Diagnostic Study

Deer-Pokegama Clean Water Partnership

Deer Lake # 31-0719

Pokegama Lake # 31-0532

Itasca County, Minnesota

MPCA CLEAN WATER PARTNERSHIP FINAL REPORT

Project # 7181

SPONSOR
Itasca County Board of Commissioners

PROJECT REPRESENTATIVE
Noel Griese, Itasca County SWCD

PROJECT MANAGER
Phil Votruba, MPCA

ITASCA COUNTY SOIL AND WATER CONSERVATION DISTRICT

Itasca County Soil and Water Conservation District

1889 East Hwy 2

July 22, 2013

AUTHORS:

Noel Griese
Lakes and Waters Specialist
Itasca County SWCD
1889 East Highway 2
Grand Rapids, MN 55744
noel.griese@itascaswcd.org

Jacob A. Smokovitz
Graduate Research Assistant
Department of Geological and Atmospheric Sciences and Environmental Science Interdepartmental Graduate Program
253 Science I
Iowa State University
Ames, IA 50011
jasmokovitz@gmail.com

Eric Ahlstrom
Water Quality Lab Coordinator
Itasca Community College
1851 East Highway 169
Grand Rapids, MN 55744
eric.ahlstrom@itascacc.edu

Randy Hedin
Water Quality Lab
Itasca Community College
1851 East Highway 169
Grand Rapids, MN 55744
randy.hedin@itascacc.edu

Dr. William W. Simpkins
Professor of Hydrogeology
Department of Geological and Atmospheric Sciences
253 Science I
Iowa State University
Ames, IA 50011
bsimp@iastate.edu

Dr. John A. Downing
Professor
Iowa State University
EEOB & ABE Departments
251 Bessey Hall
Ames, IA 50011
downing@iastate.edu

Dr. John R. Jones
Curators' Professor
Department of Fisheries and Wildlife Sciences
University of Missouri
Columbia, Missouri 65211
jonesj@missouri.edu

TABLE OF CONTENTS

GENERAL INFORMATION

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The Deer-Pokegama Clean Water Parternship Diagnostic Study was the first of its kind in Minnesota because it examined the conditions in a set of two unimpaired waters – with the objective of protecting their quality. The study brought together organizations from across the region including Itasca County, Itasca County Soil and Water Conservation District, Itasca Community College, Itasca Water Legacy Partnership, Deer Lake Association, Greater Pokegama Lake Association, and the Minnesota Pollution Control Agency.

The two-year project studied two of Minnesota's highly valued recreational waters to better understand, manage, and protect them and other lakes within the Northern Lakes and Forests Ecoregion. Deer Lake is a 4,097-acre recreational development lake. Streams draining its small watershed account for a fraction of the annual water flux (12%); most inflow is from direct precipitation (73%) and groundwater (15%). Pokegama Lake is a 6,612-acre general development lake with a surrounding watershed many times larger than Deer Lake and hydraulic connection to the Mississippi River. These surface sources deliver most of the annual water flux (68%) with precipitation (17%) and groundwater (15%) accounting for the balance. Water resides in Pokegama Lake about 1.3 years and about 17.5 years in Deer Lake. Residential and agricultural use composes about 5% of both watersheds. The remainder is forest, open water, wetlands, and grass. Both lakes were formed by glacial activity, Deer from the melting of a large ice block during deglaciation, and Pokegama is located in a former meltwater channel. Both lakes are deep (over 30 m) with numerous shallows and complex morphology. Strong thermal stratification during summer physically isolates the warm surface layer of these lakes from the deeper water column.

In spite of their regional importance, the MPCA does not have extensive data for these lakes. Existing records show a modest decline in Secchi transparency in Pokegama Lake. A two-lane causeway reconstructed in 2007 (on State Highway 169) directs storm water run-off to Pokegama Lake, raising concerns about potential impact. Deer Lake, once known as the "lake of changing colors" because of the blue and violet hues that characterize unproductive lakes, now shows a trend toward green. A cyanobacteria bloom on Deer Lake in summer 2008 increased awareness of the impact of excessive algal growth on water quality.

The nutrient content, algal biomass, and transparency of Deer Lake are consistent with oligotrophic conditions, with phosphorus (P) near the upper boundary of this category. Pokegama Lake has higher nutrients and algal biomass and is less transparent and fits the mesotrophic classification. Measurements from both lakes fit empirical models that describe an increase in algal biomass and decrease in transparency with increased nutrient loading, so these can be used to predict the benefits of remediation or the consequences of degradation. Nutrient chemistry in both lakes suggests P is the element limiting autotrophic production and, therefore, the element of concern.

Mass balance calculations indicate the net input of total P to Deer Lake is 327 kg. For context, this is the equivalent annual P output of about 370 humans, so the lake should be considered sensitive to additional P loading. Some 73% of the P input derives from direct precipitation.

Phosphorus transported by rainfall in this region (around 24 ppb) is surprisingly high and about twice the value reported from some other areas. Additional information about the source, and potential control, of atmospheric P is critical to the protection of this lake. Input of P to Deer Lake from surface streams (20% of inputs) and groundwater transport (7% of inputs) is currently less than one-third of the annual budget. Stream P concentrations are quite high in six tributaries. To maintain water quality, it would be important to remediate these sources while protecting other tributaries from degradation.

Net P input to Pokegama is 4-times that of Deer Lake and, in contrast, most of this load comes from surface sources that include tributary streams draining the surrounding watershed (49%) and inflow from the Mississippi River (30%). Some of these tributaries have surprisingly high P, given the landscape, and are candidates for remediation. Precipitation supplies 15% of the P input and groundwater supplies about 6%. The large riverine P load implies that changes to water quality in the Mississippi River would be reflected in Pokegama in the future. Stream P concentrations are quite high in several tributaries so remediation and protection of tributary inputs would be important for water quality in Pokegama as well.

Modeling shows additional P loading to Deer Lake would tip it toward mesotrophic conditions, and doubling the load would result in conditions currently measured in Pokegama Lake. Sharp increases in algal biomass and declining transparency are predicted for small, incremental increases in the P load to Deer Lake. Added nutrients to Pokegama Lake would result in similar changes; modeling indicates total P in Pokegama Lake would increase by 1 ppb for every 10% increase in the overall level of total P input causing algal chlorophyll to increase about ½ ppb with this incremental addition, resulting in transparencies declining by about ½ foot. Doubling of total P loading to Pokegama Lake would increase total P to 25 ppb, which would push the lake into the eutrophic category with low transparency and frequent algal blooms.

Groundwater is important to the water and nutrient budget of both lakes, with deep groundwater being more important than shallow inflow. Both Deer and Pokegama lakes have some areas with high groundwater P concentrations, so groundwater pollution is also a concern. This aquifer is a $CaCO_3$-type water with low dissolved O_2 (mean 0.88 mg/L), essentially devoid of NO_3-N, and showing high iron (Fe) concentrations (1.5 mg/L). The overall mean SO_4 concentration was 11 mg/L, but sampling indicated an H_2S smell to certain well water. These data, and measureable NH_3-N concentrations (mean of 0.26 mg/L), suggest a strongly reducing geochemical environment in the deep aquifer. The presence of high concentrations of dissolved organic carbon (mean of 23 mg/L) suggests the geochemical system is driven by a labile C source. The geochemical environment is important because P can travel unimpeded at high concentrations in anoxic groundwater. Isotope data in deep groundwater suggests a range of groundwater age from pre-1963 to more recent.

These lakes share a water quality problem. The deep waters of both are nearly devoid of oxygen for much of the summer; oxygen depletion is about double that normally expected from the decomposition of organic matter produced in lakes with similar trophic state. Values are on a par with those measured in eutrophic lakes. Other sources of oxygen depletion include oxygen use by organisms, decomposition of dissolved organic matter, and chemical oxygen demand of reduced chemicals (e.g., “nitrification” of ammonium or oxidation of reduced iron). These processes seem important in both lakes and are much larger than expected. Measurements show that groundwater essentially is depleted of oxygen, but carries additional oxygen demand from dissolved organics and inorganic chemicals. Groundwater inflow, from shallow and deep sources, would tend to flow toward the bottom of both basins throughout the year because regional groundwater is about 4-5° C, which is the temperature of maximum density of the water molecule (its heaviest). These inflows contribute to oxygen depletion in deep waters isolated from the warm, circulating surface layer. This rate of depletion may be due to natural phenomenon, but moderate increases in nutrient-driven primary production will exacerbate the condition.

This finding suggests both lakes are sensitive to additional nutrient enrichment. Lakes of similar trophic state, without oxygen demanding inflow, have the capacity to absorb additional nutrients without creating hypoxic hypolimnia. Deer and Pokegama lakes have less capacity to absorb additional nutrients than their overall phosphorus concentrations imply. Anoxia in water columns promote internal loading of nutrients (fueling additional production), and these low oxygen conditions are inhospitable to most organisms. In Pokegama Lake during 2012, there was low oxygen in the metalimnion, the layer immediately below the epilimnion, typically oxygenated and often a place where fish can find cool water in summer. Oxygen in the water column is essential for a healthy fishery. Lake trout populations have declined over the past decade in Itasca County lakes, perhaps because of increased oxygen demand tied to productivity. Warm-water fish communities are also at risk of stress. Optimal conditions for warm-water fish species broadly include temperatures cooler than 24 C with dissolved oxygen > 5mg/L. This situation is referred to as the temperature oxygen squeeze, and a warming climate makes it increasingly important to protect oxygen in the deep waters of these lakes. The MNDNR is also concerned about this issue (http://www.dnr.state.mn.us/volunteer/julaug08/canaries_deepwater.html). Because of the importance to fisheries and the biotic health of these ecosystems and importance of this knowledge for management and policy decisions, it seems urgent to understand the cause of these high oxygen consumption rates.

Part of the requirement for this report included proposing a program to restore good water quality. In this case, an analysis of two lakes without previously demonstrated impairment, the implementation program was crafted to protect the waters from degradation. This study determined several things that are of importance to other lakes in the area: (1) precipitation is an important source of nutrients and likely other chemicals, and (2) the lakes both have inordinately high rates of oxygen depletion in the hypoliminion. In addition, the study indicated several areas around each of the lakes where further attention is warranted. For the individual lakes, therefore, we propose that: (1) a more detailed and controlled groundwater monitoring network be established and tracked, (2) streams that are contributing excess phosphorus (e.g., out of compliance with Minnesota draft standards) be carefully examined and remediated, (3) the causes of extreme deep water oxygen consumption be analyzed and experimentally managed, (4) the two lakes be monitored continuously to act as bell-weathers of regional change, (5) road drainage modification be sought to alleviate high nutrient inputs, (6) the Mississippi River backflow be decreased if possible, and (7) a septic system improvement and education program be implemented. For regional lakes in general, we propose: (1) the implementation of a county-wide atmospheric deposition monitoring network, (2) the implementation of an analysis of the causes of hypolimnetic oxygen depletion, (3) the establishment of a program of public education and lake protection, and (4) the implementation of an analysis of deep groundwater transport and quality.

Please note: Chemical concentrations are expressed in terms of weight per unit volume; the terms micograms per liter (ug/L) and parts per billion (ppb) are equivalent and are used interchangeably in this report.

INTRODUCTION AND PROJECT BACKGROUND

Description of the Waters of Concern and Project Area

Itasca County is home to nearly 1,000 lakes and has been identified by land developers for the next major phase of lakeshore development in Minnesota. Because of the potential for increasing pressure, it is critical that local collaborative efforts increase information and knowledge regarding the quality of these invaluable water resources.

