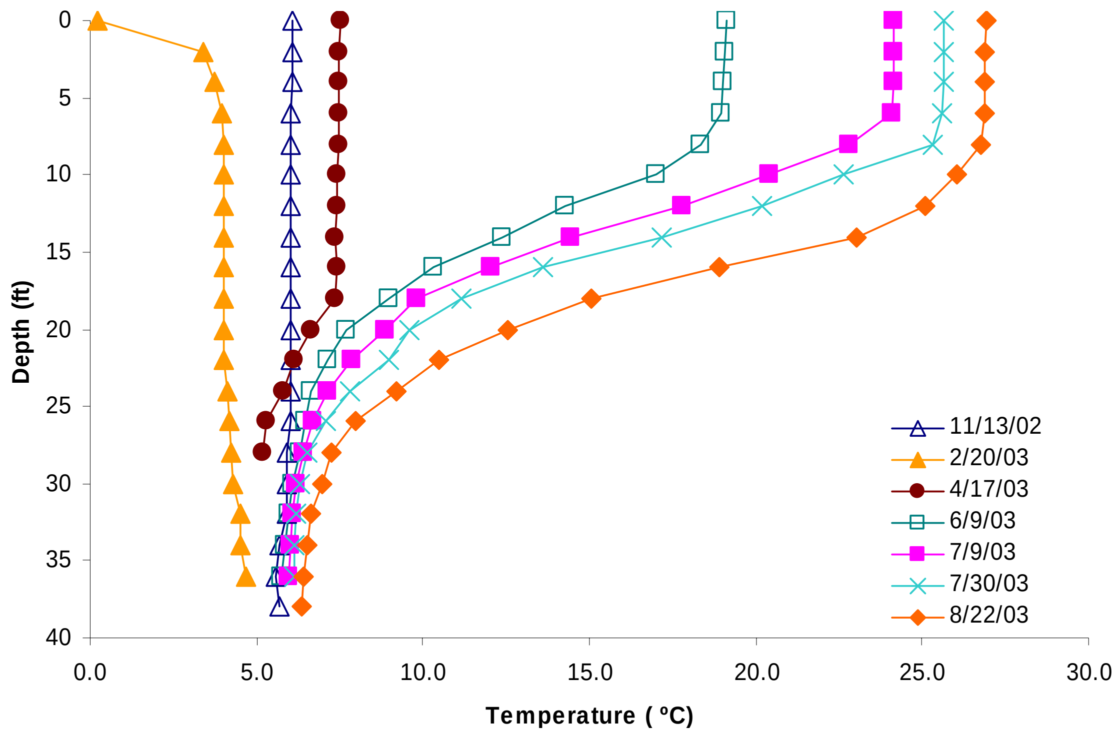

Figure 9. Profile of temperatures in Shadow Lake throughout the year.

In Shadow Lake, dissolved oxygen remained at levels capable of supporting warm water biota throughout the year. Overturn periods in November 2002 and April 2003 both showed oxygen increased in contrast to summer and winter, respectively. The April 2003 sample was taken after overturn and there was evidence that stratification had begun causing the varied dissolved oxygen concentrations shown in Figure 10. The winter sampling data in February 2003 exhibited dissolved oxygen depletion below 24 ft. As in Mirror Lake, the clear ice probably allowed higher than typical levels of plant respiration, providing oxygen to the upper layers in the early winter months.

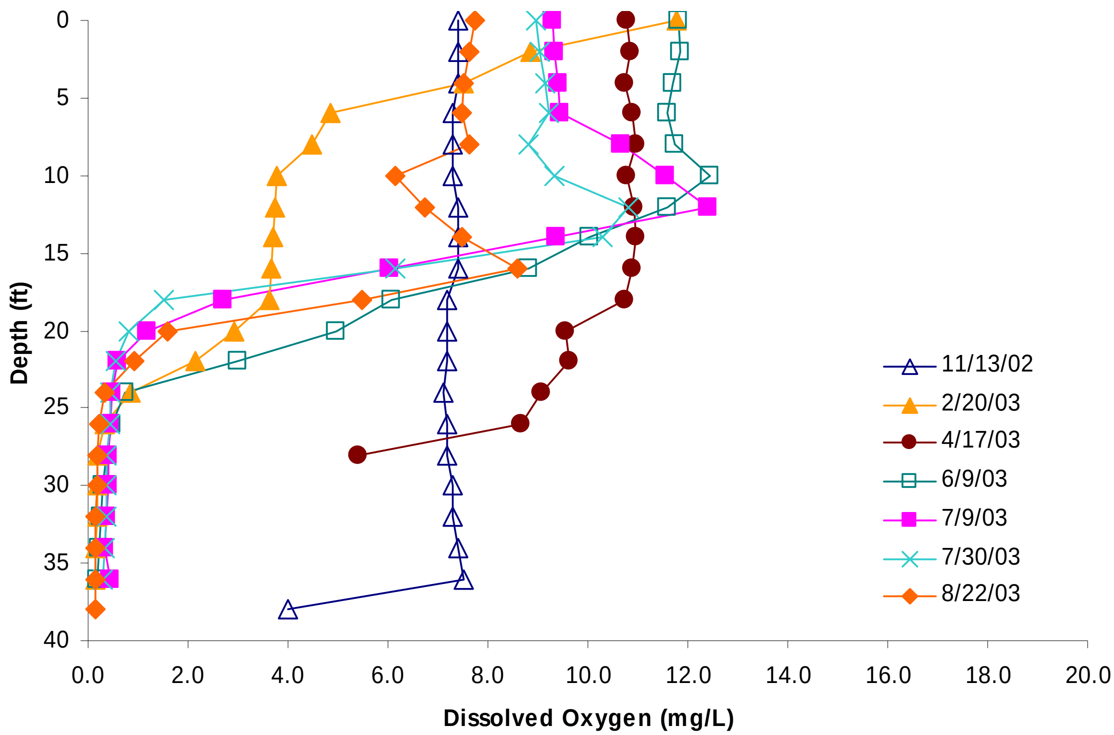

Figure 10. Profile of dissolved oxygen concentrations in Shadow Lake throughout the year.

pH

pH describes the lake water acid concentrations by measuring hydrogen ions (H^+) in solution. pH is measured on a scale ranging between 1 and 14 with lower values indicating acidic conditions and higher pH values indicating basic conditions. Lakes with low pH values often allow metals (aluminum, zinc, mercury), which can be located in the lake sediment, to become soluble. These metals can then make their way into the food chain and bioaccumulate in larger organisms (Shaw et al. 2000). Conversely, lakes with a high pH provide buffering against acidic conditions. Higher pH values are created when limestone or dolomite (carbonate minerals) are found in the watershed geology. Groundwater dissolves these rocks and once in the lake, neutralizes the acid from rainfall. The value of pH can change throughout the day, year, and depth because of chemical interaction with photosynthesizing biota, which effectively lower the pH by releasing carbon dioxide during respiration and use carbon dioxide during photosynthesis.

In Wisconsin lakes, the range of pH is ideally between 6.8 (neutral) to 9 (basic) and both lakes fit into this range. The pH in Mirror and Shadow Lakes are neutral to basic and the profiles with depth are quite similar (Figures 11 and 12). All samples were collected during the day, therefore, ph increases due to aquatic plant photosynthesis can be observed in the summer months. Also, note the decreasing pH levels lower in the water column where more carbon dioxide is present due to decomposition. Patterns of pH shift and change throughout the water column are normal.

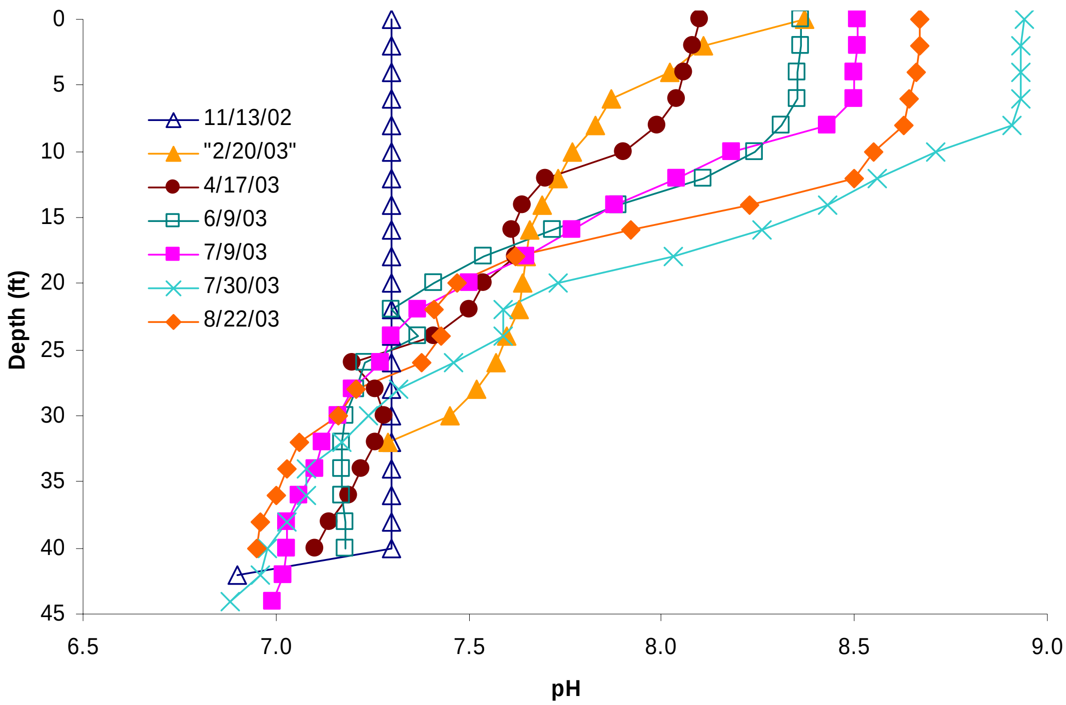

Figure 11. Profile of pH in Mirror Lake throughout the year.

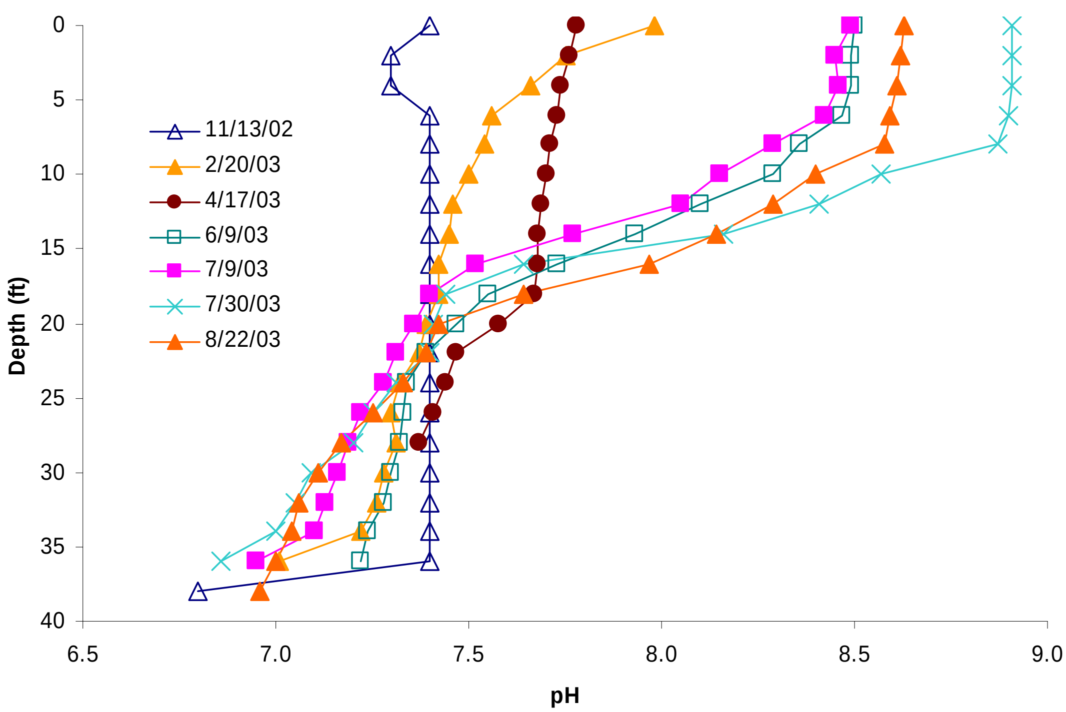

Figure 12. Profile of pH in Shadow Lake throughout the year.

Alkalinity and Hardness

Alkalinity and hardness can have tremendous impacts on the biological life within an aquatic system because of the ability of some organisms to consume calcium in the development of bones, shells, and exoskeletons. A lake's hardness and alkalinity are affected by the type of minerals in the soil and watershed bedrock, and by how much the lake water comes in contact with these minerals (Shaw et al., 2000). Lakes with geology in the surrounding watershed that contain limestone minerals such as calcite and dolomite have water with higher hardness and alkalinity (Shaw et al., 2000). The alkalinity provides acid buffering and the hardness provides calcium (Ca^{2+}) and magnesium (Mg^{2+}). Lakes with high concentrations of calcium and magnesium are called hard water lakes and those with low concentrations are called soft water lakes. Hard water lakes tend to be overall more productive and produce more fish and aquatic plants than soft water lakes (Shaw et al.,2000). Some hardwater lakes produce a substance called marl, which is a benefit to an ecosystem because it can hold nutrients such as phosphorus out of the internal cycling system of the lake (Wetzel 1972). Marl is a visible and large depositional layer on the bottom of the both lakes.

As anticipated, due to Mirror and Shadow's common origin, high alkalinity and hardness concentrations are similar in both lakes. Alkalinity in Mirror Lake ranged from 179 to 204 mg/L and total hardness ranged from 194 to 230 mg/L. Approximately half the total hardness was calcium hardness (94 to121 mg/L). Alkalinity in Shadow Lake ranged from 182 to 185 mg/L and total hardness ranged from 192 to 213 mg/L. Approximately half the total hardness was calcium hardness (93 to 213 mg/L). High concentrations of the hardness ions calcium and magnesium, categorize Mirror and Shadow as hardwater lakes (Table 4).

Table 3. Descriptive levels of hardness found in Wisconsin lakes. Hardness range for Mirror and Shadow Lakes is highlighted.

Level of Hardness	Total Hardness in mg/L as $CaCO_3$
Soft	0 – 60 mg/L
Moderately Hard	61 – 120 mg/L
Hard	121 – 180 mg/L
Very Hard	> 180 mg/L

Conductivity

Conductivity is a measure of water's ability to conduct an electric current which is a direct measure of dissolved minerals and salts in water. Many of these compounds can result naturally from dissolution of local minerals or unnaturally by wastewater from septic systems, agricultural/lawn/garden fertilizers, animal waste, and road salt runoff. Values are commonly two times the water hardness unless the water is receiving high concentrations of contaminants introduced by humans (Shaw et al. 2000).

Mirror Lake's conductivity ranged between 340 and 661 umhos from top to bottom while Shadow Lake's conductance ranged from 318 to 414 umhos (Figures 13 and 14). Both profiles exhibit normal trends in conductance profiles including increased levels at lower depths due to increased decomposition and acidic conditions that allow additional materials to become soluble. Conductance decreases throughout the summer especially in the upper layer of the lake. Decreased conductance may be due to marl formation and/or rain which can dilute concentrations. Mirror Lake's lower depths exhibited higher conductance than the lower depths in Shadow Lake (Figures 13 and 14). Increased conductance can occur because of the presence of larger amounts of decomposing materials in the bottom layer of the lake and because of Mirror Lake fails to overturn regularly. This leads to longer anoxic and acidic conditions since oxygen cannot be replenished. Mirror Lake's conductance profiles show that relatively weak mixing was observed in the spring and that much stronger mixing occured in the fall. Shadow Lake's conductance had a much more gradual increase as readings are taken to the bottom depths.