This Deer-Pokegama Clean Water Partnership project focused on gaining an understanding of the dynamics of two of Minnesota's highly valued recreational waters and their watersheds to better manage and protect their future sustainability. Both Pokegama and Deer lakes have had exceptional water quality in the past and are significant resources within the region and state because they represent the many large recreational lakes in the Northern Lakes and Forests Ecoregion that are seeing increasing development pressure.

Deer Lake is a 4,097-acre (1653 ha) recreational development lake located approximately 6 miles northeast of Deer River, Minnesota. Pokegama Lake is a 6,612-acre (2772 ha) general development lake within the Mississippi River headwaters basin, located 5 miles southwest of Grand Rapids, Minnesota. Deer Lake has a very small watershed relative to the lake area, whereas Pokegama Lake represents lakes with large hydraulic connections to surface waters (the Mississippi River).

Pokegama and Deer lakes are among Itasca County's most populated lakes, with approximately 1,383 taxable land parcels on Pokegama's 49.6 miles of shoreline and 526 on Deer's 20.3 miles of shoreline. Based on the Itasca County assessor's recent tax records, Deer Lake properties are assessed $1,145,986 in yearly property taxes with assessed shoreline values estimated to be $136,744,300. Pokegama Lake is by far Itasca County's most valued lake in terms of total taxes assessed, with annual tax revenues at $3,899,140 and assessed shoreline values of $454,988,700.

In addition to their highly valued shorelines, Deer and Pokegama Lake attract vacationers from far and wide and are both top tourist destinations every summer. There is no question about the significance of these two bodies of water to the state and county and the need to protect their water quality and in doing so their economic value.

The Deer-Pokegama Clean Water Partnership has been an important management step in the future sustainability of these highly valued recreational lakes. Given their size and significance, the completed diagnostic study of these two lakes could serve as a replicable model of non-point source pollution control for other lakes around the region and state.

Why the Project Took Place

In spite of the major economic and recreational roles played by Pokegama and Deer lakes, data availability and understanding of sources of risks to their water quality were previously lacking. The MPCA listed the availability and quality of basic monitoring data for these lakes as poor. Pokegama was listed as fully supporting designated uses by virtue of the fact that data were insufficient to indicate otherwise. Deer Lake was indicated as partially meeting designated uses, because there were too few data, or the quality was too close to water quality thresholds to determine whether or not it was impaired. Tributary data were likewise sparse, and the importance of groundwater inflow and atmospheric deposition was unknown. Both Deer and Pokegama lakes were addressed in the Itasca County Local Water Management Plan, which was updated in April 2012, but information was limited. Both lakes had, however, been ranked based on their trophic status. Deer Lake was 3rd, and Pokegama Lake was 29th in trophic status out of a 100 lakes ranked in Itasca County.

Although no major trends in water quality had been scientifically documented in Pokegama or Deer lakes prior to the CWP study, water monitoring data showed a significant but weak decline in Secchi disk transparency in Pokegama Lake and some periods of decline in Deer Lake. A two-lane causeway, which crosses Pokegama Lake, was rebuilt in 2007 to support State Highway 169. Many area residents had expressed concern about highway storm water run-off from this reconstruction, which was directed to Pokegama as the receiving body. Deer Lake has long been known by visitors and residents as the “lake of changing colors,” an acknowledgment of the blue and violet hues that characterize unproductive lakes, but residents and visitors had begun to express concerns about a changing trend of these colors toward green over the past decade. A bloom of cyanobacteria was recorded on Deer Lake during the summer of 2008, and informal reports of increased benthic and littoral algae in both lakes, a condition that is a known precursor to declining pelagic water quality in clear-water lakes elsewhere, had increased local concerns for the potential decline in the water quality of these two highly valued lakes.

Who was Involved in Carrying Out the Project

Itasca County – The Itasca County Board of Commissioners agreed to assume the role of project sponsor as a means to improve and protect Deer and Pokegama lakes. In addition, the Itasca County Surveying and Mapping Department provided GIS mapping assistance. The county also provided administrative services to help prepare the final report.

Itasca County Soil and Water Conservation District (ICSWCD) – ICSWCD administered the project budget and worked closely with MPCA Project Manager Phil Votruba on contract management and reporting. Noel Griese worked with volunteer Dr. John Downing on the project workplan and budget and collaborated with Dr. Downing and volunteer Dr. Jack Jones to oversee the year-round collection and analysis of water samples from Pokegama and Deer lakes. Volunteer coordination and training was also a primary role required to keep good communication with monitoring partners to ensure quality control of sample collection. ICSWCD staff provided necessary technical and field oversight throughout the project to ensure equipment was properly installed, maintained, and functioning. Staff were also directly involved with monitoring lakes, stream flows, shallow monitoring wells, and private deep groundwater wells.

Itasca Community College (ICC) – ICC is the certified laboratory (Minnesota Department of Health) that was responsible for analyzing project samples. ICC lab staff and interns were responsible for monitoring the lakes, streams, and shallow groundwater sites. ICC Lab Manager Eric Ahlstrom oversaw ICC interns to accomplish field monitoring, while ICC Chemist Randy Hedin oversaw the students in the lab along with lab protocols.

Itasca Water Legacy Partnership (IWLP) – One of IWLP's primary roles in the project was public relations. IWLP assisted with volunteer recruitment and public education/awareness for the project.

Deer Lake Association (DLA) and Greater Pokegama Lake Association (GPLA) – The DLA and GPLA assisted with the education, recruitment, and coordination of volunteers and monitoring activities. Each lake association had a volunteer coordinator(s) (DLA – Janna Nemeth and GPLA – Don St. Aubin, Jan Sandberg, and Randy McCarty) who communicated closely with the ICSWCD to enlist and train volunteers, get landowner access permission, and coordinate monitoring efforts. Lake association volunteers were primarily involved with monitoring stream stage, precipitation, shallow groundwater inflow, and provided access to their drinking wells for studying the deep groundwater aquifer.

Dr. John Downing and Dr. Jack Jones – Dr. John Downing and Dr. Jack Jones were the volunteer scientists for the study and provided technical oversight of the project and were responsible for running selected models and completing necessary reporting of project findings. They did this work on a completely voluntary basis. Dr. Downing collaborated with Noel Griese to develop the project workplan and budget.

Dr. Bill Simpkins and Grad Student Jake Smokovitz – Dr. Simpkins and Jake Smokovitz researched the groundwater flow and nutrient flux for Deer and Pokegama lakes from 2011-12 and utilized a 2-D groundwater flow model to estimate the role of groundwater in the two lakes. Dr. Simpkins worked on a completely voluntary basis on this project.

Minnesota Pollution Control Agency (MPCA) – MPCA Project Manager Phil Votruba provided oversight of the project budget, workplan, and reports and worked closely with the ICSWCD to make adjustments where needed. MPCA field staff (Mark Evenson, Rhonda Adkins, and Paul Schreiber) provided equipment and aided in monitoring the outlet of Pokegama Lake because of its complexity as a reservoir of the Mississippi River.

Additional contributors included:

Daniel Kendall
Limnologist/Aquatic Biologist
Iowa State University

Amber Erickson
Laboratory Analyst II
Des Moines Metropolitan Wastewater Reclamation Authority

Anthony Thorpe
Coordinator
Lakes of Missouri Volunteer Program

Benjamin Lakish

Minnesota Power

Dr. Alan Wanamaker
Assistant Professor
Department of Geological and Atmospheric Sciences

Alexander Morrison
Graduate Research Assistant
Department of Geological and Atmospheric Sciences

Nicole Neira, Kevin Shrumm, Bekah Burket, and Bianca Bello

Joey LeBlanc
Civil Engineering Tech
Natural Resources Conservation Service

DIAGNOSTIC STUDY

METHODS

Water Quality Monitoring

Field Methods

Sampling took place for two years in order to capture the full annual budget of the sources of nutrients in each lake to avoid biasing results by a single particular water-year. Samples of lake water were collected monthly, and major tributary flows were collected biweekly during the ice-free period. During the winter months, the lakes continued to be sampled except when the ice was unsafe. Sampling of the streams during the winter months was once a month and only occurred on tributaries that were not frozen solid. On each sampling occasion, samples were taken at six in-lake sites per lake, 12 known tributaries on Deer, 21 tributaries on Pokegama, and at both lakes' outfall (See Figures 1 and 2). When possible, lake sampling sites were coordinated with established sites used historically by other organizations. Site selection focused on capturing differences among bathymetrically distinct sub-basins. Preliminary stream monitoring sites and groundwater sites were estimated through GIS analysis, and then those sites were verified in the field. Three of the sites on Pokegama (sites 10, 18, and 19) were not used. Site 10 was problematic due to its proximity to the lake, which created issues with back flow, and sites 18 and 19 were anticipated ephemeral sites that had limited to no flow during most of the monitoring period.

Deer and Pokegama lakes were monitored for physical and chemical constituents (dissolved oxygen, turbidity, specific conductance, field pH, and temperature). Profiles were measured *in situ* using YSI 650 handhelds and 6920V2 sondes, which were set to take continuous measurements as the sonde was lowered at a rate of 1 meter per 15 seconds. Dissolved oxygen temp profiles were the first thing measured at each site in order to determine sampling depths and presence of a thermocline. In order to estimate lake water column distributions of constituents, samples were collected at three depths/site: an integrated mixed zone sample (0-2 meters), a metalimnetic sample (depth of thermocline), and representative hypolimnetic samples (based on lake hypsographic curve). Mixed zone samples were collected with a 2-meter integrated water-column sampler, and both the metalimnetic and hypolimnetic sample were collected with a Kemmerer sampler. If no thermocline was present, the metalimnetic sample was taken at 10 meters, and the hypolimnetic sample was taken at 20 meters or 1-2 meters off the bottom at sites shallower than 20 meters. Field sheets along with digital photos were recorded to document daily conditions. A Kestrel 2500 anemometer was used to measure wind speed, air temperature, and barometric pressure (Casper et al., 2000), and water transparency was measured in the field through the aid of a Secchi disk (Wetzel and Likens, 2000).

For most sites, the tributaries were small enough for the field technician to reach to the thalweg (middle of the channel) while standing on shore to collect the water sample. At the outflow of Pokegama, samples were taken from the bridge using the Kemmerer. Tributaries were also monitored with the YSI 6920V2 sonde and data recorded with the 650 handheld and on field sheets for each event. Sonde data were generally not taken if the tributary was not deep enough to fully submerge the sonde. Multiple discharge measurements were collected for each stream monitoring site to establish discharge rating curves in order to calculate flux and nutrient loads for each drainage basin. Most discharges were measured with a wading rod and an AquaCalc Pro coupled with a pygmy meter. A Marsh-McBirney Flo-Mate 2000 was utilized to collect low flow discharge data. ICC and the ICSWCD collected discharge measurements during most monitoring events and collected them more frequently during spring snowmelt and large storm events. Stream stage heights were read throughout the ice-free period by volunteers and field staff (Figure 3). Stage heights were measured and recorded either by staff gauge (US standard aluminum gauge) or by measuring from the culvert down to the water surface (culvert top dead center marked) with a standard tape measure. Volunteers recorded stream stage weekly and during significant rain events daily to capture the rising and falling limb of the hydrograph for the storm event. HOBO U20 water level loggers (Figures 4 and 5) were installed on a limited number of larger stream sites and the stormwater discharge pond on Pokegama to collect stream stage data at 3-5 minute intervals. Pokegama Lake had Hobo data loggers installed at sites 2, 3, 9, 10, 11, and 20, and Deer Lake had the loggers installed at sites 1, 2, and 3. Loggers were downloaded during each monitoring event.

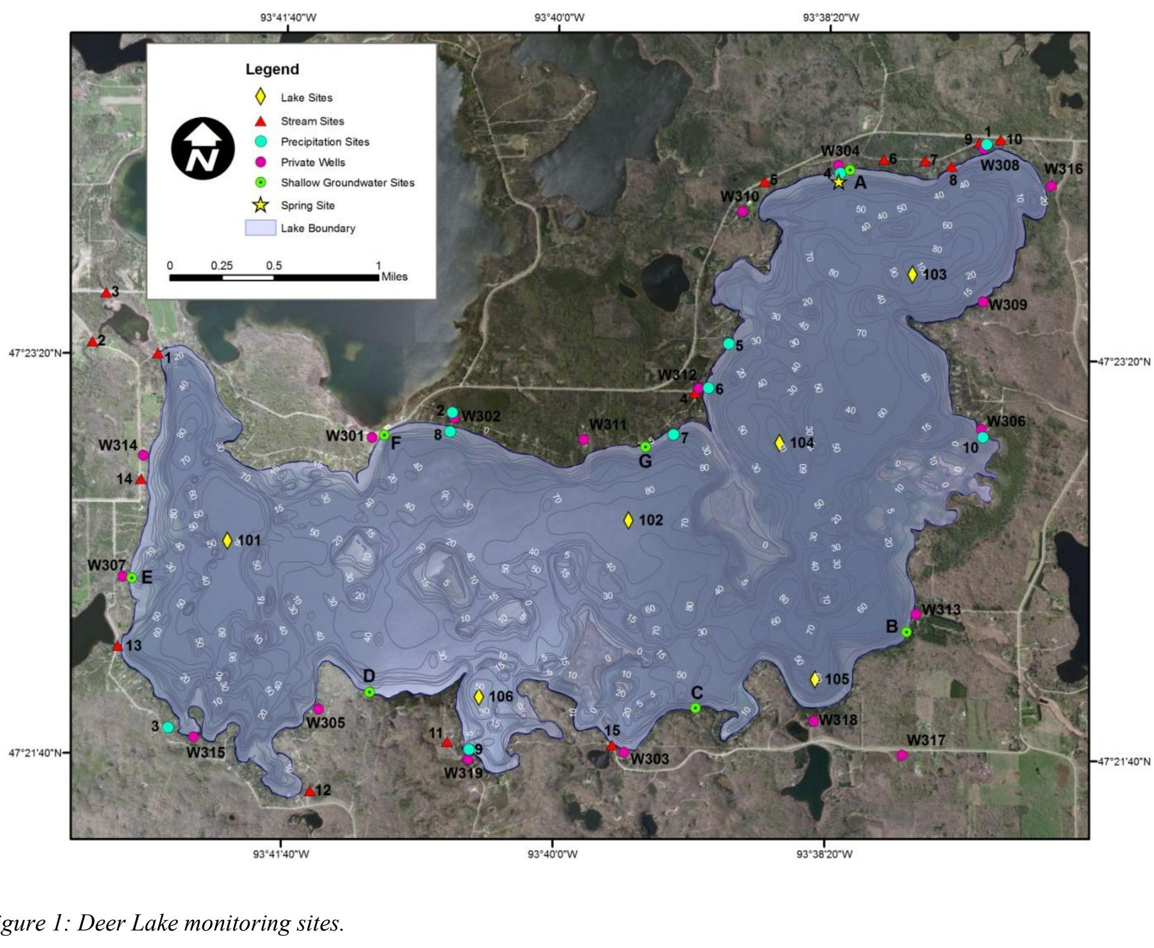


Figure 1: Deer Lake monitoring sites.

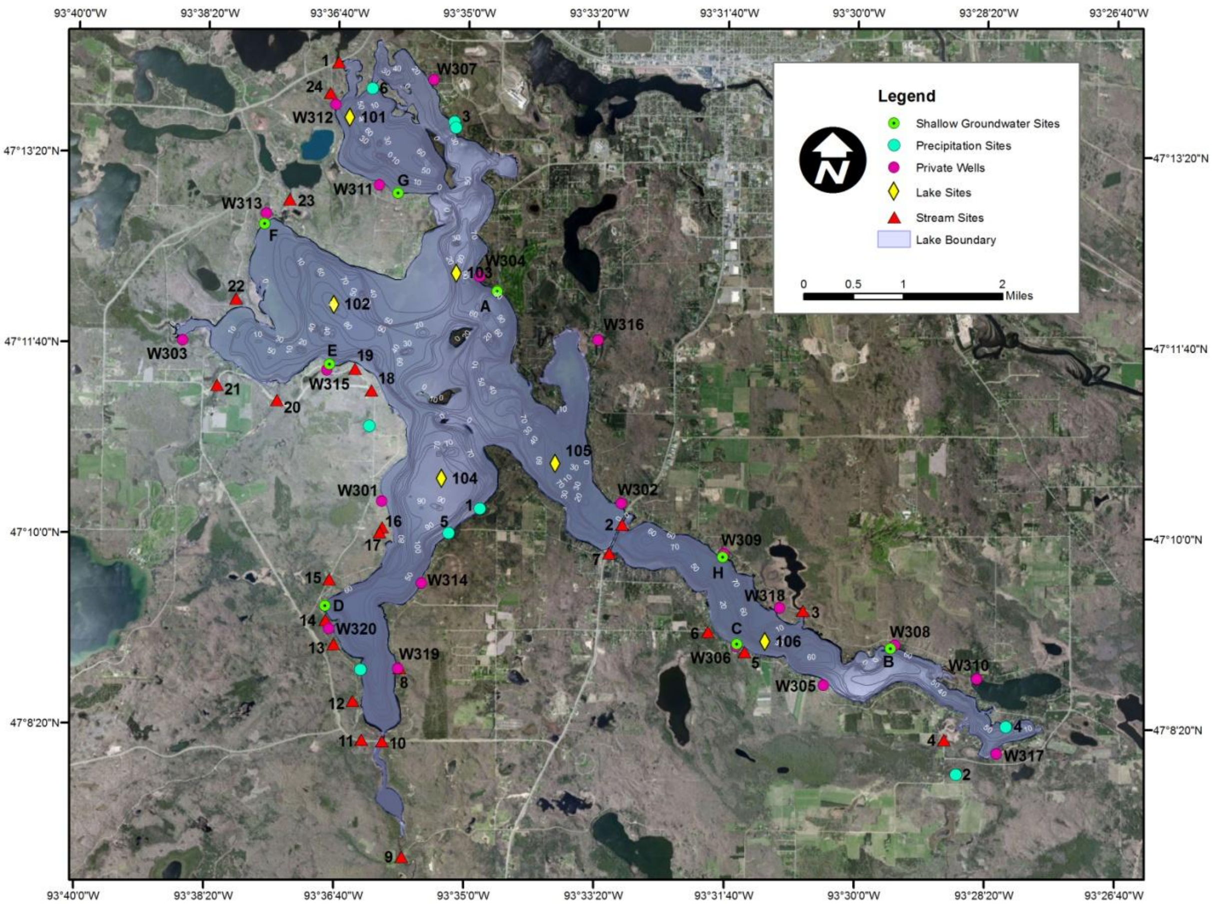


Figure 2: Pokegama Lake monitoring sites.

Figure 3: DLA volunteers measuring stream stage and discharge.

Figure 5: Air-pressure-compensated Hobo data logger

Figure 4: Stream-stage Hobo data logger.

Laboratory Methods

Laboratory methods followed those outlined in the project work plan and QAPP. Analytical methods used by the ICC Water Quality Laboratory (ICCWQL) and Pace Analytical Services, Inc. (formerly Northeast Technical Services, Inc.), are summarized in Tables 1 and 2.

Although specific analytical methods used by ICCWQL did not change, there were modifications in equipment and one methodological update. Details specific to ICCWQL are described for each method referenced in Table 1. Chlorophyll *a* samples were analyzed by non-acidified fluorometry following EPA method 445.0. Lake samples were filtered through a 1.0 μm glass fiber filter, extracted in acetone with a probe sonicator (Jeffrey et al., 1997) and measured on a Turner Trilogy 7200 fluorometer using the non-acidified module (7200-046). Total phosphorus (TP) samples were analyzed with an Evolution 300 spectrophotometer using the ascorbic acid method after persulfate digestion. All analyses through September 2012 were corrected for background turbidity using a 3-point drop correction. Samples after that date were analyzed using the same method, but the background turbidity drop correction was no longer performed because it was not needed. Before the analytical method was changed, samples were analyzed with and without the background turbidity correction, and it was found that there was no significant difference in the measured TP values ($p > 0.05$). Soluble reactive phosphorus (SRP) samples were analyzed with an Evolution 300 Spectrophotometer using the ascorbic acid method. All SRP samples were corrected for background turbidity using a 3-point drop correction. Total nitrogen (TN) samples were analyzed with an Agilent 8453 spectrophotometer using the second derivative ultraviolet spectroscopy method after persulfate digestion. True color samples were analyzed with an Evolution 300 spectrophotometer using the method described by NCASI Technical Bulletin 253. Chloride samples were analyzed with an Orion 4 Star pH-ISE meter and Orion ion selective electrode (9617BNWP). Total alkalinity samples were analyzed with an Orion EA940 and 960AC system using a ROSS Sure-Flow combination pH electrode (8172BNWP). Groundwater samples analyzed for ammonia and ammonium N (NHx), total dissolved phosphorus (TDP), and dissolved organic carbon (DOC) were filtered (nylon 0.45 μm) at ICCWQL prior to analyses. Ammonia and ammonium N (NHx) were analyzed with an Evolution 300 spectrophotometer using the manual phenate method. TDP samples were analyzed following the TP methods. DOC samples were analyzed at the U.S. Forest Service laboratory. Total suspended solids (TSS), total volatile suspended solids (TSVS), and total suspended inorganic solids (TSIS) were collected on a GF/C filter (nominal 1.2 μm), dried at 105 ºC and combusted at 550 ºC. Filters were dried and combusted prior to sample filtration. Filter weights were measured on a Denver P-114 analytical balance.

Parameter	Preservative	Holding Time	Analytical Method
Chlorophyll-a			
Raw sample	Dark, Cool to 4°C	36 hours	EPA 445.0 (Arar and Collins 1997)
Filtered sample	Dark, frozen at -20°C	28 days	
Total Phosphorus	Cool to 4°C	36 hours	SM 4500-P E (APHA, 1998)
	H_2SO_4 to pH2, Cool to 4°C	28 days	
Soluble Reactive Phosphorus	Cool to 4°C	24 hours	SM 4500-P E (APHA, 1998)
Total Nitrogen	Cool to 4°C	36 hours	Crumpton, et al. (1992)
True Color	Cool to 4°C	48 hours	NCASI Tech. Bulletin 253 (1971)
Chloride	Cool to 4°C	28 days	ASTM D512-89(99) Method C
Total Alkalinity	Cool to 4°C	36 hours	SM 2320.B (APHA, 1998)
Ammonia + Ammonium Nitrogen	Cool to 4°C	36 hours	SM 4500-NH_3 F (APHA, 1998)
Total Suspended Solids	Cool to 4°C	7 days	SM 2540 D (APHA, 1998)
Total Suspended Volatile Solids	Cool to 4°C	7 days	EPA 160.4
Total Suspended Inorganic Solids	Cool to 4°C	7 days	EPA 160.4

Table 1: ICCWQL's analytical parameters and methods.