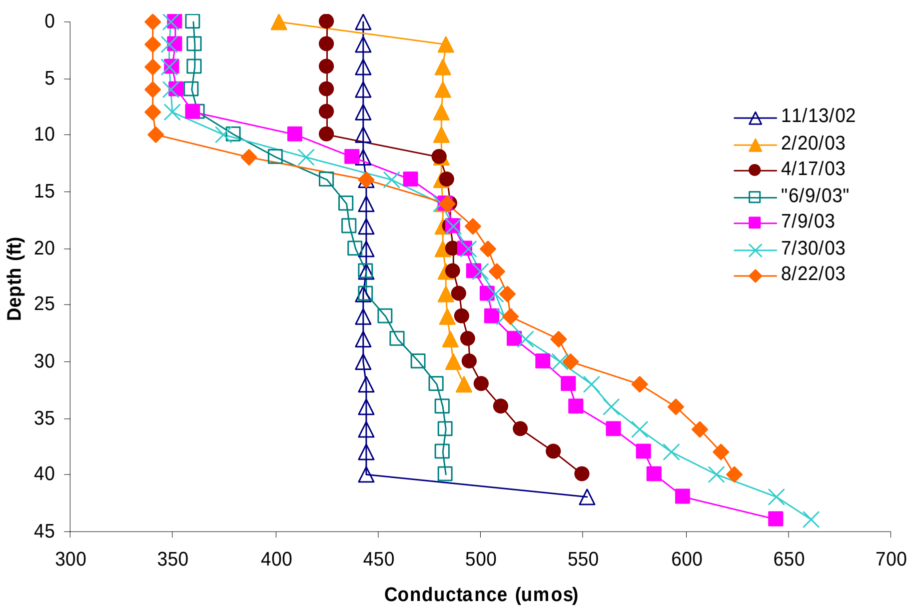

Figure 13. Profile of conductivity in Mirror Lake throughout the year.

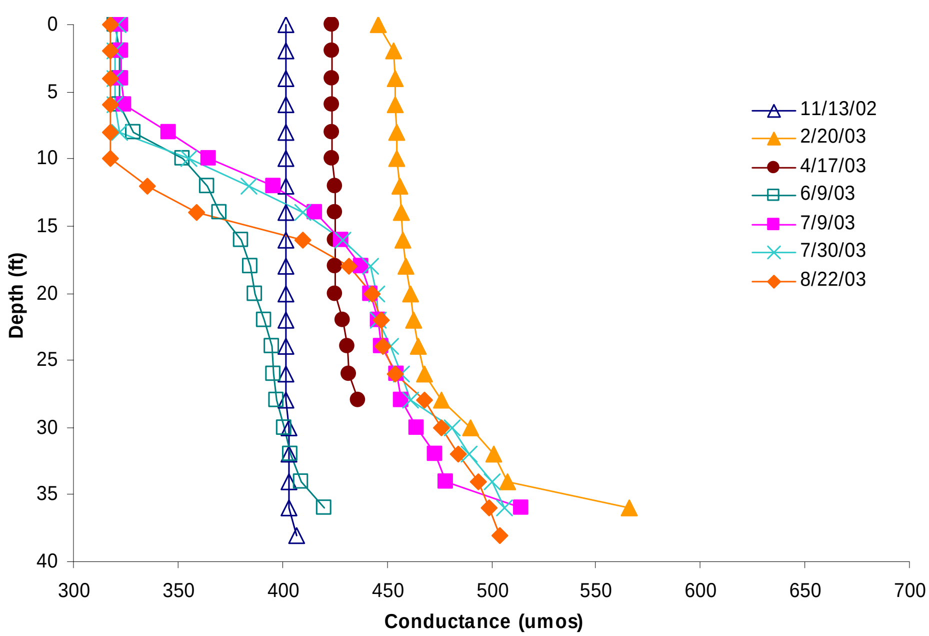

Figure 14. Profile of conductivity in Shadow Lake throughout the year.

Chloride
Chloride is not commonly found in Wisconsin rocks and soils and is usually not harmful because of its low concentrations and toxicity. Because of its naturally low concentrations, high concentrations of chloride usually indicate human inputs to water. Chloride is non-reactive in nature, and as a result, it is readily leached through the soil and into the groundwater from animal and human wastes, potash fertilizer, and road salt.

Chloride concentrations in Mirror Lake ranged from 24.5 to 44.5 mg/L while concentrations in Shadow Lake ranged from 21.5 to 27.5 mg/L. According to Shaw et al., 2000, chloride concentrations range between 3 and 10 mg/L in this region of the state. This additional chloride is likely from the use of road salt and fertilizers used on the urban roadways, lawns, and rural farms and fields located in the watersheds.

Potassium and Sodium
Concentrations of sodium and potassium are naturally very low in Wisconsin lake water. Therefore, when found in lakes, their presence frequently indicates human-related inputs. Potassium and sodium are found in potassium and sodium feldspar rocks naturally in Wisconsin; Waupaca has some local sources of these rocks (Cordua, 2004). Sources of sodium include road salts, fertilizers, and human and animal wastes. Potassium is also found in human and animal waste with other sources including potash fertilizers and organic debris such as leaves etc. (Shaw et al, 2000).

Potassium concentrations in Mirror Lake ranged from 4.8 to 5.4 mg/L and sodium concentrations ranged from 14.1 to 17.5 mg/L. Potassium concentrations in Shadow Lake averaged 2.5 mg/L and sodium concentrations ranged from 10.3 to 12.5 mg/L. These concentrations are elevated and indicate impacts from road salts, lawn and garden fertilizer, pet waste, and possibly abandoned septic drainfields. These elevated concentrations are not considered toxic to aquatic biota.

Sulfate
Sulfate naturally enters into Wisconsin lakes through geological solution in groundwater and from acid rain deposition caused by the burning of sulfur containing products such as coal. In the anoxic conditions found in the bottom layer of Mirror and Shadow Lake this sulfate is broken down into sulfide, which can readily bind to most metal elements such as iron and mercury rendering them as insoluble sulfide precipitates. Sulfate concentrations in Mirror Lake ranged from 9.3 to 10.1 mg/L and concentrations in Shadow Lake ranged from 8.4 to 8.9 mg/L. These concentrations are within the range of 10 to 20 mg/L typical of this region of the state (Shaw et al., 2000)

Water Clarity
Water clarity is a measure of light transparency measured by an instrument called a Secchi disc. The depth to which light can penetrate is important because plants need light for growth. Aquatic plants grow in the area where light penetrates to the lake bottom. The depth of water clarity is affected by algae, dissolved minerals, organic acids, and suspended solids (turbidity), all of which are able to impact light penetration due to their light absorbing capacities. In this way, water clarity is an indication of the amount of materials suspended in the water and

materials dissolved in the water (color). Secchi disk depth, turbidity, and color measurements are shown in Table 5.

Table 4. Measurements of turbidity, color, and water clarity during overturn in Mirror and Shadow Lakes, Waupaca, WI.

Date	Site	Turbidity (NTU)	Color (CU)	Water Clarity (ft)
11/13/2002	Mirror Lake	2.1	9	9
4/17/2003	Mirror Lake	1.2	9	9
11/13/2002	Shadow Lake	1.5	15	10
4/17/2003	Shadow Lake	2.2	15	6

Turbidity in the top layer of Mirror Lake ranged from 1.2 to 2.1 NTU while color remained at 9 color units throughout the study. These variables seemed to play a lesser role in the clarity of the water than did the algae. In Shadow Lake an increase in turbidity resulted in a decrease in clarity.

Table 5. Description of water clarity based on Secchi depth measurements in Wisconsin. (Shaw 2000)

Water Clarity	Secchi Depth (ft)
Very Poor	3
Poor	5
Fair	7
Good	10
Very Good	20
Excellent	32

The water clarity for both lakes ranged from poor to good, depending upon the time of year (Table 6). Fluctuations of water clarity throughout the year are normal as changes occur with available nutrients, temperature, algae and aquatic plant growth. In Mirror Lake, water clarity measurements ranged from 5 to 10 ft and in Shadow Lake water clarity ranged from 6 to 10 ft (Figure 15). During overturn, water clarity in Mirror Lake was recorded at 9 ft and at 10 ft in Shadow Lake. Water clarity was greatest in late July 2003 for both Mirror Lake (10 ft) and Shadow Lake (12 ft). Water quality in Mirror Lake was poorest in July 2003 at 5 ft and in Shadow Lake was poorest in April 2003 at 6 ft.

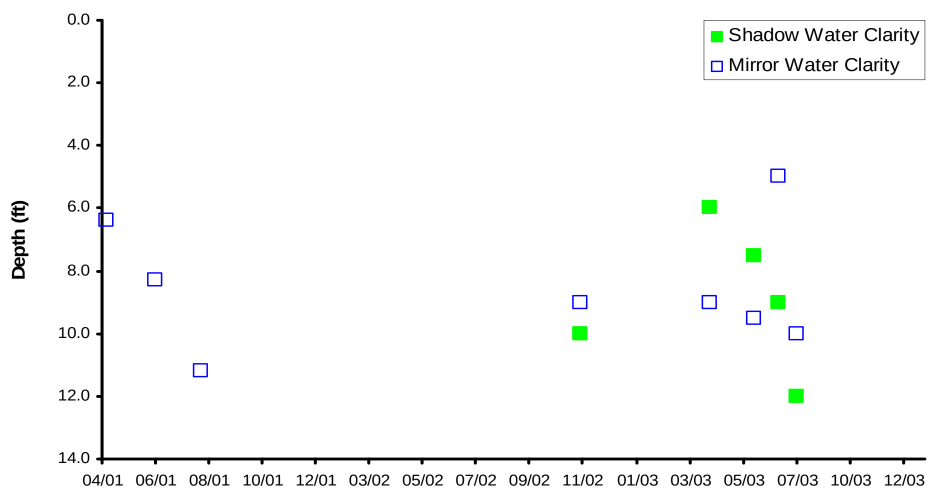

Figure 15. Water clarity measurements (ft) in Mirror and Shadow Lakes.

Chlorophyll *a*

A good indicator of the amount of algae affecting water clarity in the water column is chlorophyll *a*. Chlorophyll *a* concentrations are frequently inversely correlated with Secchi depth (the higher the chlorophyll *a* concentrations, the lower the Secchi depth). Algae and therefore chlorophyll *a* concentrations change throughout the growing season and from year to year depending on nutrient input and weather (Shaw et. al, 2000).

Mirror Lake chlorophyll *a* concentrations ranged from 1.9 to 6.6 mg/L while concentrations in Shadow Lake samples ranged between 3.7 and 9.1 mg/L. As the growing season progressed the chlorophyll *a* concentrations in Mirror and Shadow Lakes generally decreased throughout the growing season; opposite of what is naturally expected.

Algal Community

Algae are essentially microscopic plants and as such need the same things as larger plants. All photosynthetic organisms need carbon dioxide, water, sunlight, and a variety of inorganic nutrients, all in adequate amounts. The term algae is very general, this group of organisms encompasses both prokaryotic (like bacteria) and eukaryotic (like us) cell types. The algae range from single-celled to many meters long, some swim with flagella while others float or alter their buoyancy via physiological alterations. These organisms can be filamentous, colonial, tubular, sheet-like, and about every shape in between. They can be blue-green, green, yellow, black, brown, gold, pink, red, or orange.

There are nine or more major groups or divisions of algae. Each group produces its own unique set of photosynthetic pigments and each group responds differently to changing environmental conditions. Individual taxa (like a genus) are then grouped in a division based on shared characteristics (pigments, genetics, cell type, reproduction). Within that division groups are further subdivided based on more specialized, shared, and distinct characteristics relative to the other members of that division. These subgroups are called classes, orders, families, and genera. In this study we identified algae to genus and division. Algae within the same division (since they are related to each other) typically respond in a similar manner to seasonal and nutrient changes. Seasonal changes in the composition of the algal communities in Mirror and Shadow Lake were traced via changes in the relative abundance of algae at the division level.

Algae, being photosynthetic, are considered to be the primary producers in most aquatic food webs (along with aquatic plants). They are responsible for capturing solar energy via their photosynthetic pigments and using that trapped energy to convert inorganic carbon dioxide into organic sugars. These sugars store some of the captured solar energy in their chemical bonds. The algae use the sugars to make other new organic matter (proteins, carbohydrates, nucleic acids, lipids) as they grow and divide. Consumers and decomposers also use these sugars for energy and recycle much of the other organic matter as well. Algae are critically important components of the aquatic food web as many zooplankters as well as many larger consumers (snails, planktivorous fishes) have a diet based largely on algae. An often misunderstood aspect of aquatic biology is the concept of net growth rate. Net growth rates of algae are determined by the difference between growth (production of new algae via asexual and sexual reproduction) and death (consumption, parasitism, natural death). Algae differ in their digestibility (shape, size, production of sticky mucilage) and nutrient value (proteins, lipids, carbohydrates) to consumers and consequently some taxa are preferentially removed from the community by predation while others are largely ignored by consumers and continue to expand their biomass during the growing season. The algae present at any point in time is frequently based more on what hasn't been eaten than what is growing the fastest. It is often that these "not eaten" algal taxa, especially the Cyanobacteria (or blue-green algae) that become persistant bloom formers in ever earlier and longer cycles.

The microbial decomposition loop (detritivorous) is driven largely by the algae. It is in the sediments that bacterial consumption of the dead algae can reduce oxygen content to anoxic levels setting the stage for fish kills. The seasonal pattern typical of lakes like Mirror and Shadow is one of spring and summer algal growth (fed by nutrients); summer and fall decomposition in the sediments (converting organic matter to inorganic nutrients again); and resuspension of nutrients into the water column during spring and fall overturn. If there is a flux of nutrients in the fall it is possible that more algae will overwinter beneath the ice. This can lead to increasing larger standing crops of undesirable algal taxa (see section above).

Different groups and taxa also respond differentially to seasonal fluxes in temperature, oxygen, and nutrients. The types of algae present, their relative abundance, and the dynamics of the algal community over time can provide insights into trophic status and might suggest possible remediation strategies. Most aquatic algal communities are limited by phosphorus and the timing and point of origin around phosphorus availability determines when and what algae will bloom. Algal community data complements the chemical data on surface water quality and strengthens the interpretation of the results presented in the closing summary.

The algal communities were similar between Mirror and Shadow Lakes. There were 66 algal taxa (70+ species) from six algal divisions identified during the counting process in Mirror Lake (Table 7). Fifty-five of the 66 taxa from Mirror Lake were from three divisions (10-Cyanobacteria, 25-Chlorophyta, 20-Ochrophyta). These are the dominant groups in most temperate zone lakes, especially those with moderate eutrophication. Garrison and Knauer (1983), using much more intensive and extensive sampling and counting techniques found 79 genera (120+ species) in Mirror Lake. Approximately 60 of the Mirror Lake taxa from this study were present in the 1983 study. Encouragingly, the number of cyanobacterial taxa has not significantly increased in this time frame but *Oscillatoria* remains the most common taxa as in the previous study.

In Shadow Lake there were 58 algal taxa (from the same six divisions) identified (Table 8). Of these taxa, 47 were from the three dominant and typical divisions (8-Cyanobacteria, 20-Chlorophyta, 19-Ochrophyta). Garrison and Knauer (1983) did not conduct an algal assessment in Shadow Lake. The majority of the taxa are in common with those from Mirror Lake. The simpler algal community in Shadow Lake might be due to a more uniform set of environmental conditions (more regular overturn), dominance by several nuisance organisms at the expense of community diversity, or it might be an artifact of the sampling protocols.

In each lake there were a variety of taxa that waxed and waned with the seasons. However, in each lake there was an array of taxa that was present in every sample (Table 9). In Mirror Lake there were nine ubiquitous taxa representing four algal divisions, these taxa included 2

Cyanobacteria, the filamentous *Oscillatoria* and the colonial *Coelosphaerium*; the flagellated dinophyte *Peridinium*; two non-motile, colonial (*Coelastrum*, *Scenedesmus*) and one non-motile unicellular (*Oocystis*) chlorophytes; and three ochrophytes – all diatoms (*Asterionella*, *Fragilaria*, and *Synedra*). In Shadow Lake there were 8 cosmopolitan algal taxa representing five divisions. This group shared five of it's eight taxa with Mirror Lake (*Oscillatoria*, *Peridinium*, *Oocystis*, *Scenedesmus*, *Fragilaria*). The other three universal taxa in Shadow Lake were the cyanobacterium *Snowella*, the chlorophyte *Planktosphaeria*, and the cryptophyte *Chroomonas*.

The percentage that each division's taxa contributed to the overall algal community varied by lake and season and is presented in Table 10. The dominant divisions over the growing season, by percent composition, are the blue-green algae (Cyanobacteria) with 6-53%, the green algae (Chlorophyta) with 11-53%, and the diatoms and golden-brown algae (Ochrophyta) with 16-36%. These three divisions contributed over 80% of the taxa identified in either lake. The three divisions accounted for 65 to 80% of all cells counted in all samples from all dates. In the Cyanobacteria it was primarily the consistently high contributions of two taxa (*Oscillatoria* and *Coelosphaerium*) while in the other divisions there were a variety of taxa that waxed and waned with the changing environmental conditions. The majority of the cell counts came from a small subset of taxa and most taxa were rarely or infrequently encountered during the enumeration procedure.

The seasonal shifts of the algal divisions over the 2003 sampling period for Mirror Lake are presented in Figures 16 and 17. The Cyanobacteria start with a significant overwintering population of *Oscillatoria* during April and May then fade in June and July to return with substantial population increases in August and September. This fall bloom leads the group to account for over 50% of the entire algal community in September. This late season dominance may be due to a combination of optimal temperatures and nutrient availability from surface runoff.

The Ochrophyta have two distinct groups that respond differently during the year. Diatoms (Bacillariophyceae) require silica to complete their cell walls and this nutrient typically becomes limiting during the summer months and until fall overturn. The golden-brown algae (*Dinobryon*, *Synura*, *Mallomonas*, *Ochromonas*) are flagellated unicells and colonies that prefer cooler, more organically enriched water such as that seen around overturn events and early/late in the growing season. The ochrophytes produce many overwintering stages that can survive under the ice. This group therefore shows a large early season pulse of growth (from both types of ochrophytes) that tapers off after June.

The green algae are slower starters in the spring because they like warmer temperatures and generally are less persistent in their overwintering stages. This group reaches its community dominance during the June and July periods then taper off slowly during the fall. Many green algae are fairly palatable and, as preferred food items (diatoms and cryptophytes), drop in abundance during the growing season with various green algae selectively consumed. This is particularly true of the smaller, less heavily walled taxa.

Table 6. Algae found in Mirror Lake, Waupaca, WI, 2003.

Division	Genus	Division	Genus
		Ochrophyta	*Achnathes*
Cyanobacteria	*Anabaena*		*Asterionella*
	Aphanizomenon		*Cocconeis*
	Chroococcus		*Cyclotella*
	Coelosphaerium		*Cymbella*
	Gloeotrichia		***Diatoma***
	Merismopedia		*Dinobryon*
	Microcystis		*Fragilaria 1*
	Nostoc		*Fragilaria 2*
	Oscillatoria		*Gomphonema*
	Snowella		*Mallomonas*
			Melosira
Dinophyta	*Ceratium 1*		*Navicula 1*
	Ceratium 2		*Navicula 2*
	Peridinium		*Nitzschia*
			Ochromonas
Chlorophyta	*Ankistrodesmus*		*Stephanodiscus*
	Botryococcus		*Synedra 1*
	Bulbochaete		*Synedra 2*
	Carteria		*Synura*
	Chlamydomonas		
	Chlorella	Euglenophyta	*Astasia*
	Closterium		*Euglena 1*
	Coelastrum		*Phacus 1*
	Cosmarium		*Phacus 2*
	Crucigenia		*Trachelomonas 1*
	Elakatothrix		*Trachelomonas 2*
	Euastrum		
	Gloeocystis	Cryptophyta	*Chroomonas*
	Haematococcus		*Cryptomonas*
	Micrasterias		
	Mougeotia		
	Oedogonium		
	Oocystis		
	Pediastrum		
	Planktosphaeria		
	Scenedesmus		
	Selenastrum		
	Spirogyra		
	Staurastrum		
	Tetraedron		

Table 7. Algae found in Shadow Lake, Waupaca, WI, 2003.

Division	Genus	Division	Genus
Cyanobacteria	Anabaena	Ochrophyta	Achnathes
	Chroococcus		Asterionella
	Coelosphaerium		Cocconeis
	Gloeotrichia		Cyclotella
	Merismopedia		Cymbella
	Microcystis		**Diatoma**
	Oscillatoria		Dinobryon
	Snowella		Fragilaria 1
			Fragilaria 2
Dinophyta	Ceratium 1		Gomphonema
	Ceratium 2		Mallomonas
	Peridinium		Melosira
			Navicula 1
Chlorophyta	Ankistrodesmus		Navicula 2
	Botryococcus		Nitzschia
	Carteria		Ochromonas
	Chlamydomonas		Synedra 1
	Chlorella		Synedra 2
	Closterium		Synura
	Coelastrum		
	Cosmarium	Euglenophyta	Astasia
	Crucigenia		Euglena 1
	Elakatothrix		Phacus 1
	Gloeocystis		Phacus 2
	Micrasterias		Trachelomonas 1
	Oedogonium		Trachelomonas 2
	Oocystis		
	Pediastrum	Cryptophyta	Chroomonas
	Planktosphaeria		Cryptomonas
	Scenedesmus		
	Selenastrum		
	Spirogyra		
	Staurastrum		

Table 8. Dominant Algal Taxa in Mirror and Shadow Lakes, Waupaca, WI, 2003.

Divison	Genus	04/17	05/20	06/17	07/14	07/30	08/22	09/30
		n	n	N	n	n	n	n
Cyanobacteria	Coelosphaerium	9	8	22	21	5	**100**	66
	Oscillatoria	**100**	**100**	20	33	**100**	83	**100**
Dinophyta	Peridinium	22	31	41	12	31	12	6
Chlorophyta	Coelastrum	5	9	5	26	12	16	9
	Oocystis	11	40	72	45	38	22	13
	Scenedesmus	27	21	52	31	11	6	4
Ochrophyta	Asterionella	4	50	33	21	4	8	3
	Fragilaria 1	11	21	24	44	20	10	3
	Synedra 1	24	6	29	17	12	31	10

Division	Genus	04/17	05/20	06/17	07/14	07/30	08/22	09/30
		n	n	N	n	n	n	n
Cyanobacteria	Oscillatoria	**100**	**100**	14	**100**	**100**	**100**	**100**
	Snowella	9	8	2	17	20	10	9
Dinophyta	Peridinium	3	28	20	8	7	8	1
Chlorophyta	Oocystis	14	29	**100**	33	41	26	44
	Planktosphaeria	15	2	14	9	8	21	10
	Scenedesmus	9	13	22	39	20	11	30
Ochrophyta	Fragilaria 1	7	9	2	20	11	6	26
Cryptophyta	Chroomonas	34	19	4	23	10	24	31

Table 9. Algal Abundance, by Division, in Mirror and Shadow Lakes, Waupaca, WI.

MIRROR	04/17	05/20	06/17	07/14	07/30	08/22	09/30
Cyanobacteria	21	23	6	11	25	40	53
Dinophyta	12	11	15	7	12	6	2
Chlorophyta	11	18	50	53	28	24	18
Ochrophyta	32	36	26	26	16	17	17
Euglenophyta	8	8	3	2	5	6	9
Cryptophyta	16	4	0	0	15	7	2

SHADOW	04/17	05/20	06/17	07/14	07/30	08/22	09/30
Cyanobacteria	29	28	5	27	28	25	36
Dinophyta	2	8	12	5	1	2	11
Chlorophyta	18	16	55	28	30	27	24
Ochrophyta	29	33	20	28	32	34	15
Euglenophyta	5	8	7	6	6	6	8
Cryptophyta	18	7	1	6	3	6	7

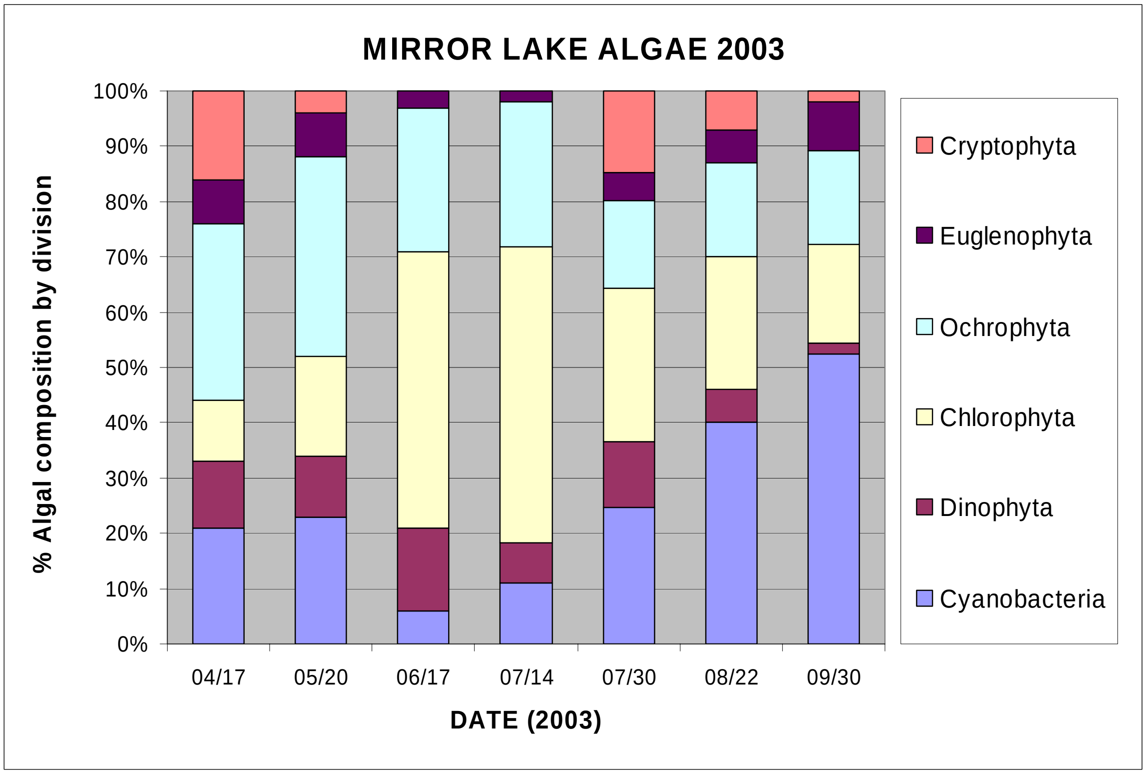

Figure 16. Algae in Mirror Lake, Waupaca, WI.

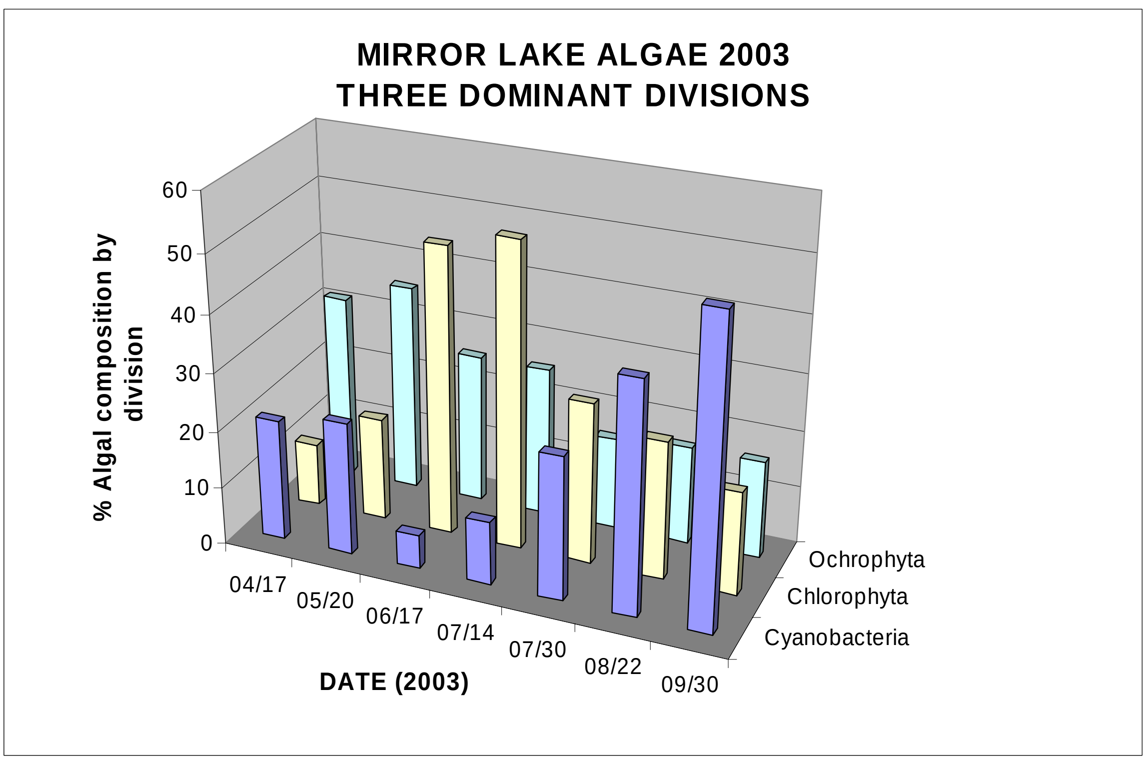

Figure 17. Dominant Algal Divisions in Mirror Lake, Waupaca, WI.

The seasonal shifts of the algal divisions over the 2003 sampling period for Shadow Lake are presented in Figures 18 and 19. The patterns are similar to those seen in Mirror Lake but the magnitudes are somewhat dampened. The Cyanobacteria overwintered well and started strong in April but dropped in overall abundance during June. Perhaps because of greater and earlier nutrient availability in Shadow Lake the mid-summer depression of cyanobacterial populations is less significant and shorter, with blue-greens returning early in July and continuing through the rest of the growing season but never contributing more that 40% of the population seen in the cell counts. As in Mirror Lake most of the cyanobacterial are from two or three taxa (*Oscillatoria*, *Coelosphaerium*, *Snowella*).

The Ochrophyta reached their peak abundance during May when silica was still available and both groups (diatoms and golden-browns) found satisfactory growing conditions. After several common diatom taxa began to drop in numbers during the summer the late season ochrophyte dominants included taxa that can utilize organic nutrients as well as inorganic ones. These include *Mallomonas*, *Ochromonas*, *Synura*, and *Dinobryon*. There was no obvious explanation for the reduced ochrophyte abundance during September.

Chlorophytes started slowly and built to numerical dominance during June. They maintained a significant (approximately 25%) portion of algal community for the rest of the growing season. Several common taxa represented the majority of cell counts, the other taxa were rarely more than small contributors to the overall green algal dominance.

The algae found in Mirror and Shadow Lakes are typical of moderately-impacted, temperate zone lakes in North America. No taxa are unique or dangerous. None of the identified taxa are associated with toxicity or pathologies. These taxa are generally ubiquitous and frequently dominate similar bodies of water. The general seasonal pattern of algal succession in both lakes is the same.