Parameter	Preservative	Holding Time	Analytical Method
Nitrate + Nitrite Nitrogen	H_2SO_4 to pH2, Cool to 4°C	28 days	EPA 353.2 Rev 2.0
Total Suspended Solids	Cool to 4°C	7 days	USGS I-3765-85
Total Suspended Volatile Solids	Cool to 4°C	7 days	USGS I-3765-85
Total Organic Carbon	H_2SO_4 to pH2, Cool to 4°C	28 days	SM 5310 C-00
Total Alkalinity	None	14 days	SM 2320 B-97
Silica	HNO_3 to pH2, Cool to 4°C	6 months	EPA 200.7

Table 2: Pace Analytical Services' analytical parameters and methods.

Bathymetry and Hypsometry Methods

Bathymetric maps for Deer and Pokegama lakes were obtained from the Minnesota Lake Finder site (http://www.dnr.state.mn.us/lakefind/index.html) of the Minnesota DNR (Figures 6 and 7). Maps were georeferenced and digitized in ArcGIS, and the areas of each depth contour interval were determined. Areas and depth contours thus obtained were used to construct hypsographic tables and curves (Table 3 and Figure 8). The hypsographic curves show that Deer Lake has a gradual shore slope, whereas Pokegama has a more extensive shallow area, but similar maximum depth. These data were used to calculate day-to-day changes in water storage in the lakes from water levels measured at the outfalls, hypolimnetic volumes for hypolimnetic oxygen depletion estimates, and for weighting lake nutrient content estimates.

		Deer Lake		Pokegama	
Z (ft)	Z (m)	Percent Below Z	Area at this depth (m2)	Percent Below Z	Area at this depth (m2)
0	0.0	100.00	16527590	100.00	27721802
5	1.5	89.34	14765155	68.75	19057553
10	3.0	82.69	13667411	45.13	12511317
15	4.6	78.04	12897885	44.86	12435844
20	6.1	73.34	12121663	38.71	10731057
30	9.1	66.03	10912710	33.07	9168958
40	12.2	54.14	8947806	26.25	7278139
50	15.2	40.10	6626783	19.16	5311022
60	18.3	25.67	4242269	10.47	2902721
70	21.3	15.22	2515660	6.66	1846863
80	24.4	7.65	1263650	4.58	1269844
90	27.4	2.62	433839	0.03	6998
100	30.5	0.06	9189	0.00	666
110	33.5	0.00	0	0.00	0

Table 3: Hypsographic (depth-area) data for Deer and Pokegama lakes.

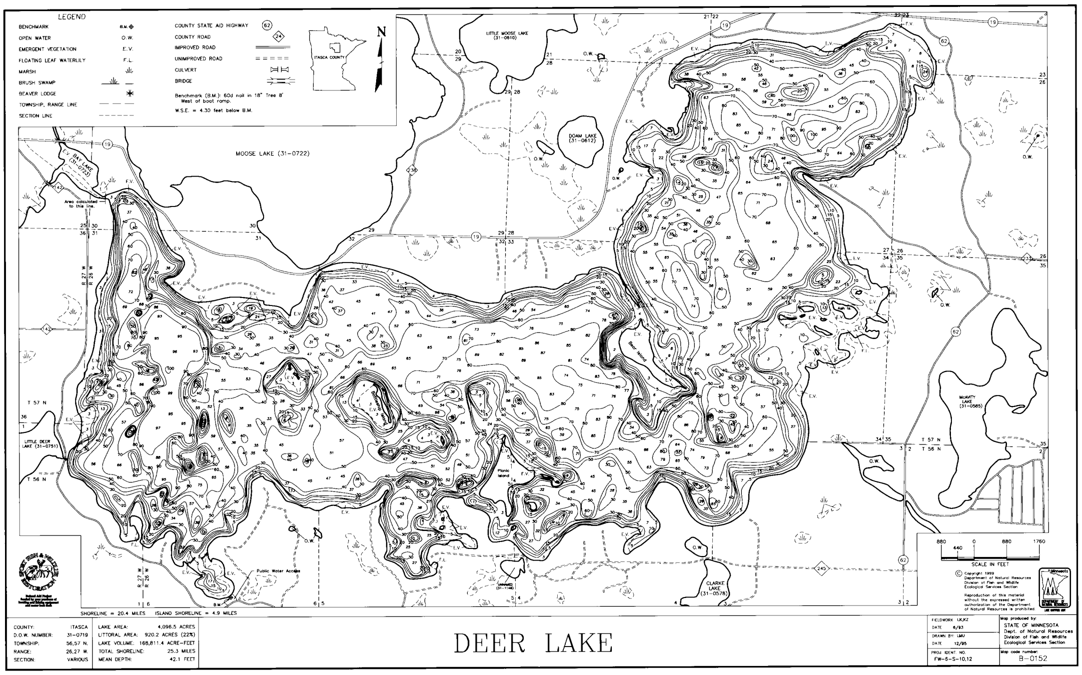


Figure 6: Minnesota DNR bathymetric map of Deer Lake.

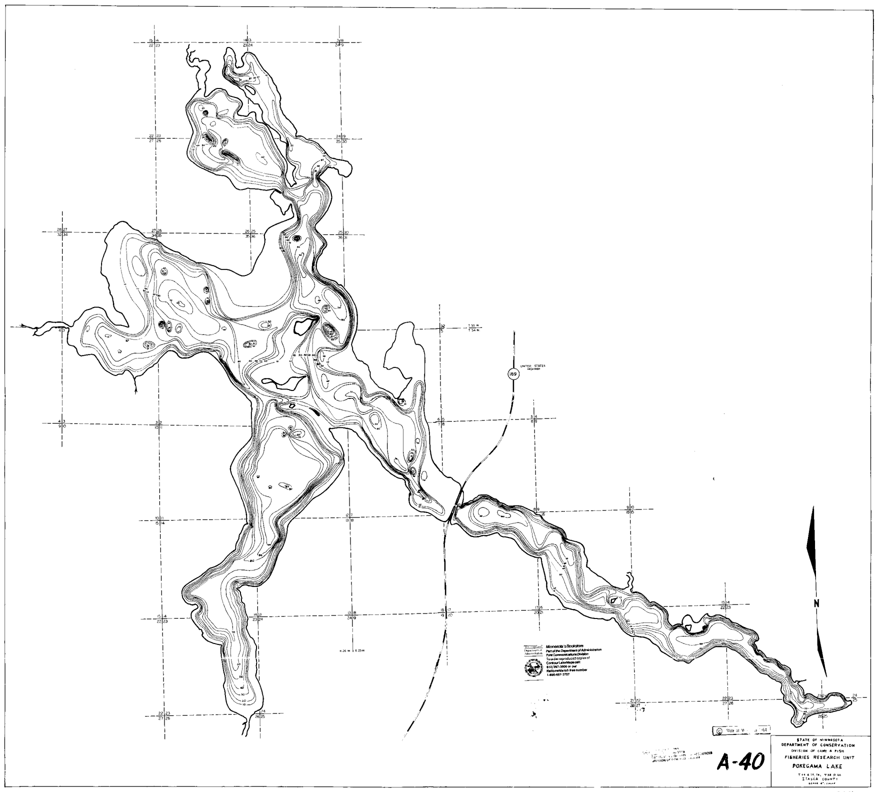


Figure 7: Minnesota DNR bathymetric map of Pokegama Lake.

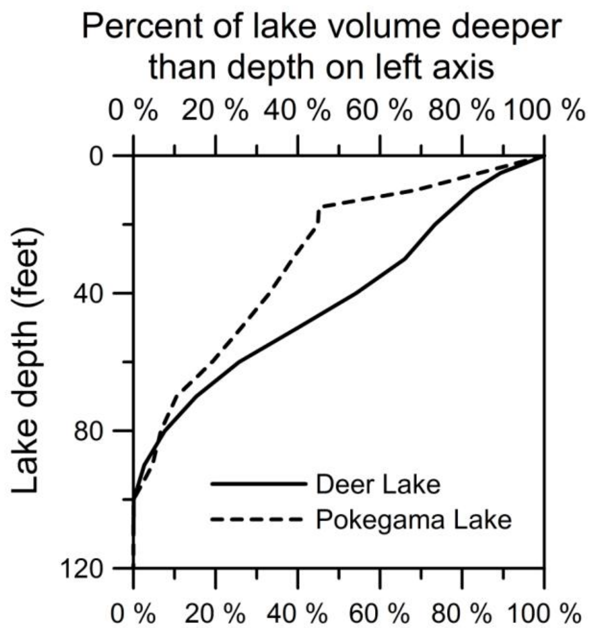


Figure 8: Hypsographic curves for Deer and Pokegama lakes estimated from Minnesota DNR's bathymetric maps.

Rainfall Collection Methods

Precipitation during the first year of the study was monitored using three wet-dry deposition samplers (Figure 9) to collect rainfall chemistry in each watershed, and ten bulk precipitation samplers (Figure 10) were placed on floating platforms for volunteers to measure rainfall amounts (Anderson and Downing, 2006; Blake and Downing, 2009). Samplers were placed at the end of docks in areas away from tree canopies. During the second year of the study, project staff determined the need to switch to Stratus rain gauges (Figure 11), which are manufactured to United States Weather Bureau specifications and used throughout the country by official weather observers for accurate weather reporting. This change was made to reduce the possibility for sample contamination and to increase ease of use for volunteers. The gauges were placed in open areas near volunteer homes that were devoid of tree canopy and were measured immediately after rainfall events. Gauges for monitoring rainfall chemistry were constructed from the Stratus rain gauges. ICC prepped 125ml sample bottles that were placed within the rain gauge with a protective cap over the gauge (Figure 12). At the start of a rainfall event, the volunteer would remove the cap to begin sample collection and removed the sample once the bottle was full or the rainfall event was completed. Samples were then labeled, frozen, and picked up by the ICCWQL to be analyzed for total phosphorus and total nitrogen. Samples with visible contamination were not used in calculations, nor were samples with abnormally high phosphorus values.

Figure 9: Ben Lakish (ICC Lab) and a wet-dry deposition sampler.

Figure 10: Bulk precipitation sampler.

Figure 11: US Weather Bureau Stratus rain gauge.

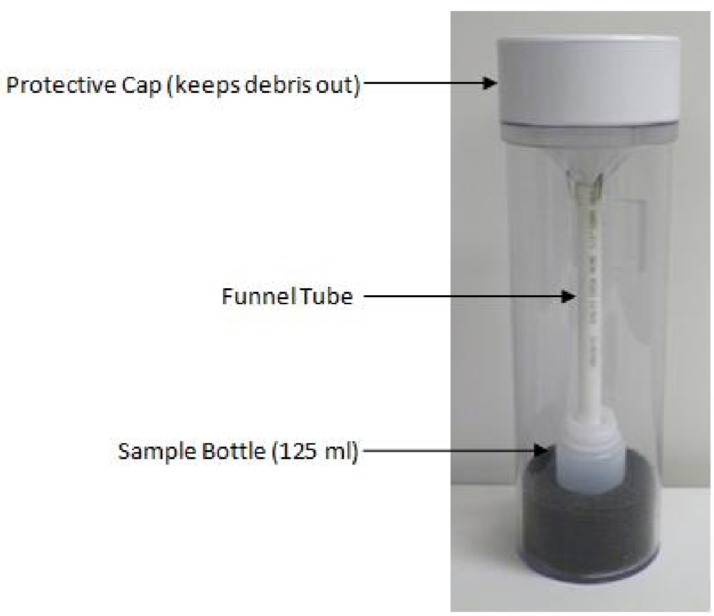


Figure 12: Modified Stratus rain gauge for chemistry analysis.