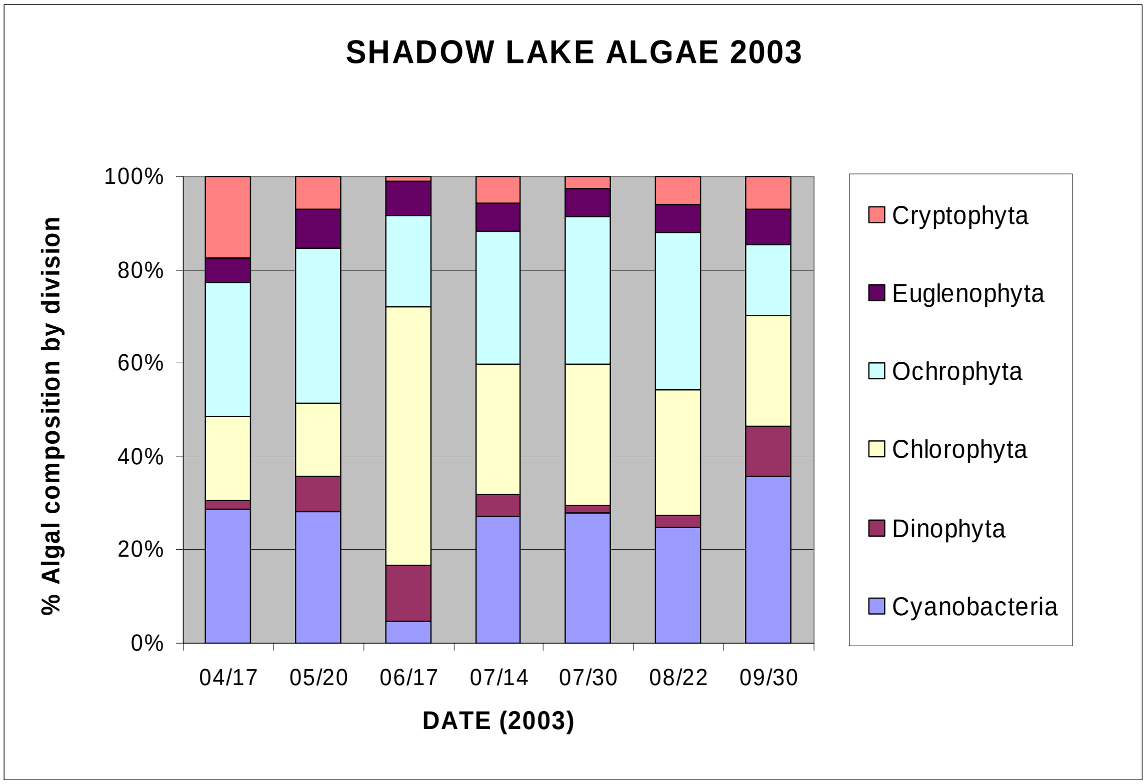

Figure 18. Algae in Shadow Lake, Waupaca, WI.

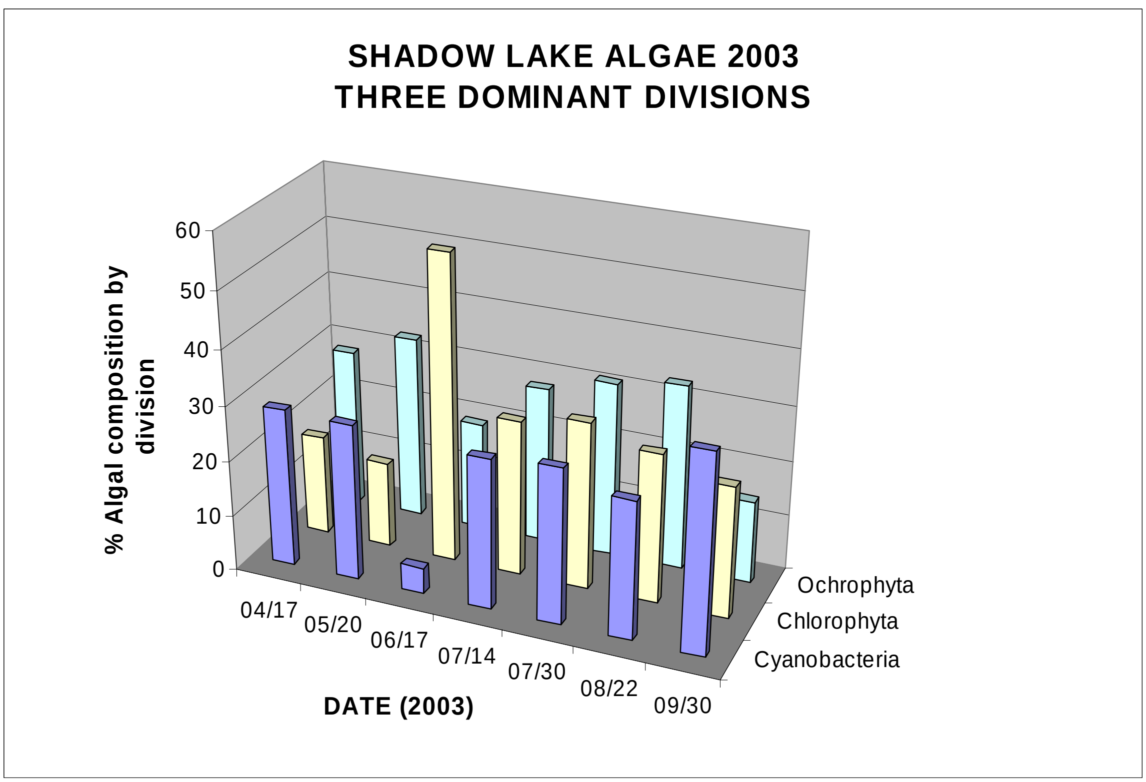

Figure 19. Dominant Algal Divisions in Shadow Lake, Waupaca, WI.

There appears to be a significant overwintering population of algae, particularly the cryptophytes and Cyanobacteria. The spring thaw and overturn provides adequate nutrient supplies to stimulate growth of all algal groups. The dominant spring algal flora is cyanobacterial and ochrophytes, both diatoms and golden-brown algae. To a lesser extent there are spikes of cryptophytes and euglenophytes while water temperatures are cool and organic material is resuspended. As temperatures rise and nutrients (except silica) remain available the community becomes dominated by green algae and dinophytes while the Cyanobacteria and diatoms are reduced in abundance. As water temperatures cool during the fall the Cyanobacteria made a substantial return, codominating with the green algae. As in the spring, the return of cooler water and resuspended organic matter in the fall also brings with it a flush of englenophytes and cryptophytes.

The number of algal taxa, the groups (divisions they represent), and their seasonal patterns indicate moderate levels of eutrophication in both lakes, with Shadow seeming to suffer more from cyanobacterial blooms. The pattern of cyanobacterial dominance will likely continue to expand in duration and abundance as nutrients are washed into the lakes from the watershed. This continued addition of nutrients exacerbates the already high internal nutrient loading that is resuspended with each overturn event. While alum precipitation was done in the past the useful life expectancy of an alum treatment is well past and it is likely that in addition to the ongoing input of nutrients from the watershed there is a steady supply of internal nutrient material being re-released from the sediments every time these lakes overturn. Typically, lakes in this situation see earlier and earlier cyanobacterial blooms that last longer and break up later in the fall. This can lead to reduced aesthetic and recreational value in the lakes. Reduction of watershed nutrient contributions, bufferr/riparian vegetation strips for the shoreline, and expansion of rooted macrophyte populations (that compete with algae for space, light, and nutrients) can all serve to reduce the problems but will unlikely solve them entirely.

Nitrogen

Nitrogen is an important biological element. It is second only to phosphorus as a key nutrient that influences aquatic plant and algal growth in lakes. In Wisconsin, minimal nitrogen occurs naturally in soil minerals, but it is a major component of all plant and animal tissue, and therefore organic matter. It is often found in rainfall with precipitation as the primary nitrogen source in some seepage and drainage lakes. It also travels in groundwater and surface runoff; therefore, nitrogen enters the system both as soluble and particulate forms. Sources of nitrogen are often directly related to local land uses including septic systems, sewage treatment plants, lawn and garden fertilizers, and agricultural sources.

Nitrogen enters and exits lakes in a variety of forms. The most common include ammonium (NH_4^+), nitrate (NO_3^-), nitrite NO_2^-, and organic nitrogen. These forms summed yield total nitrogen. Aquatic plants and algae can use all inorganic forms of nitrogen (NH_4^+, NO_2^-, and NO_3^-); if these inorganic forms of nitrogen exceed 0.3 mg/L in spring, there is sufficient nitrogen to support summer algae blooms (Shaw et al., 2000). Ammonium is the most available form of nitrogen to aquatic plants.

There are significant concentrations of nitrogen in Mirror Lake. However, during much of the year, organic nitrogen (which is the particulate form) becomes less available for aquatic plant use.

Dissolved nitrogen concentrations were greatest during overturn as nitrogen rich bottom water mixed with the upper water. As the season progressed plants began to utilize the nitrate and ammonium leaving most of the total nitrogen in the water column as organic nitrogen in the upper layer. Ammonium concentrations are were great enough to facilitate aquatic plant growth if sufficient phosphorus was available at the same time. In the bottom layer of the lakes, high concentrations of ammonium were present due to anoxic conditions and releases of nitrogen during the decomposition of plant and animal tissue. In the winter season nitrogen concentrations were dispersed throughout the column as plants decomposed and released some of the stored nutrients (Table 11).

In Shadow Lake, nitrate at overturn was near the level needed to initiate nuisance algae blooms during the summer. This level dropped in the growing season as plants and algae began to uptake it for growth. When plants were decomposing in the winter it was re-released to the water (Table 12).

Table 10. Concentrations of nitrogen in Mirror Lake at various depths throughout the year.

Layers and Season	NH4 (mg/L)	NO2+NO3-N (mg/L)	Organic N (mg/L)	Total N (mg/L)
Top				
Spring Overturn	0.88	0.28	1.44	0.56
Fall Overturn	0.67	0.04	0.76	1.43
Growing Season Average	<0.01	0.01	0.74	0.75
Winter	0.56	0.08	1.08	1.72
Middle				
Spring Overturn	1.07	0.18	0.63	1.88
Fall Overturn	-	-	-	-
Growing Season Average	-	-	-	-
Winter	0.61	0.12	0.90	1.63
Bottom				
Spring Overturn	1.89	0.08	0.50	2.47
Fall Overturn	-	-	-	-
Growing Season Average	2.47	0.01	1.11	3.59
Winter	0.70	0.12	1.12	1.94

Table 11. Nitrogen concentrations in Shadow Lake at various depths throughout the year.

	NH4 (mg/L)	NO2+NO3-N (mg/L)	Organic N (mg/L)	Total N (mg/L)
Top				
Spring Overturn	0.43	0.44	0.45	1.32
Fall Overturn	0.51	0.12	0.57	1.20
Growing Season Average	0.005	0.01	0.81	0.82
Winter	0.38	0.3	0.80	1.48
Middle				
Spring Overturn	-	-	-	-
Fall Overturn	-	-	-	-
Growing Season Average	-	-	-	-
Winter	0.57	0.2	0.62	1.39
Bottom				
Spring Overturn	-	-	-	-
Fall Overturn	-	-	-	-
Growing Season Average	2.95	0.01	1.10	4.06
Winter	1.2	0.04	0.8	2.08

Total Nitrogen to Total Phosphorus Ratio

In Wisconsin lakes, either nitrogen or phosphorus concentrations control the amount of algae and aquatic plant growth. In lakes that are limited by nitrogen the ratio of total nitrogen to total phosphorus is 10:1. (For every 10 nitrogen molecules there is 1 phosphorus molecule.) If limitation varies from year to year there is a ratio between 10:1 and 15:1. When lakes are limited by phosphorus ratios are above 15:1 (Wetzel, 2002).

Total nitrogen to total phosphorus ratios for Mirror and Shadow Lakes are shown in Table 13. Phosphorus was the limiting element (indicated by ratios above 15:1) in most samples collected from both Mirror and Shadow Lakes. During some conditions nitrogen was the limiting nutrient and therefore should also be reduced whenever possible.

Table 12. Total nitrogen to total phosphorus ratios in Mirror and Shadow Lakes, Waupaca, WI.

Date	Layer	Mirror Lake TN:TP	Shadow Lake TN:TP
04/24/01	Top	34:1	
06/21/01	Top	22:1	
08/15/01	Top	15:1	
11/13/02	Top	13:1	18:1
02/20/03	Top	16:1	9:1
02/20/03	Middle	14:1	19:1
04/17/03	Top	16:1	22:1
04/17/03	Middle	10:1	
07/31/03	Top	22:1	18:1

Phosphorus

In Wisconsin, phosphorus is the most significant limiting nutrient for most lakes. Phosphorus is the primary element that leads to the development of nuisance algae (Wetzel 2002; Cogger 1988). Phosphorus is present naturally on the lake shore and in the watershed, found in the soil and plants. It transfers to the lake from the erosion of soil, animal waste, septic systems, fertilizers, inland recycling, and atmospheric deposition. In a study on urban lakes by the United States Geological Survey's Waschbusch, Selbig, and Bannerman, it was determined that streets and lawns were contributing 80% of the dissolved phosphorus to the urban lakes, with lawns contributing more than streets.

High concentrations of phosphorus are primarily transported to lakes in surface runoff. Phosphorus is reactive and adheres to soil particles. If those particles are disturbed or if water containing phosphorus from decaying vegetation and fertilizer is conveyed directly to the lake, phosphorus is transferred from land to water. Soil has a large capacity to hold phosphorus but where there are significant sources of phosphorus (i.e. barnyards, septic drainfields, over application of fertilizer) the soil holding capacity can be exceeded allowing excess phosphorus to leach to the groundwater. Once in a lake, a portion of the phosphorus becomes part of the aquatic system in the form of plant and animal tissue or sediments. The phosphorus continues to cycle within the system, and is very difficult to remove once it enters.

In this study, two forms of phosphorus were measured: soluble reactive phosphorus (SRP) and total phosphorus (TP). SRP is dissolved phosphorus in the water column that is readily available for plants and algae to utilize. It is usually present in low concentrations, and re-circulates quickly (Wetzel 2002). TP is a measure of the dissolved phosphorus plus organic and inorganic particulate phosphorus suspended in the water. Examples of organic phosphorus would be decaying plant or animal matter or phosphorus that is bound to soil particles.

TP is used as a measure of overall lake phosphorus because its concentrations are more stable than SRP. Phosphorus availability can vary when the lake is stratified since oxygen concentrations and pH can cause reducing conditions in the bottom layer (*hypolimnion*) of the lake. Reducing conditions result in the release of soluble phosphorus from sediments and decaying plants and animal material. During spring and fall overturn, phosphorus-laden water mixes with the rest of the lake water, making it available to algae and aquatic plants. Phosphorus can form insoluble precipitate with calcium (marl), iron, and aluminum under appropriate conditions helping to reduce phosphorus concentrations and overall algal growth (Shaw et al. 2000). However, it should be noted that the alga *Chara* is present in both Mirror and Shadow Lake. *Chara* can lower the pH around its leaflets and make bound phosphorus available for its use.

The year this study was performed, Mirror Lake did not completely mix in the spring. During spring overturn, TP concentrations were 32 ug/L (Table14). These concentrations were a result of the phosphorus rich water in the hypolimnion mixing with the less concentrated upper layers of water. This concentration was high enough to produce algae blooms and significant aquatic plant growth in the summer. TP during the summer growing season was much lower, because some of the phosphorus was being used by algae and aquatic plants and was tied up with marl that is produced in warmer temperatures. Marl formation is a result of calcium precipitating out of solution and into a solid. When this formation occurs, phosphorus can become trapped in the particle, rendering phosphorus unavailable for use by plants. Fall overturn concentrations were 19 ug/L. During the winter when the lake was once again layered, concentrations increased with depth. In February concentrations were elevated to 33 ug/L in the hypolimnion.

Table 13. Concentrations of soluble reactive phosphorus and total phosphorus in mid lake samples collected from Mirror Lake, Waupaca, WI.

Layer and Season	**No. Samples**	**SRP** (ug/L)	**TP** (ug/L)
Top			
Spring Overturn	1	2	32
Fall Overturn	1	2	19
Growing Season Average	3	6	17
Winter	1	7	26
Middle			
Spring Overturn	1	3	17
Winter	1	6.0	21
Bottom			
Spring Overturn	1	38	88
Growing Season Average	3	14	77
Winter	1	7	33

TP concentrations in Shadow Lake during spring overturn were 29 ug/L, which was high enough to support nuisance levels of algae and aquatic plants through the summer. As observed in Mirror Lake, TP concentrations in the summer were reduced due to association with marl production and uptake by aquatic plants. Whenever the lake was stratified, the bottom layer of the lake had high concentrations (Table 15).

Table 14. Concentrations of soluble reactive phosphorus and total phosphorus in mid lake samples collected from Shadow Lake, Waupaca, WI.

Layer and Season	**No. Samples**	**SRP** (ug/L)	**TP** (ug/L)
Top			
Spring Overturn	1	2	29
Fall Overturn	1	2	21
Growing Season Average	3	8	14
Winter	1	9	14
Middle			
Winter	1	9	27
Bottom			
Growing Season Average	3	54	62
Winter	1	22	69

For the most part, these phosphorus concentrations suggest a nutrient rich lake, but are not unanticipated given the location and history of these lakes. They remain around the concentration found prior to storm sewer diversions and aluminum treatment in the 1970s. This is partially due to the marl production in the lakes, but phosphorus inputs in many marl lakes in Central Wisconsin have exceeded the capacity for marl to buffer the effects of phosphorus. Exceeding marl production capacities can result in significant algal and aquatic plant growth. Therefore, lowering phosphorus application is desired in order to reduce phosphorus inputs especially to Mirror Lake. Reducing inputs will reduce the production of filamentous algae and the amount of oxygen being consumed by decomposers in the lake bottom during times of stratification.