GIS and Watershed Assessment Methods

The use of geographic information systems (GIS) was utilized to provide a means of delineating watershed boundaries and assessing the land use/vegetation configuration, slope and soil hydrologic groups, and their potential influence on water quality in these lakes. Data sources included the Minnesota DNR Data Deli (http://deli.dnr.state.mn.us), the Multi-Resolution Land Characterization (MRLC) consortium (http://www.mrlc.gov/finddata.php), Minnesota Geographic Data Clearinghouse (MGDC) (http://www.mngeo.state.mn.us/chouse/data.html), the USDA-NRCS Soils Data Mart (http://soildatamart.nrcs.usda.gov/), and local GIS sources including Itasca County (http://207.171.101.128/website/Itasca_Internet/viewer.htm). Data included, but was not limited to, the boundaries of lakes, watersheds at different hydrologic unit code resolution, stream/flow networks, parcel ownership boundaries, and roadways. Raster datasets included landuse/landcover, aerial photography, digital elevation maps (DEMs), lake bathymetric maps, soil maps, and slopes derived from the DEMs. Data sets of monitoring sites were also created for the project through the aid of ArcGIS and handheld Garmin 76csx units.

Lake watersheds were downloaded from the DNR data deli and overlain on 1:24k USGS topographic maps and aerial photography to delineate drainage areas for each stream subwatershed based on contour analysis. Subwatersheds were then overlain onto the National Land Cover Database 2006 (NLCD2006), a 16-class, 30-meter spatial resolution land cover classification scheme, to characterize the land uses and impervious surfaces within both watersheds. The Itasca County Surveying and Mapping Department also assisted with estimating the number of septic systems within each drainage area along with information on whether the system was used by a permanent or seasonal residence in order to estimate days each system is used annually. This was achieved by overlaying the county's parcel ownership layer with the subwatershed layer.

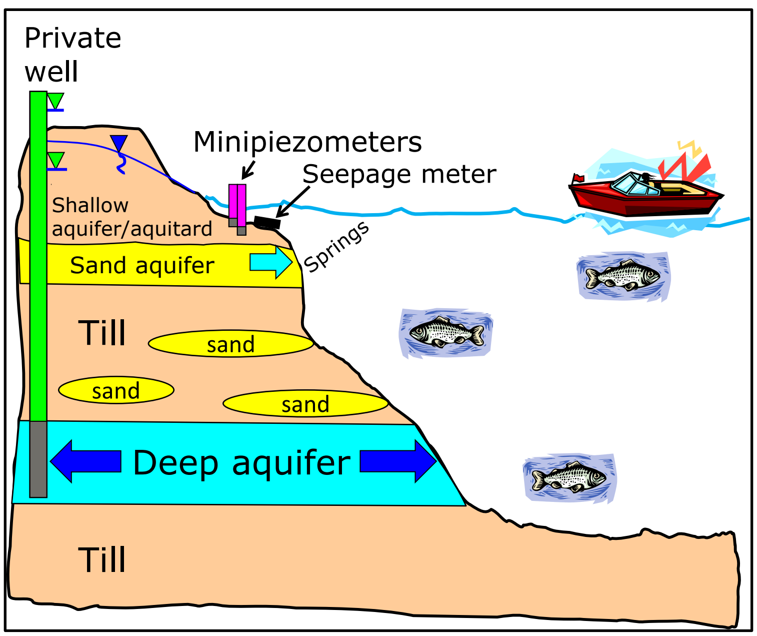
Groundwater Analysis

Conceptual Model of Hydrogeology and Groundwater Flow

Because deep monitoring wells were not installed specifically for this project, it was necessary to rely on previously published studies (Winter, 1973; Jones, 2004; Jones, 2007) and well logs obtained from the Minnesota County Well Index. The index is maintained by the Minnesota Department of Health and the Minnesota Geological Survey (http://mdh-agua.health.state.mn.us/cwi/cwiViewer.htm), and in combination with the previous studies, made is possible to assess the hydrogeologic setting of the study area. The major aquifers used for drinking water in the Grand Rapids area occur in the glacial sand and gravel units (glaciofluvial aquifers) and the Biwabik Iron Formation, where yields can approach 3875 L/m (1000 gpm) and 1938 L/m (500 gpm), respectively. As many as three subsurface glaciofluvial aquifers have been identified that span depths from the surface to greater than 61 m (200 ft), with the upper and middle aquifers the most continuous regionally and reaching thicknesses of 15.2 to 33 m (50 to 100 ft) thick, particularly in buried bedrock valleys (Oakes, 1970; Winter, 1973; Jones, 2004).

The well logs examined in this study varied somewhat in the quality of geologic description, however, Benes Well Drilling, Inc., installs most of the wells in the region, and their geologic descriptions are fairly detailed and consistent. Although many well logs from private wells were examined, at least 20 from the Deer Lake area and 19 from the Pokegama Lake area proved useful for assessing the geology. Some of those wells were also used for water-level measurement and geochemical sampling. Well logs showed that most private wells are completed at depths of 12 to 35 m (40 to 115 ft) in sand and gravel units and are located a few to several meters from their respective lake; hence, a hydraulic connection was assumed between the lake and the groundwater in the aquifer tapped by the well. Two domestic wells were finished in the Precambrian slate at depths of about 69 m (225 ft) near Pokegama Lake, however, wells drilled to those depths appear to be an exception near the lakes.

Based on the cross sections constructed for this investigation, a simplified conceptual model of groundwater interaction with the lakes was developed (Figure 13). It was assumed that the shallow-water-table aquifer is in direct communication with the lakes at the shoreline and that groundwater discharge from that aquifer can be quantified using seepage meters installed in the nearshore area. Minipiezometers there also provided information on the direction and magnitude of the hydraulic gradient. Springs showing higher discharge (see later section) likely develop where sand units intersect the lake at shallow depth (depicted by the shallow sand aquifer and other sand units in Figure 13). It was then assumed that a second groundwater contribution to the lakes originated from a single Deep aquifer (Figure 13) that is likely equivalent to the middle and/or lower aquifer of Jones (2004). Discharge from this aquifer was estimated using Darcy's Law (Simpkins, 2006). Although it was assumed that groundwater from this aquifer discharges



Shallow water-table (unconfined) aquifers/aquitards discharge to the shoreline areas where flow is monitored by seepage meters and minipiezometers. Shallow confined aquifers intersecting the shoreline may produce large groundwater discharge and springs. Deeper confined aquifers may provide discharge groundwater to the lake and/or allow lake water to move into the aquifer.

Figure 13: Conceptual model of groundwater interaction with the lakes.

to the lakes, the lakes could also recharge groundwater. Stable isotope (δ^{18}O and δ^{2}H) and radioactive isotope (^{3}H) analyses of groundwater in the Deep aquifer were used to elucidate recharge/discharge relationships and flow paths, as well as to estimate groundwater age and travel times. The Deep aquifer is important not only because it provides an additional source of water not measured by the seepage meters, but because it may provide a means of connecting the hydrology of the lakes in the region.

Calculation of Discharge from Shallow Groundwater

Discharge of shallow groundwater to nearshore areas was estimated using standard seepage meters and minipiezometers. The literature on use and deployment of these devices for this purpose is voluminous, and the reader is referred to the summary by LaBaugh and Rosenberry (2011) for further information on their use in lakes. Minipiezometers (Figure 14) consisted of a Solinst 615 drive point attached to 1.2 m (4 ft) of 2.54 cm (1 inch) diameter cast-iron pipe containing 1.5 m (5 ft) of 1.6 cm (5/8 inch)-ID polyethylene tubing connected to a hose-barb on the drive point. They were installed with a fencepost driver at two depths at each site to estimate the vertical hydraulic gradient and direction of groundwater flow. Each minipiezometer was installed at least 15.2 cm (0.5 ft) below lake sediment, was separated in depth by at least 20.3 cm (8 in), and was driven no more than 61 cm (2 ft) into the lake bed. Water-level measurements in the minipiezometers were made using a Solinst 102M, coaxial electric water-level tape to ± 0.3 cm (0.01 ft).

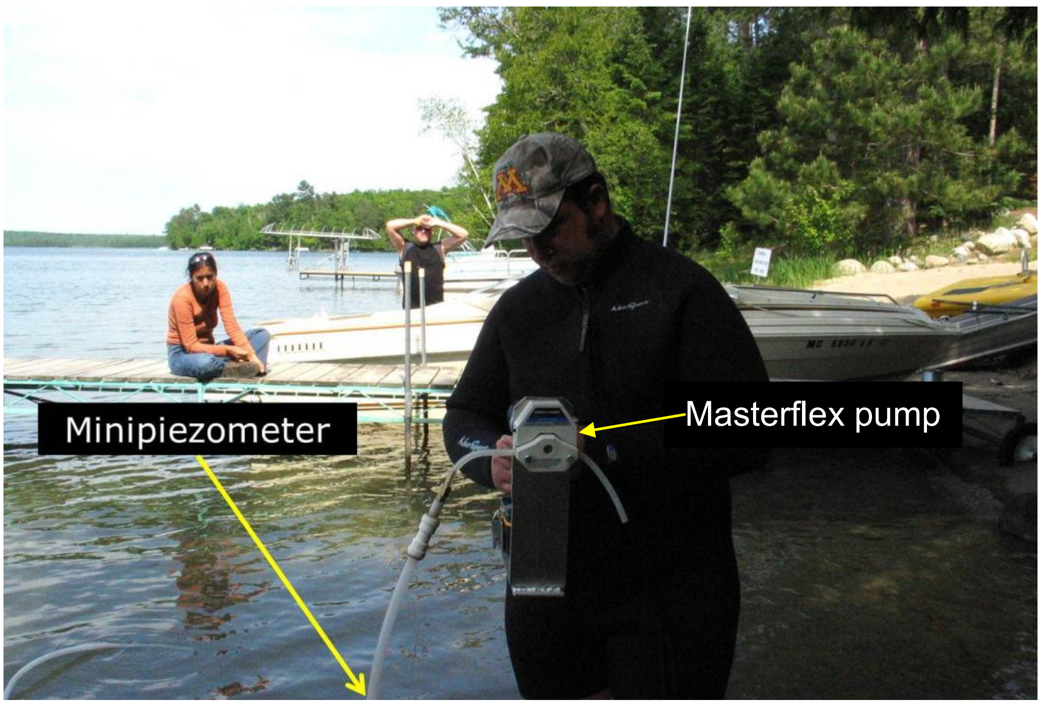


Figure 14: Using Masterflex pump to collect groundwater sample from minipiezometer.

Seepage meters were installed in sets of 6 (2011) and 4 (2012) at seven sites on Deer Lake labeled A-G (Figure 15). At Pokegama Lake, meters were installed in sets of 6 (2011) and 4 (2012) at six sites in 2011 and seven sites in 2012 (Figures 16 and 17), which are representative of Zones A, B, C, D, F, G, and H. Site E was planned, but never established due to access issues. In 2012, Pokegama Site C was moved 303 m (1000 ft) to the southeast due to a landowner request. Site G was added in 2012, and the zones associated with Sites A, F, and H were adjusted slightly to accommodate the addition.