INFLOW/OUTFLOW WATER QUALITY

The source of water and path it takes to the lakes is important to the in-lake water quality. Understanding how water is moving to the lakes and the quality of the water helps to determine management strategies for the lakes. Water enters the Mirror/Shadow Lake system via direct precipitation, groundwater, surface water runoff, and two direct inflows to Shadow Lake. A review of past studies suggested much of the inflow to the lake system came through groundwater and while this is true, runoff form the urban area surrounding the lakes is also important.

In urban settings, the amount of water and speed at which the water reaches the lake via surface runoff is frequently increased due to several factors including reduced amounts of tree, shrub, and tall vegetation, which increase the amount of precipitation that reaches the ground. In a forested setting leaves and stems intercept some of the precipitation traveling to the ground. Some precipitation may be used by the vegetation, evaporate from the vegetation, or simply be slowed by the vegetation decreasing the rate at which water is hitting the ground as water slowly drips off leaves long after a storm has ended. The amount of impervious surface also effects water movement. Impervious surfaces (roofs, streets, sidewalks, and compacted soil) do not allow water to soak into the ground and results in more runoff. Water on impervious surfaces moves swiftly and is not filtered as it would be with vegetation. Swiftly moving water carries particles and nutrients from the land surface and deposits them into the lake system.

In this study, streams flowing into Shadow Lake and out of both lakes were measured during baseflow and event flow periods. Baseflow is the water flowing in a stream when only groundwater is contributing to it. Event flow is the flow that occurs during storm events or snowmelt. Measurements that were collected included samples for analysis of total suspended solids (TSS), nitrogen (NO_2+NO_3-N, NH_4, total Kjeldahl nitrogen), phosphorus (SRP and TP), chloride, and chemical oxygen demand. Nutrient loading was estimated using the baseflow chemical concentrations and measured water volume.

The wetland inflow was sampled nine times, the channel from Shadow Lake to the Crystal River was sampled six times, and the channel from Mirror to Shadow Lake was sampled eight times between March and August 2003. One set of samples was collected during baseflow and the remaining samples were collected during or immediately after events. Siphon samples were used to collect samples from all of the inflows and outflows during July and August 2003.

The inflows and outflows of Mirror and Shadow Lakes were sampled and flow was measured to supplement rating curves. However, the extremely slow flow, soft mucky bottoms, and weed growth made estimation of the channels yields (total quantity of nutrients) challenging. Small errors in velocity that easily occur with little flow, lead to over or underestimations when multiplied over the channels larger areas.

Total Suspended Solids

Total suspended solids (TSS) are a measure of the particles suspended in water that can be trapped by a filter. TSS enters the lakes through streams or rainwater. In Mirror and Shadow Lakes the primary sources of TSS include soil erosion, street sand, pet waste, trash, leaves, grass clippings, etc. TSS can also be formed in the lake as algae, plant and animal tissue and waste, microscopic animals, or by re-suspension of bottom sediments. As discussed earlier, cultural disturbances can increase the amounts of particulates to lakes.

TSS concentrations in lakes naturally fluctuate. Rain causes increases in TSS by washing deposited material from the watershed. Also, during the growing season the adjacent wetlands grow algae and plants that can be released to the lakes. Finally, sediments that have settled at the lake bottom can be re-suspended with agitation created by wind or motorboats in shallow water or during lake mixing in spring and fall.

TSS can reduce water clarity, increase water temperature by absorbing heat from the sun, and increase the nutrient load to the lake since nutrients are attached to TSS particles. Also, increased TSS often blocks light used by submerged vegetation, which decreases photosynthetic activity and oxygen production. Furthermore, TSS that deposits on lake bottoms may alter aquatic habitat and increase nutrient and organic matter leading to accelerated aging of the lake (*eutrophication*) and oxygen depletion.

TSS concentrations are shown in Tables 16 and 17. These concentrations varied for all of the inflows and outflows depending upon location and size of storm. In the channel from Shadow Lake to Crystal River, baseflow concentrations were 2 mg/L and event flow concentrations ranged from 3 to 38 mg/L. In the wetland draining to Shadow Lake, baseflow concentrations were 2 mg/L and event flow concentrations ranged from 0.5 to 56 mg/L. The event that had concentrations lower than baseflow concentrations indicated that the water moving through the wetland was actually diluting the amount of sediment normally in the stream. The high concentrations measured in these channels show that throughout the year, significant amounts of material move into the lake system. As would be expected, the channel from Mirror to Shadow Lake did not vary with flow as dramatically with baseflow concentrations of 0.50 mg/L and event flow concentrations ranging from 0.05 to 5 mg/L.

Nitrogen

Major forms of nitrogen were analyzed and are shown in Tables 16 and 17. These forms were described earlier in the surface water section. Throughout most of the sample period, ammonium was in relatively low concentrations, and much of the nitrogen moving to/from the system was in the organic form (associated with particles). Overall, the event samples had higher concentrations of nitrogen than baseflow.

Table 15. Chemical analysis of samples collected from Mirror and Shadow Lake inflows and outflows during baseflow conditions (July 2003).

Site	NO_3-NO_2 (mg/L)	NH_4 (mg/L)	Organic N (mg/L)	Total N (mg/L)	TP (ug/L)	SRP (ug/L)	Cl^- (mg/L)	TSS (mg/L)
Channel Shadow Lake to Crystal River	0.01	0.01	0.88	0.89	15	4	25.5	2
Wetland to Shadow Lake	0.06	0.01	0.81	0.87	104	53	73.0	2
Channel Mirror to Shadow Lake	0.01	0.01	0.89	0.90	21	11	34.5	0.50

Table 16. Average concentrations of chemicals collected from Mirror and Shadow Lake inflows during event conditions. (March-August 2003)

Site	NO_3+NO_2 (mg/L)	NH_4 (mg/L)	Organic N (mg/L)	Total N (mg/L)	TP (ug/L)	SRP (ug/L)	Cl^- (mg/L)	TSS (mg/L)	COD (mg/L)
Channel Shadow Lake-Crystal River	1.09	0.04	0.76	1.89	39	9	12	11.3	26.6
Wetland-Shadow Lake	0.44	0.40	1.29	2.13	224	158	112	14.8	45.8
Channel Mirror-Shadow Lake	0.11	0.16	0.87	1.14	35	5	28	2.2	28.9

Phosphorus

Phosphorus concentrations varied between the three channels. The channel from Shadow Lake to the Crystal River had total phosphorus (TP) ranging from 13 to 93 ug/L and soluble reactive phosphorus (SRP) concentrations ranging from 3 to 15 ug/L. Regardless of flow conditions, phosphorus concentrations were always high coming from the wetland to Shadow Lake; TP concentrations ranged from 69 to 768 ug/L and SRP concentrations ranged from 17 and 616 ug/L. The channel from Mirror to Shadow Lake had TP concentrations ranging from 14 to 108 mg/L and SRP concentrations ranging from 1 to 13 mg/L.

In both channel outflows phosphorus concentrations were below mid-lake concentrations. This means the lakes are acting as phosphorus sinks - taking in more phosphorus than is leaving. More detailed discussion of phosphorus contributions can be found in the modeling section.

Chloride

Chloride concentrations in the channel between Shadow Lake and the Crystal River ranged between 6.5 and 25.5 mg/L. The wetland inflow to Shadow Lake had concentrations ranging from 27.5 to 478 mg/L and the channel from Mirror to Shadow Lake ranged from 24 to 35.5 mg/L.

The channels leaving Mirror and Shadow Lakes had higher concentrations of chloride, which demonstrates that much of the chloride is entering the system from groundwater (Tables 16, 17). These levels are comparable to those found Mirror and Shadow Lakes. Concentrations from the wetland are significantly higher during events. A road bisects the area between the wetland and Shadow Lake and may be a big source of chloride at this site.

Chemical Oxygen Demand

At times of event flow, chemical oxygen demand was measured in the inflows and outflows of Mirror and Shadow Lakes. Chemical oxygen demand is a quantitative measure of how much organic matter and metals are in the water that consume dissolved oxygen.

In the channel between Shadow Lake and the Crystal River chemical oxygen demand was between 9.8 and 19.2 mg/L. The wetland inflow to Shadow Lake had concentrations ranging from 18.9 to 98.7 mg/L and the channel from Mirror to Shadow Lake ranged from 17.7 to 50.10 mg/L. These concentrations are all high and indicate that large amounts of oxygen consuming materials are moving to and between the lakes. Some of these materials are likely responsible for the oxygen challenges exhibited in Mirror Lake.

GROUNDWATER

Groundwater flowing into and out of the lakes was assessed using mini-piezometers (small wells). These wells were installed every 200 feet around the perimeter of Mirror and Shadow Lake in 18 in of water. Thirty-one sites were evaluated in Mirror Lake and 49 sites in Shadow Lake (Figures 20 and 21). Groundwater inflow/outflow was quantified and samples for chemical analysis were collected from inflow sites to determine groundwater quality.

Groundwater Inflow and Outflow

Mirror Lake is a groundwater discharge area where regional groundwater flow leaves the aquifer and becomes lake and stream flow. Groundwater was flowing into Mirror Lake at 35% (11 of 31) of the sites. That suggests regional groundwater inflow on about one-third of the shoreline. As depicted in Figure 20, inflow areas were on the north and northeast shores of the lake where the lake substrate is sandy. Only 1 of the 31 sites was found to have groundwater outflow. This site was located adjacent to the municipal well on the east shore; therefore, this outflow may have been a result of the pumping well. The lack of groundwater outflow is due to the surface outflow that drains to Shadow Lake. Water takes the easiest flow path out and the channel outflow provides the easiest path for exiting water.

Sixty-one percent (19 of 31) of the sites had limited connection with groundwater. The fine marl sediment paired with thick layers of organic muck seal the bottom of the deeper portions of the lake preventing substantial groundwater inflow in depths greater than 4 ft. This can cause redirection of the groundwater to other flow paths around the lake and entry points within the lake.

Using the average hydraulic conductance and site specific inflow measurements, the total groundwater inflow for Mirror Lake was estimated at 0.27 ft^3/sec. Although this estimation has some uncertainty, it does show the importance of groundwater inflow to the water budget of Mirror Lake. We assumed the locations measured to be representations of the areas that surrounded them.

Groundwater inflow was observed around Shadow Lake at 23 of 49 sites (47%). These sites were distributed around the majority of the lake, with most inflow concentrated along the northern and western shores (Figure 21). The eastern shore had little inflow with the exception of sites S13 and S14. Fifty-three percent of the sites (26 of 49) had no flow or static flow. None of the sites sampled indicated groundwater outflow. This is likely due to the surface water outflow on the lake's southern shore that creates easy outflow of water draining towards the Crystal River. Similar to Mirror Lake, Shadow Lake is acting as a groundwater discharge area.

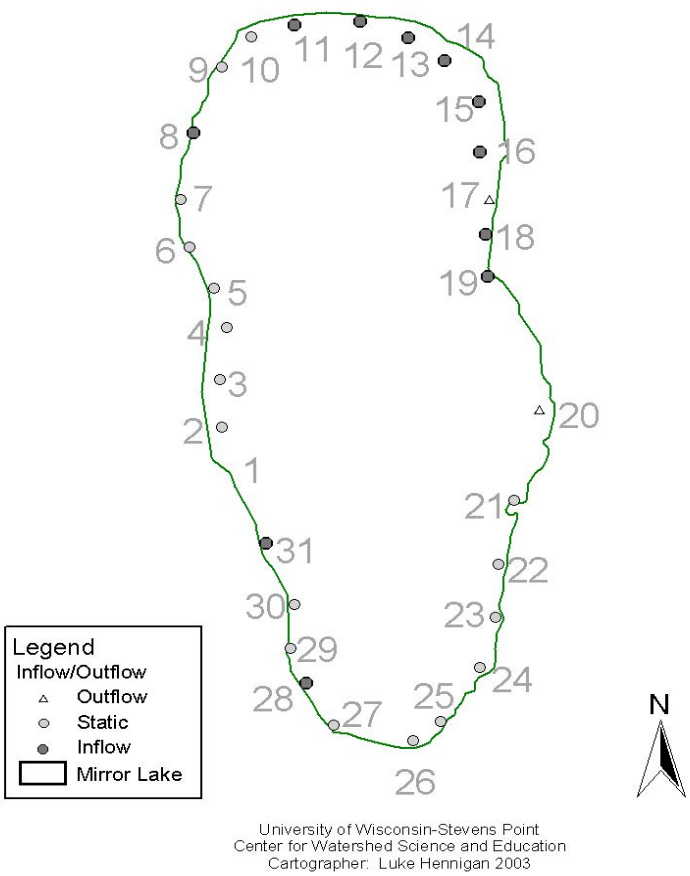

Figure 20. Groundwater flow conditions in Mirror Lake Waupaca, WI Summer 2003.

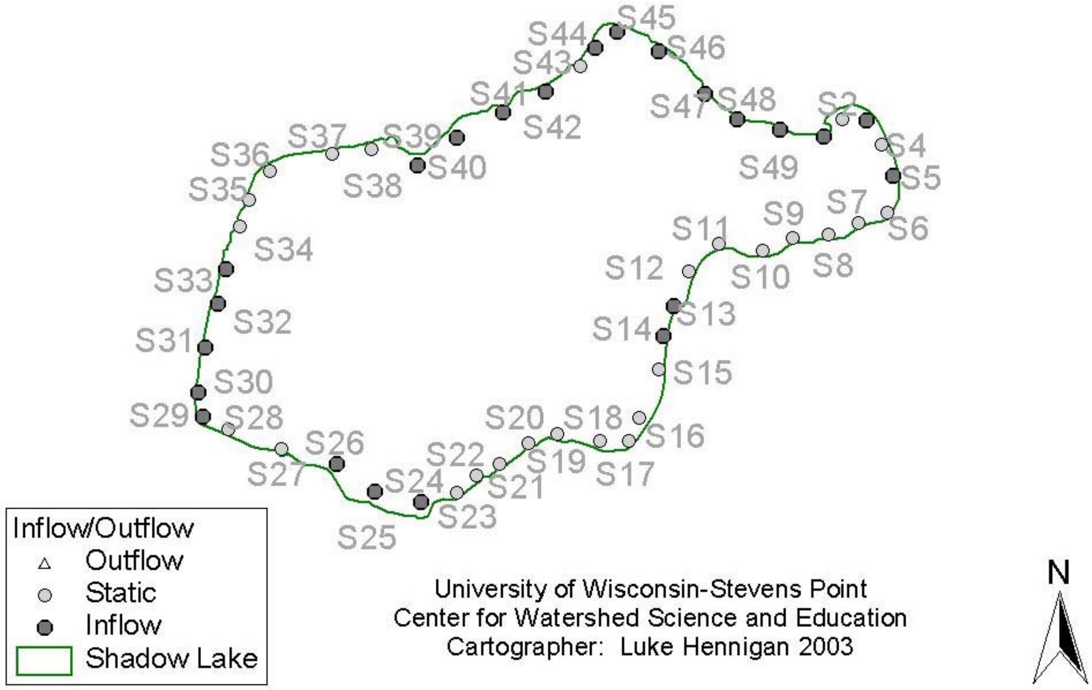

Figure 21. Groundwater flow conditions in Shadow Lake Waupaca, WI Summer 2003.

Temperature

Groundwater temperature conveys general information about the source of water in the mini-piezometers. It is assumed that colder groundwater originates in the far western portions of the Mirror/Shadow Lake groundwater watershed (Figure 22 and 23), whereas warmer temperatures would be representative of more local recharge. Temperature was measured at all inflow sites.

Nine of the 11 sites (82%) that were sampled in Mirror Lake had temperatures that were greater than 19°C (Figure 22). Groundwater that was colder than 19°C was measured at Sites 31 and 13.