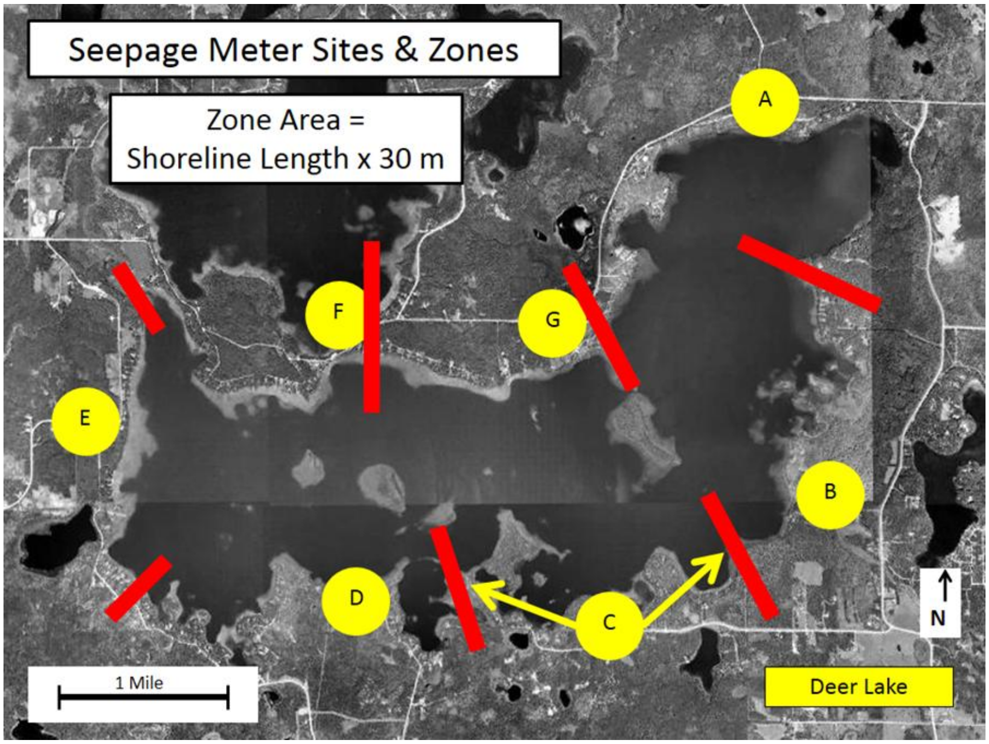


Figure 15: Location of seepage meter/minipiezometer monitoring sites and seepage zones on Deer Lake.

Zone boundaries are indicated by the red vertical bars. Site location was based on geology and landowner access within the zone. Each meter site was used for calculation of a groundwater discharge for the zone that it represents.

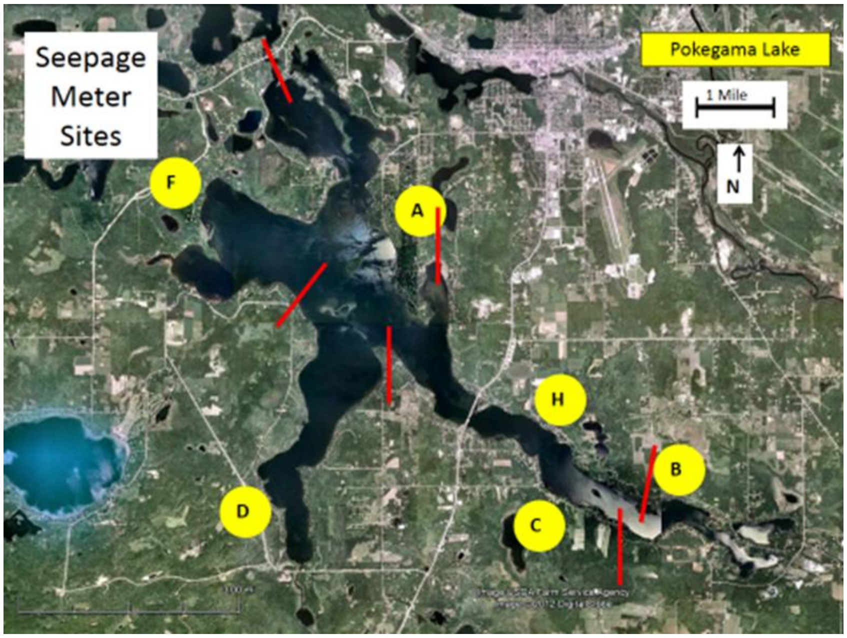


Figure 16: Location of seepage meter/minipiezometer monitoring sites and seepage zones on Pokegama Lake in 2011.

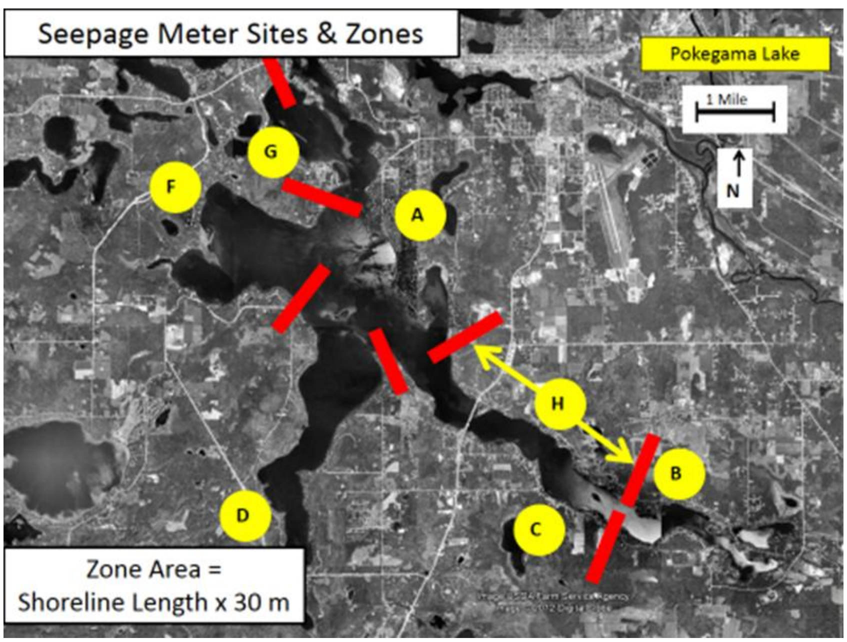


Figure 17: Location of seepage meter/minipiezometer monitoring sites and seepage zones on Pokegama Lake in 2012.

Zone boundaries are indicated by the red vertical bars. Site G was added in 2012. Site location was based on geology and landowner access within the zone. Each meter site was used for calculation of a groundwater discharge for the zone it represents.

Seepage meters were constructed (Figure 18) using the top 25 cm (10 in) of a steel 208.2 L (55 gal) storage drum. The main opening was closed and a 1.9 cm (¾ inch) pipe thread elbow (male) wrapped in Teflon tape was threaded into the vent port. The meters were installed (Figure 19) in groups of two, side-by-side between 5 to 20 m from shore in knee- to waist-deep water, depending on aquatic vegetation and presence of lake-bottom obstructions. Each meter was installed about 20 cm (8 in) into the lakebed and allowed to equilibrate for 24 hours. At this point, the seepage meter design departed from standard construction (Figure 20).

Figure 18: Students from Grand Rapids High School constructing seepage meters.

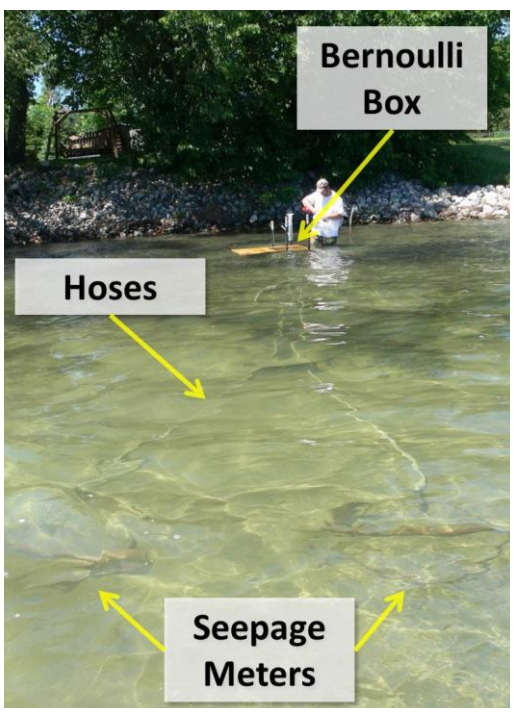


Figure 19: Shallow groundwater seepage meter site.

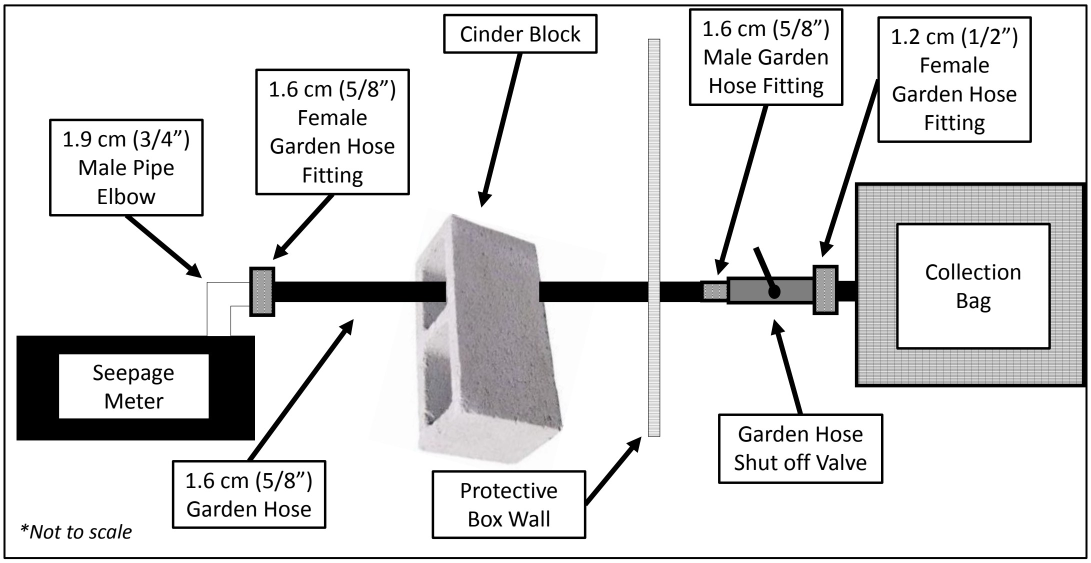


Figure 20: Schematic diagram showing seepage meter (left side) hoses to the seepage collection bag housed inside a protective box.

Instead of attaching a seepage collection bag directly to the seepage meter outlet, a 1.6-cm-diameter (5/8 inch) garden hose (mean length ~4.5 m long) with standard garden hose connections was attached to each seepage meter on one end (through a cement cinderblock to prevent the hose from floating) and to a large box housing the collector bag on the other end. Protection of the collector bags was employed in July 2011 to shield the bags from Bernoulli effects (Cable et al., 2006; Simpkins, 2006). Measurements made before July 2011 demonstrated much greater variability than post-shielding data, and the data were omitted from the analysis. The box-end of the hose consisted of a male garden hose connection, followed by a common garden hose shut-off valve, and attached to the seepage collector bag fitted with a 1.2 cm (½ inch) female garden hose connection. Seepage collector bags, consisting of Void-Fill™ 15-L capacity 45.7 x 45.7 cm (18 x 18 inch) polyethylene bags (VF1818), were filled with 1L of water prior to emplacement. The fill neck of the bag was removed and a 1.25 cm (½ inch) female garden hose adapter was inserted into the bag port and secured with two zip-ties. The seepage collector bags attached to the valve inside the box and were positioned to ensure unobstructed flow into and/or out of the bag when the box lids were shut. The valves were opened from the outside of the box (Deer Lake) or just prior to the lid closing (Pokegama Lake).