Groundwater entering Shadow Lake had variable temperature, with groups of sites that exhibited similar temperatures (Figure 24). Sites S39 to S43 along the north shore of the lake, Site S2 on the northeast shore, and Sites S24 to S29 on the southwest shore had some of the coldest groundwater, with temperature ranging from 13 to 17°C. Sites S44 to S5 contained warmer water that had temperatures greater than 18°C.

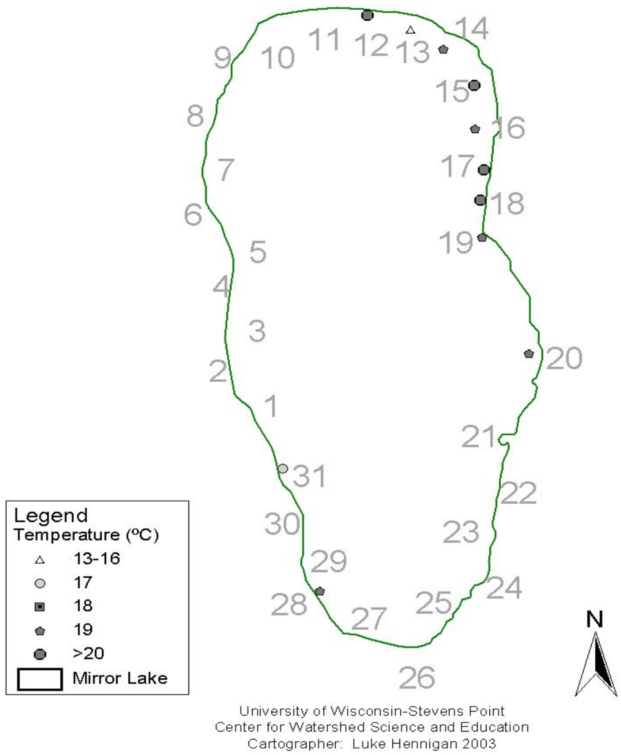

Figure 22. Groundwater temperatures measured from mini-piezometers in Mirror Lake Waupaca, WI Summer 2003.

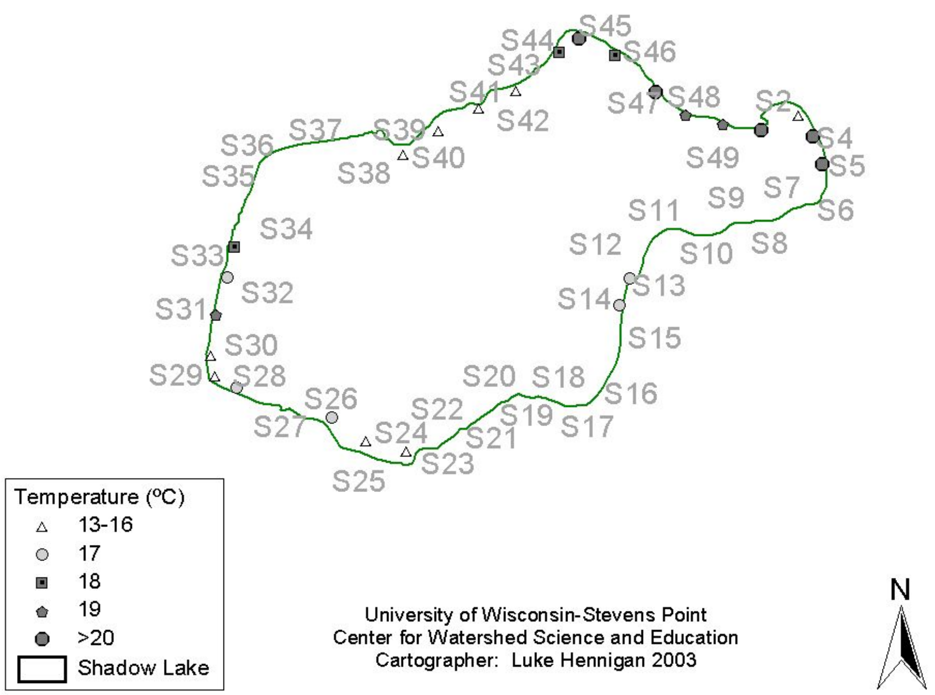

Figure 23. Groundwater temperatures measured from mini-piezometers in Shadow Lake Waupaca, WI Summer 2003.

Conductivity
Groundwater conductance values are naturally higher than in-lake values because of groundwater's increased contact with geological material along its flow path to the lakes. As the groundwater comes in contact with minerals, interactions between minerals and water cause minerals to dissolve. Generally, longer contact with the geologic substrate causes more dissolution to occur. These natural constituents are the primary natural ions that effect conductivity measurements. Groundwater also receives dissolved molecules from pollutants that have infiltrated to the groundwater including chloride and nitrate. Groundwater entering Mirror Lake had higher than normal measurements of conductivity in 9 of the 11 sites with readings above 800 µmhos (Figures 24 and 25).

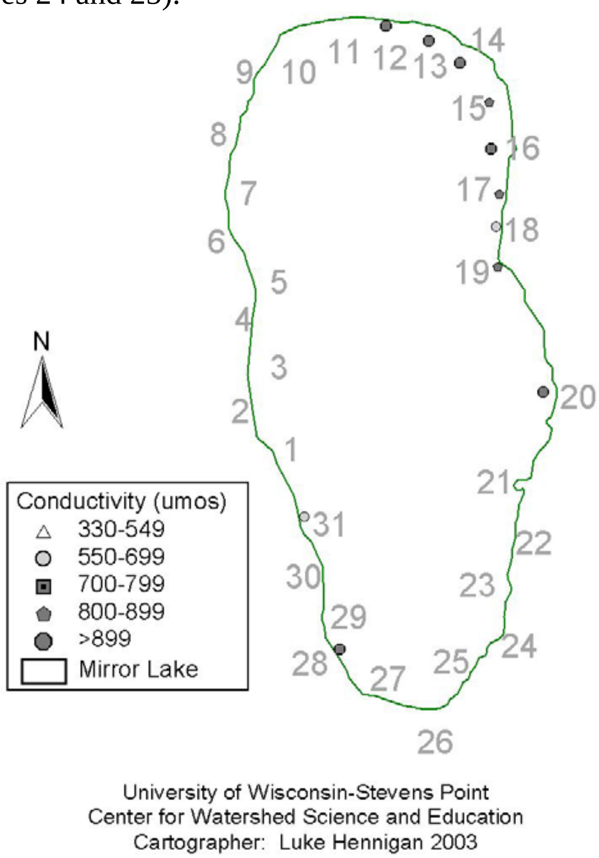

Figure 24. Conductance of groundwater flowing into Mirror Lake Waupaca, WI Summer 2003.

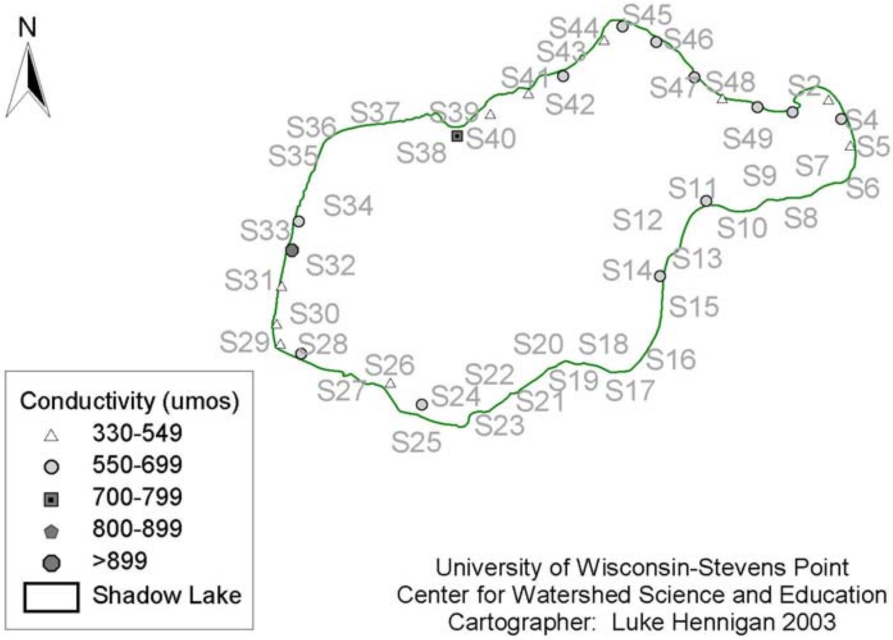

Figure 25. Conductance of groundwater flowing into Shadow Lake Waupaca, WI Summer 2003.

Chloride

As in surface water, chloride can be an indication of impacts from human activities. Chloride is very soluble and readily infiltrates to groundwater. Concentrations in groundwater entering Mirror Lake were clearly above the regional background concentrations of 9.5 mg/L (P.A.Kammerer, 1981), with concentrations between 23.5 and 42 mg/L shown in Figure 26.

Chloride concentrations in groundwater entering Shadow Lake ranged from 1.5 to 164 mg/L (Figure 27). These concentrations are a result of the urban location of the lakes; inputs of chloride would be expected from various locations throughout the watershed. Local urban sources can include road salt, pet waste, lawn and garden fertilizer and sources from further out in the watershed may include animal waste, septic systems, and fertilizer.

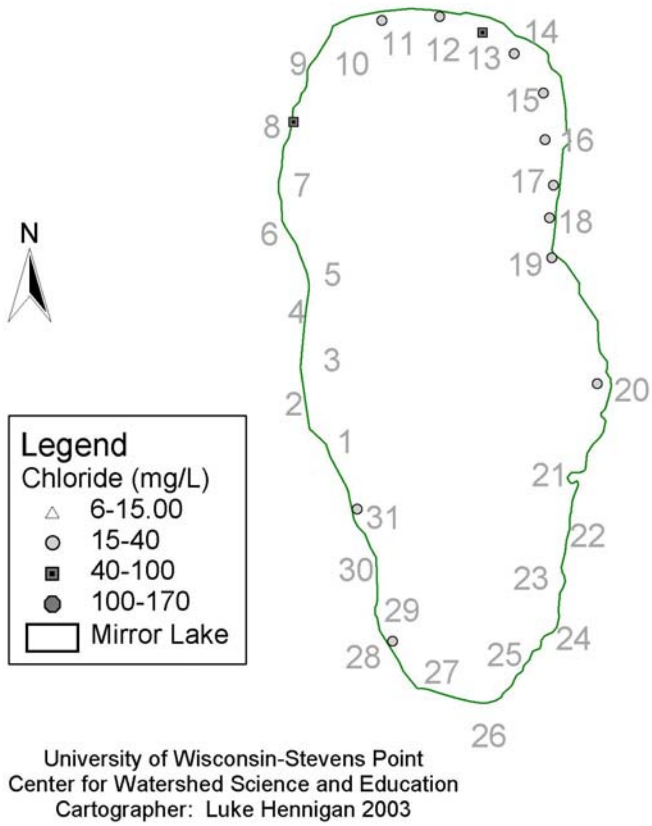

Figure 26. Chloride concentrations in groundwater entering Mirror Lake Waupaca, WI Summer 2003.

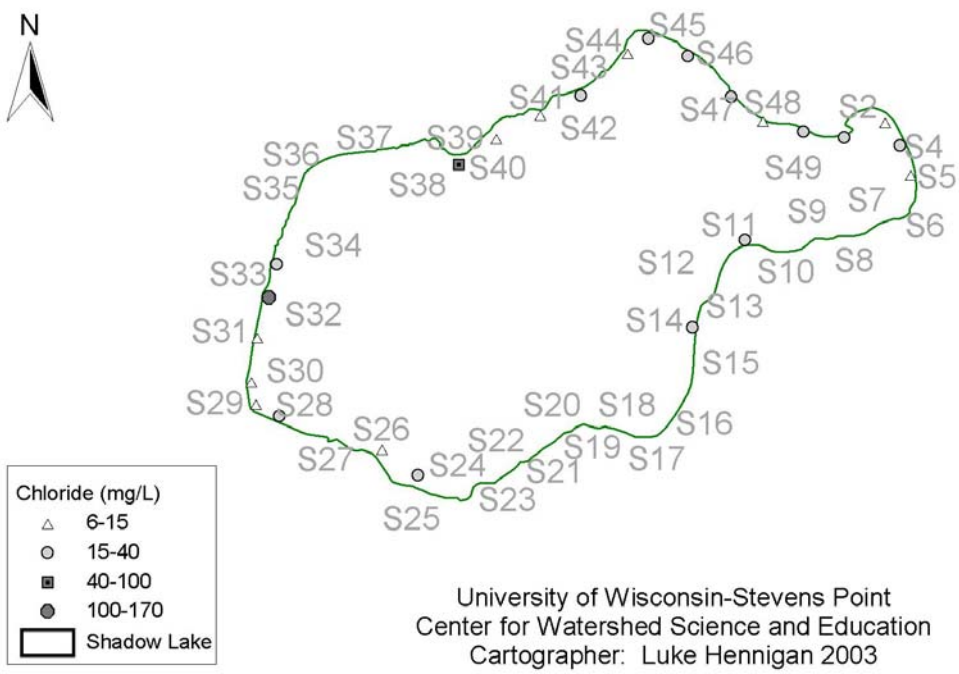

Figure 27. Chloride concentrations in groundwater entering Shadow Lake, Waupaca, WI Summer 2003

Nitrogen

Nitrate concentrations in groundwater entering both Mirror and Shadow Lakes were low for this region of the state. Mirror Lake had concentrations between 0.01 and 1.84 mg/L. Site M8 had the highest nitrate+nitrite-N concentration of 1.84 mg/L. This site also had elevated concentrations of chloride. Groundwater entering Shadow Lake had concentrations that ranged between 0.02 and 0.1 mg/L.

Ammonium concentrations in groundwater entering Mirror Lake ranged from 0.01 to 4.77 mg/L (Figure 28). Groundwater entering Shadow Lake had concentrations that ranged from 0.005 to 10.37 mg/L (Figure 29). The elevated ammonium measured at some of the sites may have natural sources. Most are located in the proximity of historic and/or existing inflows/outflows.