Boxes for the seepage collector bags at the two lakes differed in their construction. On Deer Lake, boxes (Figure 21) were constructed using 2 cm (¾ inch) Oriented Strand Board (OSB) plywood with a 5 x 5 cm (2 x 2 inch) interior frame and outside dimensions of 60.9 H x 60.9 W x 91.4 cm L (24 x 24 x 36 inch). Two 7.6 cm (3 inch) door hinges and two 7.6 cm (3 inch) latches secured the plywood lid. Six 5 cm (2 inch) holes were drilled in the side of the box to allow hose entry. The boxes were buoyant, so four to six basketball-sized rocks were placed at the bottom. The boxes were submerged and secured to four 1.5 m (5 ft) steel T-posts using eight 6.4 x 12.7 x 1.2 cm (2.5 x 5 x ½ inch) U-bolts. At Pokegama Lake, the box (Figure 22) consisted of a 170.3 L (45 gal) HDPE (Sterilite™) storage tote that was reduced to 38.1 H x 50.8 W x 78.7 L cm (15 x 20 x 31 inches). The top was framed with 5.1 x 15.2 cm (2 x 6 in) pine wood with dimensions of

58.4 x 86.3 cm (23 x 34 in). The lid was constructed of 1.3 cm (½ inch) OSB plywood to fit flush with the frame, fitting inside and attached to the frame with two 7.6 cm (3 inch) door hinges. The lid was locked using a 10.1 cm (4 inch) door hasp. The plastic tote was secured inside the frame with 5 x 10.1 cm (2 x 4 in) pine lumber and wood screws. Eight to ten softball-sized cobbles were placed in the box to keep the box from floating, and a watermelon-sized boulder was placed on the lid to reduce wave/pumping action on the lid. The box was then submerged and secured to four 1.5 m (5 ft) steel T-posts using four 6.4 x 12.7 x 1.2 (2.5 x 5 x ½ inch) U-bolts. Hoses were inserted through six 2.5 cm (1 inch) holes drilled near the bottom of the box.

Figure 21: Deer Lake groundwater collection box.

Figure 22: Pokegama Lake groundwater collection box.

Measurements of flow into the seepage collector bags were made once a week during a one week period (Deer) or once a week during a two-three day period (Pokegama) between approximately June and September. The physical approach to each box and seepage meter area ensured as little sediment and seepage meter disturbance as possible. At this point, protocol dictated that the valves be shut and the box opened. Due to the box construction on Pokegama, the box was opened very slowly, and then the valves were closed. After the valves were closed, the bags were disconnected from the hose, removed from the box, and their water volume measured to the nearest 10 mL in a 1 L graduated cylinder. Raw seepage values were measured in units of m^3/hr and converted to a mean seepage flux in units of cm/day by taking the mean of all positive seepage values at a site and dividing by the cross-sectional area of the seepage meter. A date range was specified and assigned to a period (about one week). A mean value of seepage flux was calculated from the previous and succeeding seepage flux values to replace missing flux values (i.e., 2011). Estimation of shallow groundwater seepage fluxes during non-recording periods (generally October to April) was performed by plotting seepage fluxes by site (A,B,C, etc.) through time (from the start date) to determine flux trends. Based on these graphs, it was assumed that seepage flux during the missing weeks was equal to 50% of the mean seepage flux value of the previous measurement year. Studies elsewhere suggest a 35 to 50% decrease in seepage flux during the winter months (Rosenberry, 2011). Values calculated by this method were added as “pseudo-periods” to data from each site.

Seepage meters at each site demonstrated both positive values (groundwater discharge to the lake) and negative values (lake recharging groundwater), often occurring in side-by-side meters. However, it was reasoned that seepage meter measurements in 2011 and 2012 should all indicate groundwater inflow (positive seepage flux) based on water levels indicating upward groundwater flow in adjacent minipiezometers and in the Deep aquifer system. An evaluation of negative seepage values at each site showed factors other than groundwater flow likely affected their readings; i.e., gas accumulation in the seepage bags (thus restricting flow), animals disrupting the seal at the meter/sediment interface (allowing leakage of water from the bags), or animals contorting the bags within the protective boxes (yielding false negative or zero flow). Negative seepage fluxes were thus removed from the analysis, with the one exception at Pokegama Lake. Due to heavy rainfall in the lake watershed in June and early July 2012, water was held at the Pokegama Dam to prevent downstream flooding, effectively raising the lake stage about 0.9 m (3 ft) above normal. This reversed the hydraulic gradient and forced lake water vertically into the shallow groundwater at Zone G and produced negative seepage values. Groundwater inflow to the seepage meters (positive seepage fluxes) resumed after the lake stage declined on July 10th, 2012.

Each meter site was located in an area (Zone) measured in ArcMap that was used (along with the seepage flux from the meter) to calculate the shallow groundwater discharge to the lake. Groundwater discharge (Q) into the lake for each period was calculated by multiplying the seepage flux per period times the effective area over which the discharge occurs; i.e., the distance outward from the shoreline times the length of the seepage zone (A, B, C, D, etc.) represented by each site. The distance outward from the shoreline was estimated at 30 m (100 ft) based on the lake bathymetry. The annual groundwater discharge and volume were calculated by summing the groundwater discharge for each period during the calendar year.

Calculation of Nutrient and Chloride Flux from Shallow Aquifers

Nutrients and Cl from groundwater in minipiezometers were sampled using a Masterflex pump head attached to an 18V Ryobi cordless drill via an aluminum frame, similar in design to Woessner (2007). Samples were taken after at least three well volumes were evacuated from the minipiezometers. Samples were analyzed for NO_3-N, Total Dissolved P, Soluble (dissolved) Reactive P, and Cl using lab methods described above. These are the common forms of N and P found in groundwater, as opposed to NH_4-N, Total N and Total P, which are more commonly used in lake studies. Interpretation of Total P is problematic in groundwater if the wells contain sediment. If values of TDP and SRP were found to be similar, then only the TDP value was reported. To determine the nutrient flux, the concentration (mg/L or μg/L) was multiplied by the estimated groundwater discharge (Q) for the period (see previous section) for each constituent, thus producing a nutrient load in kg/period. For the periods without a recorded measurement, the mean value of the previous and next measurement was calculated and used for that period. The annual mean concentration value was used during the fall, winter, and spring periods. Individual load values from the periods were summed to produce an annual load of nutrients and Cl from shallow groundwater.

Calculation of Groundwater Discharge from the Deep Aquifer

Groundwater discharge (Q) to the lakes from the Deep aquifer was calculated from 33 wells at the lakes (Figure 23) using estimates of transmissivity (T), hydraulic gradient (I), and the length of shoreline along which the discharge occurs (P, the aquifer perimeter). A form of Darcy's Law:

Q = T * I * P

was used in the discharge calculation. The spreadsheet program TGUESS (v.05 beta 1; Bradbury and Rothschild, 1985) was used in conjunction with specific capacity data from well logs to estimate T. Arithmetic and geometric mean values of T (m^2/s) were calculated. However, because the thickness of the aquifer is different in the two lakes, a value for hydraulic conductivity (K) was also needed, which was calculated by dividing T by the mean thickness (b) of the aquifer. Estimating thickness (b) from well logs was difficult because most all of the wells are partially penetrating and the total thickness of the aquifer is unknown. As a result, thickness of the aquifer (and thus Q) may be underestimated. Mean values of b were 3.3 m (10.75 ft; N=19) and 4.5 m (14.64 ft; N=14) in Deer and Pokegama lakes, respectively. To determine hydraulic gradients, elevation surveys (Figure 24) were performed on the same wells using a GPS unit to within ± 1 cm (± 0.033 ft). Water levels under non-pumping conditions (or after the pumps had been idle for 10 minutes) were measured in the wells during summer 2011, winter 2012, and again in summer 2012 to the nearest 0.30 cm (0.01 ft) with a Solinst Model 102M electric tape. Water levels were converted to hydraulic head values. Hydraulic gradients were calculated by taking the difference between the hydraulic head at the well and USGS stage for the lake and then dividing that quantity by the linear distance between the well and the nearest point on the lake perimeter. Hydraulic head generally declines during the winter months (October to April), a process that effectively decreases the hydraulic gradient and groundwater discharge to the lake.

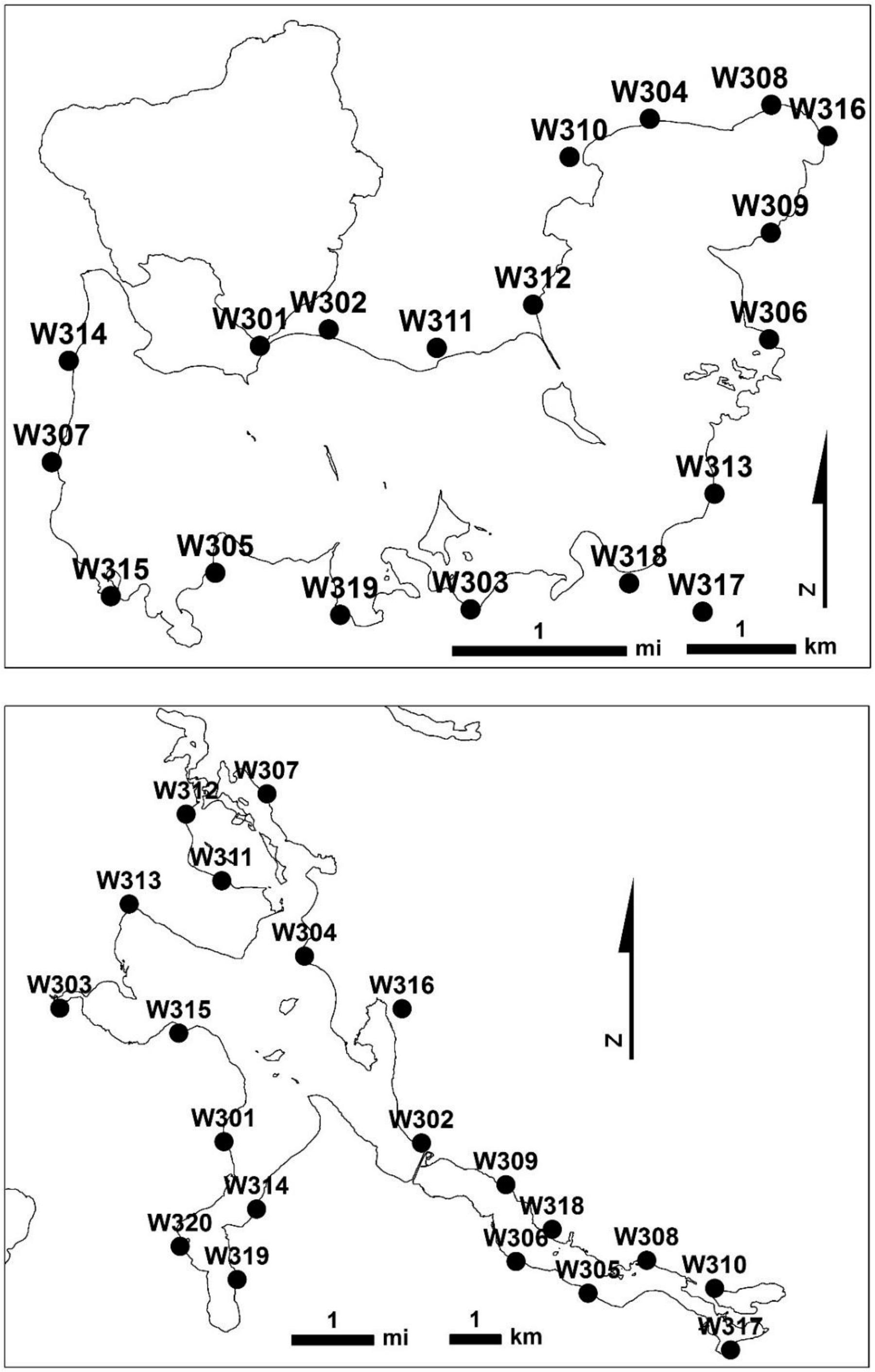


Figure 23: Location of private wells on Deer Lake (top) and Pokegama Lake (bottom), where water levels measurement and geochemical sampling occurred during the study.