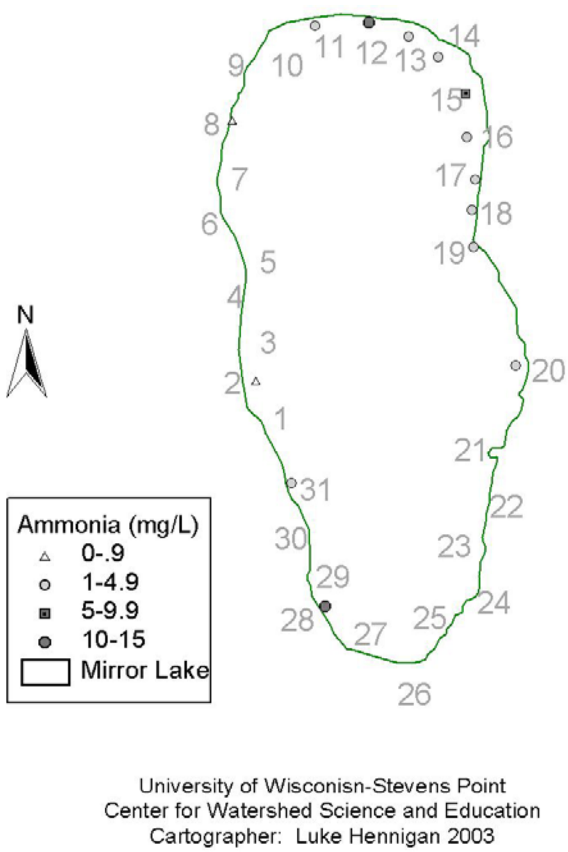

Figure 28. Ammonium concentrations in groundwater entering Mirror Lake Waupaca, WI Summer 2003

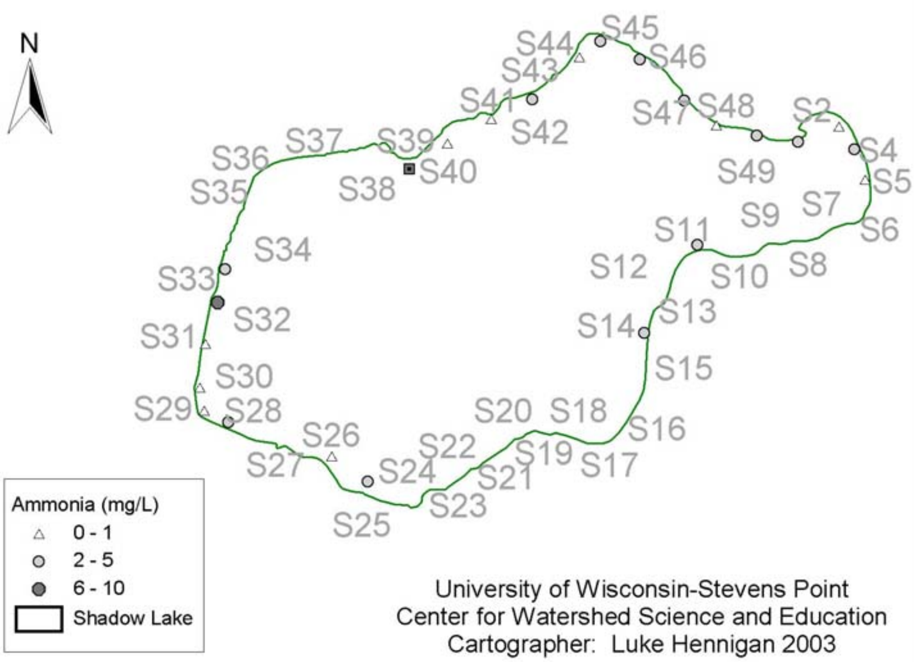

Figure 29. Ammonium concentrations in groundwater entering Shadow Lake Waupaca, WI Summer 2003

Reactive Phosphorus

Groundwater entering Mirror Lake had soluble reactive phosphorus (SRP) concentrations that ranged from 1.5 to 1,200 µg/L with large variability in concentrations from site to site (Figure 30). In central Wisconsin, phosphorus is generally found in very low concentrations in groundwater. Sites 19 and 20 had the lowest phosphorus concentrations at 1.5 µg/L. Sites 11 and 12 on the northern shore had the highest concentrations of SRP, 793 and 1,200 µg/L, respectively.

Some additional sampling and surveys have been conducted to identify the source of the phosphorus inputs; however, additional studies still need to be conducted. Additional investigation will continue beyond the duration of this study.

Groundwater flowing into Shadow Lake had SRP concentrations that ranged between 0.5 and 314 µg/L (Figure 32). SRP concentrations were shown to follow trends in areas with significantly elevated ammonium concentrations. Sites near the inflows, outflows, or culvert drainages all had elevated concentrations of phosphorus (Sites S44, S45, S31) (Figure 31). Locations with lower temperatures had lower phosphorus concentrations suggesting that groundwater that came through longer, deeper flow paths contained lower phosphorus concentrations. Elevated phosphorus concentrations likely come from shallower flow paths or are created when shallow groundwater mixes with interstitial water, decomposing organic material, or mineral deposits.

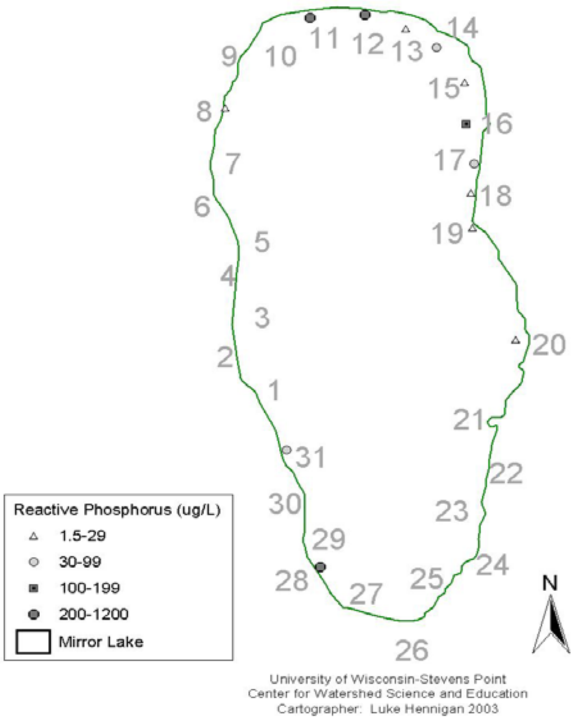

Figure 30. Soluble reactive phosphorus concentrations in groundwater entering Mirror

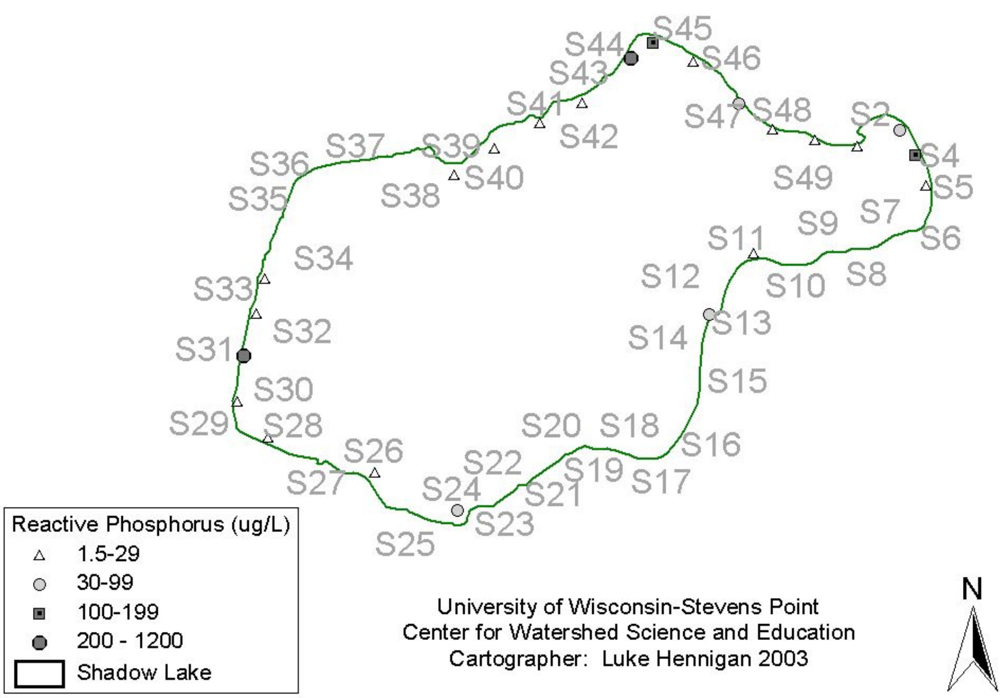

Figure 31. Soluble reactive phosphorus concentrations in groundwater entering Shadow Lake Waupaca, WI 2003.

COMPUTER MODELING

SIMULATING LAND USE IMPACTS ON PHOSPHORUS TRANSFER

Phosphorus is typically present at concentrations ranging between 0.01 to 0.2% in soils and plants. That can result in hundreds of pounds of phosphorus present near the shore in the soil and vegetation. Development, agriculture, and urbanization can have significant impacts on phosphorus transfer from land to water. Studies in Wisconsin have shown phosphorus transfer from cultivated and urbanized land that exceed 0.5 to 1 lb/acre/year (Panuska and Lillie). That could be a 50-fold increase from undeveloped, forested areas. While the reasons for this increase are complex, they are related to development impacts on the: 1) the quantity of water entering a lake; 2) the availability of phosphorus to the flowing water; and, 3) the path that the water takes to the lake.

Availability of phosphorus to water moving through land depends on the form of phosphorus on the land, how the water moving from land to water contacts this phosphorus, and what mechanisms are available to retain the phosphorus during transport. Research has shown higher concentrations of phosphorus in water contacting soil when soil phosphorus contents are higher, during plant decay, and when suspended sediment levels are higher. Concentrations of phosphorus in water contacting forest litter, urban lawns or agricultural cropland can have phosphorus concentrations of several milligrams per liter (Garn, 2002; Grasczyk, 2001; Sharpley, 1995).

High concentrations alone do not necessarily accelerate phosphorus transfer from land to water. The combination of phosphorus transfer to water and water movement to lakes, may retain phosphorus as the water moves on or through the land. Water paths offering more opportunity for reaction with soil and vegetation can lead to lower phosphorus loss. For example, in areas of variable slope and heterogeneous surface characteristics, runoff paths may be short and may route water to depressions where it can infiltrate prior to being transferred directly to surface water. In that case, water may be taken up by plants or move to the lake through subsurface pathways. Subsurface transport is typically slow, and allows much more time and opportunity for filtration of particulate phosphorus and adsorption of dissolved phosphorus. In contrast, impervious surfaces such as roofs, driveways or areas of reduced infiltration such as graded turf, cultivated fields or compacted soils offer more direct runoff pathways. Those paths offer less retention of particulates, less opportunity for adsorption of dissolved phosphorus, and increased transfer of higher phosphorus concentrations to the lake.

Simulation Approaches

Most approaches for estimating the transfer of phosphorus to surface water link different rates of phosphorus transfer with different land uses. Beginning with observations that watersheds with high amounts of urbanization or agricultural activity have surface waters with higher phosphorus concentrations, unit area loading coefficients (amount of phosphorus likely transferred per year) were developed from several studies. More site-specific approaches have based phosphorus transfer on characteristics of the watershed such as impervious area. We sought to compare several site-specific approaches to estimate the transfer with the export coefficients. Three approaches were investigated: 1) the simple runoff coefficient approach; 2) measure the extent of impervious area and use measured phosphorus concentrations to approximate runoff; and, 3) combine a more detailed pervious/impervious simulator with a likely storm distribution for runoff estimation and combine with estimated phosphorus concentration.

Export Coefficients

Using the compilation of export coefficients developed from Wisconsin studies, an urban area phosphorus export between 0.3 and 2 pounds of phosphorus/year is shown to occur by WDNR in their lake water quality model (WILMS). A WDNR report by Panuska and Lillie report export coefficients on the low end of this range for the Mirror Lake studies in the 1970s.

Impervious Area Estimate

Impervious surface is one measure used to estimate phosphorus transfer from urban areas to water. The simplest application estimates the runoff from the percentage of impervious land in the watershed, and then converts that to phosphorus load (e.g., pounds/year) by assuming an average runoff concentration (CWP, 2000). This method is based on the observation that the fraction of the storm that appears as direct runoff increases with the percentage of the watershed that is impervious. At the upper end, if 100% of the land area was impervious or did not allow for infiltration, it would be expected that most of the precipitation would runoff. At the low end, even if there is no impervious surface, only a small percentage of the water (typically estimated as 5% in this simple approach) is expected to runoff. At intermediate levels of impervious cover, the runoff is interpolated. While this approach likely characterizes the most significant controls on direct runoff, particularly in those areas which do not allow for infiltration, it does not allow adjustment for different soil types or other variables influencing the runoff volume.

Pervious/Impervious/Storm Simulation Method

A variety of more detailed approaches are available for predicting runoff and phosphorus export (SLAMM, P8, SGWATER). We employed a method similar to these that estimates runoff from three different land uses: impervious, developed pervious, and undeveloped pervious using the NRCS curve number (NRCS, 1985) and then based on the amount of "connection" between the impervious area and the surface water, assumed a portion of the runoff from the impervious area to be redirected onto the pervious area where some of water can infiltrate. Although this model allows inclusion of more permeable soil types if that is prevalent in an area, urban land uses often result in small areas of pervious and considerable compaction of those areas. An important feature of this more detailed approach is the "connectivity" between impervious surfaces and the lakes. For example, pavement that is connected to the lake through a storm water conveyance system is considered "directly connected." Precipitation that runs off the pavement is likely to have little opportunity for infiltration prior to discharge to the lake. In contrast, water that runs off roofs or other impervious surfaces and onto lawns might have the opportunity to infiltrate. In urban areas with a moderately high density, much of this type of impervious surface also appears to respond as if "directly connected." That likely reflects factors that act to reduce infiltration, such as the movement of water in channels, across lawns, or the compaction of urban soil that reduces infiltration (CWP 2000). Once the runoff volume is estimated, it is multiplied by the anticipated runoff concentration to compute the export load.

Table 17 shows the average annual phosphorus export estimated using the different methods. It is apparent that the different simulation approaches provide different estimates of phosphorus loading. The export coefficient approach and pervious/impervious model approaches provide somewhat similar total loads and are both based on more site specific considerations. In general, these estimates can be viewed as approximate likely annual loads, and also provide an opportunity to compare the likely magnitude of phosphorus inputs from the different sub-watersheds.

Table 17. Phosphorus load estimates for Mirror and Shadow Lakes.

Sub-watershed	Area (acre)	Impervious %	Estimated Annual Phosphorus Export (lb/year)		
			Export Coefficient Method (1)	Impervious Area Method (2)	Pervious / Impervious Method (3)
Mirror North	25.5	15	9.1	13.1	6.8
Mirror South	2.1	0	0.7	0.3	0.2
Mirror Park	4.8	17	1.7	2.7	1.4
Wetland East	14.9	54	8.0	22	11.2
Wetland West	52.8	10	14.1	20	10.8
Shadow Drainage	52.5	20	18.7	33	17.2
Shadow North	10.5	24	3.7	7.7	4.0
Shadow Northeast	2.0	0	0.5	0.3	0.2
Shadow East	18.3	32	6.5	17	8.7
Urban	50.8	55	27	75	39
Harrison	35.5	19	13	21	23
Total			103	212	122

Notes

(1) Export coefficient method assumed export coefficient range of 0.3-0.6 lb/acre/year based on Mirror Lake data cited in Panuska and Lillie (WDNR Research Management Findings, April 1995, *Phosphorus loadings from Wisconsin Watersheds: Recommended phosphorus export coefficients for agricultural and forested watersheds*). Here 0.6 lb/acre/year used for impervious surface greater than 50%; 0.4 for impervious between 15 and 50%; and 0.3 for less than 15% impervious.

(2) Impervious area method estimated annual runoff volume using R_v=0.05+0.009(I) (adopted from Watershed Protection Techniques Technical Note 2(2):364-368 *Simple and Complex Stormwater Pollutant Load Models Compared*) where R_v is the runoff coefficient (fraction of precipitation which becomes runoff) and I is the percentage impervious for the subwatershed. An annual precipitation of 30 inches was assumed and a concentration of phosphorus in the runoff of 0.4 mg/l (based on the overall flow weighted mean for the Harper Basin outfall in the urban runoff study in Madison WI: (Waschbush, R.J., Selbig, W.R., and Bannerman, R.T., 1999, *Sources of Phosphorus in Stormwater and Street Dirt from Two Urban Residential Basins in Madison, Wisconsin*, 1994-95, WRIR-99-4021, http://wi.water.usgs.gov/pubs/WRIR-99-4021/index.html).

(3) Pervious/Impervious method estimated annual runoff using a modification of the NRCS curve number approach assuming curve number of 98 for impervious areas and 70 for all pervious areas (based on Table in NRCS TR-55, 1985 and assuming soil group B for pervious areas). 80% of the runoff from the impervious areas was assumed directly connected to the outlet and 20% redirected as additional storm depth on the pervious areas. Storm distribution and frequency based on 30 year average of 24 hour storm depths. Median storm size within each category was simulated separately and annual runoff volume was the sum of all storms. Annual runoff volume multiplied by assumed total phosphorus concentration of 0.4 mg/l (based on volume weighted average of Harper Basin, Madison WI storms in 1995, see Waschbush reference above).

THE BIG PICTURE

Mirror and Shadow Lakes receive water through various sources. These sources of water have changed over time with urbanization, increased impervious surface, stormwater diversions away the lakes, etc. The primary water sources have been calculated using measurements taken in this study and (with the exception of direct precipitation) are shown in Figure 32. Both of the lakes receive most of their water from groundwater. Lesser percents are associated with surface water inflow that enters the lake as overland runoff or as stream inflow.

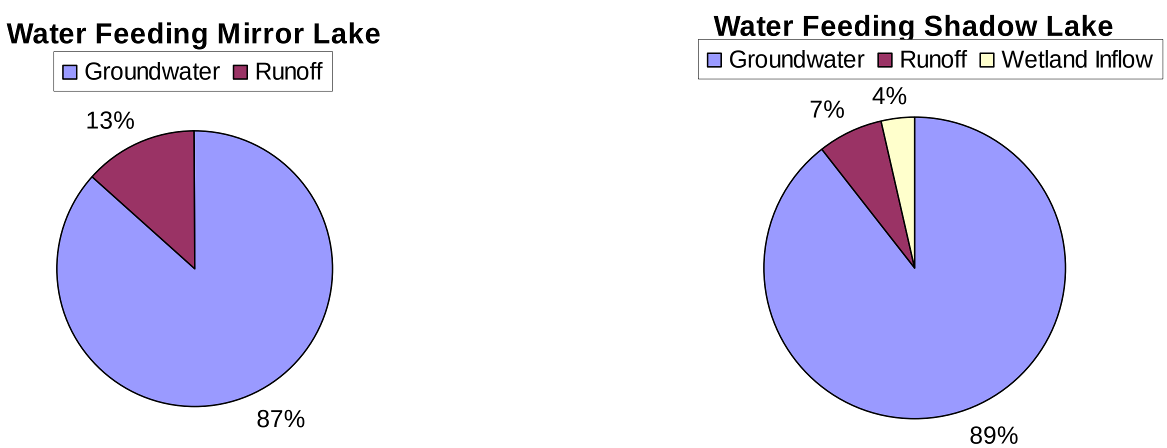

Figure 32. Primary sources of water to Mirror and Shadow Lakes.

The water flowing to and between the lakes carries the dissolved and particulate nutrients that were present on the land, in the groundwater, or in the surface water to the lake. In discussions throughout this paper we have identified sources of these nutrients. We have also measured the volume of water from various sources. When both the volume of water and the nutrient concentrations are combined, the total amount of nutrient loading to the lake can be estimated. One of the findings of this study was an area of very high interstitial pore water phosphorus and relatively permeable sediment on the north shore of Mirror Lake. Although the source and impact of these inputs are still being studied, that area is particularly problematic with respect to a lake nutrient budget. Figure 33 shows the amount of total phosphorus and total nitrogen that various water sources entering the lakes. Figure 33 assumes that the high pore water concentrations and groundwater input rates observed at those two locations (11 and 12) can be transferred to the area surrounding them. If so, that area would contribute 166 pounds of phosphorus to the lake annually. Comparison to the total in Figure 33 shows that to be more than 75% of the annual phosphorus load in our nutrient budget. While the north shore of Mirror Lake appears to be an important source of phosphorus to the lake, the actual phosphorus input from that location and its source will require additional delineation. Groundwater contributed the greatest loads of both phosphorus and nitrogen to the lakes.

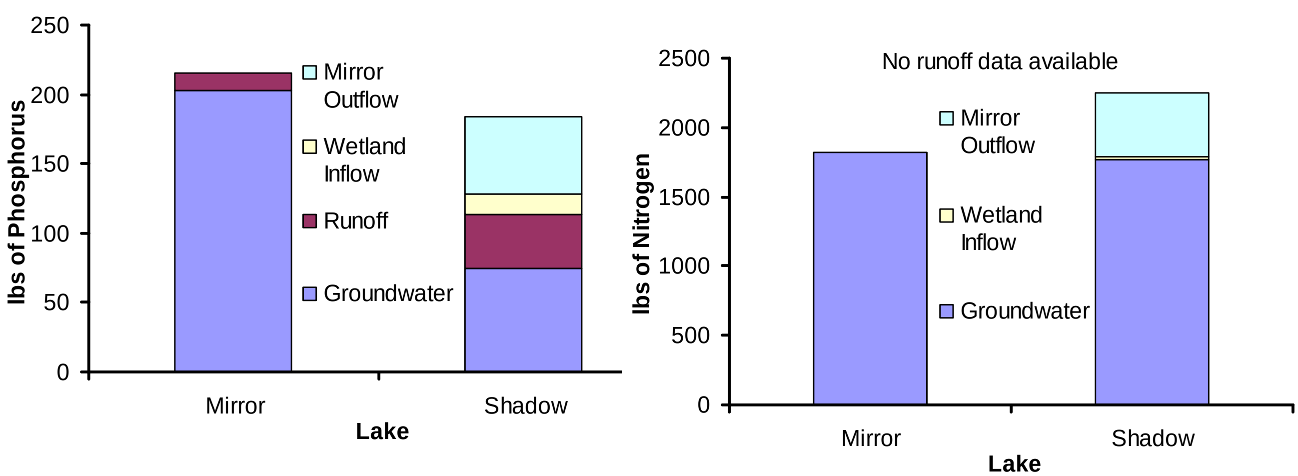

Figure 33. Shadow and Mirror Lake nutrient budget from the various sources of inflow and outflow.

CITIZEN EDUCATION

An organizational meeting for the Friends of Mirror and Shadow Lake was held May 14, 2003. All riparian landowners received an invitation to the meeting. Information and meeting notice was placed in the local newspaper and signs were posted in the community. The Lake Watchers student-monitoring group presented information on past monitoring results and UW-Stevens Point explained the monitoring that will be done for the grant as well as grant goals. The county Land and Water Conservation Department presented information on shoreline management and discussed soil-testing opportunities. A presentation was made on plant material appropriate for shoreline plantings. The Friends Group met periodically throughout the project for progress reports and consists of 12 regular members and several others who couldn’t make meetings but were interested in lake improvement.

One of the first projects for the Friends of Mirror and Shadow was to organize and run a Lake Festival on July 9, 2003 in the City of Waupaca South Park. Fifty-three people attended the event. Pontoon boat rides were offered to view the shoreline of Shadow Lake, the Adopt-a-Lake monitoring volunteers offered testing demonstrations, UW- Stevens Point Cooperative Extension (Lynn Markham, Shoreland Specialist) presented information on shoreline management and frog identification. Besides oral presentations, a display area was set up with information and handouts on these topics and general water quality information. The City of Waupaca and the Waupaca Leo Club provided a free picnic supper.

Representatives from the Friends Group spoke at the annual Inland Lakes District meeting. They introduced their organization and asked for support for water quality improvement in the lakes.

The Friends Group with the assistance of the Fox-Wolf Watershed Alliance held a citywide meeting to report on the results of the study. Invitations were sent to riparian landowners and an announcement was placed in the local newspaper. Twenty-three people attended the presentation. A discussion of possible next steps was held and a meeting date was set to prioritize the suggestions and develop an action plan.

CONCULSIONS AND RECOMENDATIONS

- This study confirmed that oxygen transfer to Mirror Lake can be problematic for two reasons. First, the lake does not always mix well in the transitional seasons, and second, even when it mixes, the oxygen demand of the bottom water can overcome the transfer of oxygen from the atmosphere. Evidence for this were the temperature profiles in the spring showing the top warming and the bottom of the lake still not completely mixed with the surface (e.g., high conductivity, low oxygen). In the fall, the lake was relatively well mixed from top to bottom (e.g., conductivity uniform), but the oxygen levels were low throughout the lake. During this study, oxygen levels in the winter were relatively high. That may reflect the relatively clear ice that allowed substantial photosynthesis under the ice or enough mixing and oxygen transfer occurred after fall overturn and before ice cover formed. Based on our observations, oxygen introduction in fall may be useful in those years when there is insufficient transfer prior to ice formation, but care should be taken to minimize mixing of bottom water in the lake as that will likely exert a significant oxygen demand and may offset the introduction of oxygen.

- Phosphorus is entering the lakes via groundwater, runoff, and surface inflow. External nutrient sources to the lake exist, but another substantial source of phosphorus is nutrients within the lakes. This study found evidence that littoral zone (lake edge) sediments may be acting as a source of phosphorus and oxygen problems in the bottom of the lake. Subsequent phosphorus release also provides phosphorus to the lake surface (particularly during overturn and mixing events). In-lake phosphorus levels suggest that Mirror Lake is a eutrophic lake and Shadow is a mesotrophic lake. Phosphorus concentrations remain lower in the lakes than they were prior to the storm sewer diversion and alum treatment.

- Inputs of nutrients to the lakes are greater than outputs. This study found water and phosphorus enters Mirror and Shadow Lakes through groundwater and surface runoff. In addition, Shadow Lake receives nutrients in flow from the wetland area and the Mirror Lake outflow. The estimated annual load of phosphorus into Mirror Lake was 203 lbs from groundwater and 10 lbs from the surface watershed. These totals are below the phosphorus inputs prior to the storm sewer diversion. Opportunities still exist for reducing external phosphorus loads. Surface runoff into the lakes is likely a significant source of external phosphorus load. Reducing runoff volume and concentration can be accomplished by encouraging infiltration in the drainage areas and runoff contact with fertilizer, pet waste and decaying vegetation. Particular attention should be paid to the buildup of these materials on hard/impervious surfaces as they can be more directly transferred to the lake.

- Filamentous algae were observed in the water below steep slopes that are draining to the lake, especially those without vegetative buffers and with mowed lawns.

- The algae found in Mirror and Shadow Lakes are typical of moderately-impacted, temperate zone lakes in North America. No taxa are unique or dangerous. None of the identified taxa are associated with toxicity or pathologies. These taxa are generally ubiquitous and frequently dominate similar bodies of water. The general seasonal pattern of algal succession in both lakes is the same.

- Littoral zone observations indicated that many property owners are leaving in-lake aquatic plants in place. This is good for fish, amphibian, and macroinvertebrate habitat. It is also beneficial to have large plants using the phosphorus to reduce availability to algae.

- Though the wetland has minimal flow to the lake, concentrations of phosphorous and total suspended solids are very high.

- Riparian buffers should be protected or reintroduced. Taller unmowed vegetation will help to filter sediment and nutrients, prevent erosion, and provide habitat for wildlife.

Water moves to Mirror and Shadow Lakes via surface runoff, groundwater, and direct precipitation. Pollutants and other contaminants can enter the lake directly through these processes. Areas immediately surrounding the lake generally have the largest impact on lake water quality. However, much of the groundwater originates further out in the groundwatershed, so the land uses in the watershed can also affect the lake's water quality. Efforts to reduce sediment and nutrient inputs to the lakes should be made by both shoreland residents and landowners within the watershed.

Landuse in the watershed is predominantly developed urban residential. These conditions result in significantly more impervious surface which results in more runoff carrying particles and associated nutrients. The impervious surfaces include building roofs, driveways and roads, and compacted soil found below urban lawns. Typically, some of the precipitation in this region infiltrates the soil which can help to filter out sediments and nutrients. Impervious surfaces reduce infiltration, so best management practices for developed areas have been designed to increase infiltration, slow water movement, and filter water, ultimately reducing the delivery of these impurities to the lakes. Best management practices include rain gardens which are designed to capture water from roofs and allow it to slowly infiltrate into the soil and groundwater, near shore buffers to help filter and slow runoff water, elimination or reduction of fertilizers. Prior to fertilization, soil tests should be conducted to determine if fertilizer application is necessary.

Some of the lake shoreline lacks sufficient shoreline vegetative buffers to remove sediments, nutrients, and pollutants from runoff and to provide habitat for aquatic wildlife. The state standard for a functional buffer is thirty-five feet from the water. Buffers should be re-established in these areas, and should include grasses, forbs, shrubs, and trees. Existing native shoreline vegetation around the lake should be protected and efforts should be made to establish more natural vegetation in shoreline riparian areas. This vegetation provides many benefits to the lake ecosystem. The grasses and shrubs filter out sediments, which flow from adjacent areas. The vegetation also uses nutrients that would otherwise flow to the water, taking up some phosphorus and nitrogen.

Shoreland owners should continue to allow aquatic plants to be established in the lake bottom. Cleared areas are desirable sites for invasive aquatic plants to take hold and become nuisances. In-lake vegetation creates a microenvironment suitable for marl formation, which can further limit available phosphorus. It also provides habitat and food for fish, aquatic insects, reptiles, amphibians, waterfowl, and other birds. Aquatic plants in shallow water help to buffer the impact of waves on the shoreline, thus, reducing erosion and the need for rip-rap.

Motorized watercraft use (boats and personal water crafts) should be conducted in a way to allow the establishment of shoreline vegetation and reduce mixing of sediments into the water column. Turbulence and wakes produced by boating activity disrupt the rooting of the plants and can re-suspend sediment and phosphorus. No wake zones should be implemented within 200 feet of the shoreline in accordance with Wisconsin state law.

A management plan should be developed for Mirror and Shadow Lakes and should include a vision and goals for the lakes. It should identify ways to achieve goals and should be incorporated into the City plans where appropriate. Many people should be involved in this process and inclusion of local and state professionals is strongly encouraged. Technical support is available from the UW-Extension, the Waupaca County Land Conservation Department, the Department of Natural Resources, and consultants.

Routine water quality monitoring is recommended to assess the status of the lake over time and during various climatic conditions. Water chemistry can change over time in response to changes in land use practices. Throughout the year measuring and reporting temperature and dissolved oxygen profiles would be useful, particularly in Mirror Lake. Secchi depth measurements are useful to take during the summer, and at a minimum, annual sampling for water quality analysis during overturn would be useful to document long term trends in water quality.

Stratification in Mirror Lake has positive and negative effects. The positive effects are the sealing of nutrients, metals, and other harmful decomposition byproducts in the bottom, which discourages increased algal and macrophytic growth throughout the water column. However, it also creates anoxic conditions that slows decomposition, makes various nutrients and metals soluble, and stops the productivity of cold water biota in the summer months. In Mirror Lake, aeration during part of the year is necessary to maintain a healthy fishery. This should be done in the late fall, prior to ice on and should include aerating above the metalimnion to avoid mixing the lake and releasing phosphorus into the water column. Dissolved oxygen should be monitored weekly throughout the winter to determine if additional aeration is warranted.

With an ever-expanding population of people looking for lake front property and recreation, there will be increasing demand on Wisconsin's, Waupaca's, and Mirror and Shadow Lake's freshwater resources. In an article on the future of Wisconsin Lakes, Gary Peterson, a University of Wisconsin postdoctoral who studies ecological management, said that 'the future will depend on the interactions between those who occupy the land and the land itself: "it's about the connection between people and nature."' Raw data was used to define the models and conclusions of this report can try to predict what will happen in the future, but ultimately the future lies in the hands of those who reside around the lake, live within its watershed, and use the lakes. By engaging yourself and your neighbors in the care taking process of these lakes you will create a community and lake, which will reflect your efforts.

Mirror/Shadow Lake Work Plan

The Friends Group met on May 19, 2004 to develop an action plan for restoring and protecting Mirror and Shadow Lakes. After discussion, the following items were selected for further work:

1. Continuing the volunteer monitoring group was selected as the top priority of the group. The director of the student program informed the group that the students would no longer be available for monitoring. Sandy Testin was elected as the new chair of the monitoring committee. She will work with Dave Furstenburg, director of the school group, and citizens who had indicated an interest in monitoring to conduct training and continued collection of water samples. The City of Waupaca offered to assist with the purchase of any additional equipment.

2. A shoreline restoration project was chosen for public education. Ellen Hooker, chair, will work with the city to identify a site in the city park for shoreline restoration to be completed this summer (2004). The Friends Group will create a brochure to go with the project as well as a handout on phosphorus free fertilizer. These will be given to all shoreline property owners. This committee will coordinate their efforts with a county program on fertilizer education.

3. There is an established Garden Walk event in the Waupaca area. Kari Esbensen will contact the chair of that event and request that examples of rain gardens and good shoreline habitat be added possibly to this year's walk, and definitely for 2005. She will also call the county Land and Water Conservation Department for information on their rain garden program and share that with the Friends Group.

4. The Friends Group agreed that it was important to adopt the Mirror Lake aeration recommendations presented in the final report. John Edlebeck, City Public Works Director will place the purchase of a new aerator in his budget. The Friends Group will speak in favor of this purchase at the budget meeting.

5. An additional concern was brought up by Louis Baumgartner regarding the loss of turtles in the area due to ingesting Styrofoam from bait buckets and other sources. Linda Stoll of Fox-Wolf Watershed Alliance will contact the DNR for information and pass this on to Louis. He will work with the Friends Group to educate people about this issue.

The Friends of Mirror and Shadow Lake will schedule a full-group meeting in September of 2004 to review summer activities, elect group officers and select actions for 2005.

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APPENDICES