Figure 24: Joey LeBlanc (NRCS) surveying well elevation.

The remaining parameter, P, is a source of great uncertainty, making the cross-sectional area through which groundwater flows to the lake ill-defined. The P value was calculated by determining the mean value of the elevation of the Deep aquifer in the well logs and then extrapolating that value to a bathymetric map to find its intersection in the lake. Based on this analysis, the value for P for both lakes was determined using the 15-m (50-ft) bathymetric contour. A smoothed line was drawn to connect the intersection points, it was measured using ArcMap software, and that was used for the value of P.

Calculation of Nutrient and Chloride Flux from the Deep Aquifer

Similar calculation procedures to those used in the Shallow aquifers were repeated here for the Deep aquifers. A mean and standard deviation value were determined for NO_3-N, TDP, and SRP (2011 only) for the 33 wells for the periods in which samples were taken and analyzed. Not all periods where water flux is estimated were represented by samples taken from the wells, but because these systems seem to be regional in nature, there may not be substantial variation in their values. Therefore, a value was estimated for the periods with no data by simply calculating a mean value from periods on either side. The number of samples within a period is not constant because Period D5 (Summer 2012) included two samples from new private wells and one sample from the older wells sampled in 2011. Concentrations found below their respective detection limit were replaced by ½ the detection limit value.

Sampling and Geochemical Analysis of Groundwater in the Deep Aquifer

Groundwater geochemistry of the deep aquifer system was assessed by sampling groundwater from the private wells using a set of standard procedures. Following water-level measurement in each well, a 15.2 m (50 ft) hose (drinking water type) with a shut-off valve was attached to the pressure tank and connected to a drain or allowed to port away from the tank. If the pressure tank was not accessible, the nearest outside water spigot was used, provided the water was not softened. With the pump turned off, the pressure tank was emptied in order to obtain a fresh water sample and remove pressure tank sediment. The pump was cycled on and off until the water ran clear, at which point it was deemed acceptable for sampling. This procedure was used for every groundwater sampling event in the wells.

To obtain the field parameters of temperature, specific conductance, pH, and dissolved O_2, a YSI 650 handheld data recorder with a YSI 6920V2 submersible sonde was used in conjunction with a clean 18.9 L (5 gal) bucket. The sonde was inserted into the bucket, and the output end of the hose was placed in the bottom of the bucket. The bucket was filled slowly and let to overflow until the temperature, conductivity, pH, and dissolved O_2 readings stabilized, about 5 to 10 minutes later.

Groundwater samples were obtained after field parameters were recorded. A 0.9 m (3 ft) length of 1.3 O.D x 0.95 cm I.D. (1/2 x 3/8 in) polyethylene tubing was attached to the drinking water hose using a nylon garden hose reducer fitting, and water was allowed to pass through the tubing for one minute to clean the line. A one L unfiltered whole water sample was taken for the following analyses at the ICCWQL: Total Nitrogen (TN), Nitrate+Nitrite-Nitrogen (NO_3+NO_2 -N), Ammonium Nitrogen (NH_4-N), Total Phosphorus (TP), Soluble Reactive Phosphorus (SRP), Total Dissolved Phosphorus (TDP), Chloride (Cl^-), and Alkalinity (mg $CaCO_3$). Three 125 mL samples filtered through a Geotech 0.45 µm high capacity Dispos-a-filter were then gathered for cation (Ca, Mg, K, Na, Fe, Si, Sr, Al, and Mn), anion (Cl^-, NO_3, PO_4 , an SO_4) and total dissolved organic carbon (DOC) analysis. Finally, a 20-mL scintillation vial was used to collect a stable isotope sample. All samples were stored on ice or refrigerated until analysis. Cation samples were preserved using 1 mL of 5M nitric acid. For each subsequent well sampling, only a 1 L unfiltered whole water sample and a 20 mL stable isotope sample were gathered in addition to a hydraulic head measurement. Six 1 L private well samples were collected at Deer Lake, and three at Pokegama Lake were sampled in the winter of 2011 for tritium. See Table 4 for a more specific listing of the timing of sampling and analysis.

Sampling Season for Private Wells	Analysis Performed
Summer 2011	TN, NO_3+NO_2- N, NH_4-N, TP, SRP, TDP, Cl, Alkalinity (mg/L as $CaCO_3$), Cations*, Anions*, DOC*, Stable Isotopes, Temperature*, Dissolved O_2*, Specific Conductance*, pH*
Winter 2011	TP, Cl, Stable Isotopes
Summer 2012	NO_3+NO_2 - N, NH_4-N, TDP, Cl, Alkalinity (mg/L as $CaCO_3$), Cations*, Anions*, DOC*, Stable Isotopes, Temperature*, Dissolved O_2*, Specific Conductance*, pH*
	*performed only on first sampling of each well

Table 4: Timing of sampling and analysis.

Cation, anion, and DOC analyses were performed at the United States Department of Agriculture (USDA) Forestry Sciences Laboratory in Grand Rapids, Minnesota. Cations were analyzed using Standard Method 3120 B (American Public Health Association et al., 2005) and inductively coupled plasma (ICP) optical emission spectroscopy (OES) on a Thermo-Elemental Iris Intrepid ICP-OES with a radial torch. Anions were analyzed using Standard Method 4110 B (American Public Health Association et al., 2005) and a Dionex DX-500 high performance liquid chromatography (HPLC) unit. DOC was analyzed using Standard Method 5310 B on a Shimadzu Total Organic Carbon Analyzer, Model TOC-V CPH, using non-dispersive infrared analysis. See Table 5 for analytical detection limits reported for the USDA Forestry Sciences Laboratory in Grand Rapids, Minnesota.

Analyte	Detection limit (mg/L)	Precision (mg/L)
	Anions	
Cl	0.1	±0.03
Br	0.1	±0.03
PO_4	0.14	±0.05
SO_4	0.14	±0.05
NO_3- N	0.1	±0.03
	Cations	
Ca	0.02	±0.007
Mg	0.01	±0.003
K	0.08	±0.03
Na	0.01	±0.003
Fe	0.02	±0.007
Si	0.02	±0.007
Sr	0.01	±0.003
Al	0.06	±0.02
Mn	0.01	±0.003
	Organic Carbon	
DOC	0.50	±0.17

Table 5: Analytical detection limits and precision for cations, anions, and DOC analysis performed at the USDA Forestry Sciences Laboratory in Grand Rapids, Minnesota.

Analyses of Stable Isotope Data in Shallow and Deep Aquifers

Stable isotopes $\delta^{18}O$ and $\delta^{2}H$ in water are conservative environmental tracers commonly used to understand groundwater/surface water interaction, particularly in lakes where surface evaporation causes a large fractionation effect (Krabbenhoft et al., 1990; Rosenberry et al., 2011; Jones et al., 2013). Samples included precipitation (2011-12), minipiezometers (multiple times), private wells (three times), the two lakes (multiple times), and streams (occasionally) for a total of about 1500 samples, of which 364 samples were selected to analyze. Samples were analyzed in the Iowa State University, Department of Geological and Atmospheric Sciences, SIPERG Laboratory using a Picarro L1102-i Isotopic Liquid Water Analyzer, which utilizes Wavelength-Scanned Cavity Ringdown Spectroscopy. Values are reported as ratios of the heavy to the light isotope ($\delta^{18}O$ and $\delta^{2}H$) versus a reference standard (VSMOW) in delta notation (units of per mil or ‰):

$$\delta^{18}O_{sample} = \left[\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{reference}} - 1 \right] \times 1000$$

(Clark and Fritz, 1997). The combined uncertainty (analytical uncertainty and average correction factor) for all samples in this study was ± 0.11‰ and ± 0.42‰ (VSMOW), for $\delta^{18}O$ and $\delta^{2}H$ respectively.

Analyses of Tritium (^{3}H) in the Deep Aquifer

The radioactive isotope tritium (^{3}H) reached its peak activity in the atmosphere in the 1960s due to atmospheric testing of nuclear weapons and has been used to date recent groundwater. Because of radioactive decay and a half-life of 12.43 years, this technique is not quite as useful as it was 10 to 20 years ago. Nevertheless, it provides a qualitative age of groundwater that can be used to screen for potential samples for the more accurate $^{3}H/^{3}He$ dating. The units of tritium measurement are Tritium Units (TU), where 1TU = 3.221 Picocuries/L. Tritium was analyzed on eight samples (four from groundwater near each lake) at the Environmental Isotope Laboratory, University of Waterloo (Canada), by direct scintillation counting after electrolytic enrichment. The detection limit was 0.8 TU, and analytical precision for the samples ranged from ±0.3 to ±1.3 TU. In general, less precise measurements are associated with higher ^{3}H activities.

Calculation of Groundwater Discharge from Shallow Springs

Whereas seepage meters measure the diffuse flow of groundwater into lakes, springs may also provide a significant point source of groundwater (Winter, 1999). Studies of groundwater flow by the U.S. Geological Survey at Shingobee Lake, approximately 85 km to the southwest of Deer Lake, have shown spring discharges up to 0.0029 m^3/s near the shoreline (Rosenberry et al., 2000; Kishel and Gerla, 2002; Rosenberry et al., 2011). In general, springs provide concentrated flow where more permeable fine sand layers within the silt units intersect the lakebed and streambed (Figure 25).

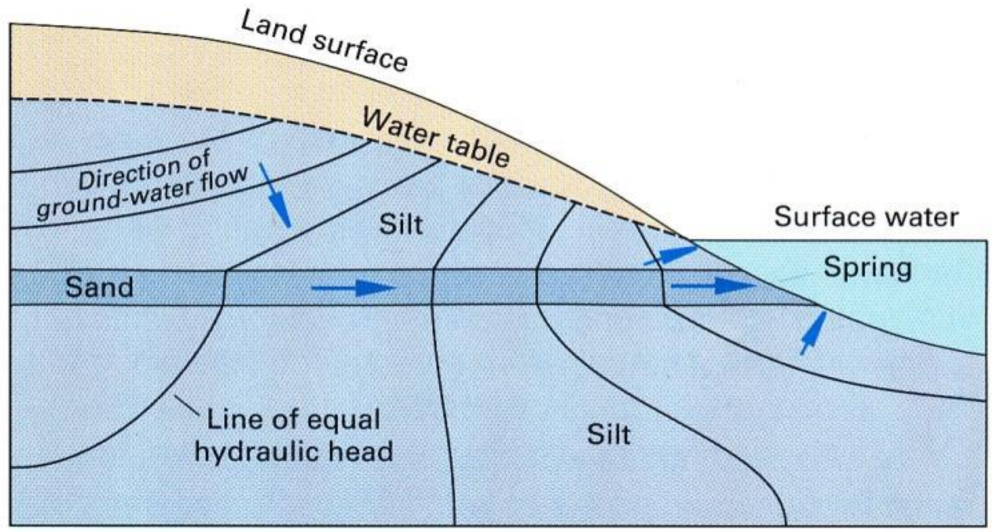


Figure 25: Conceptual diagram showing how springs occur in the near shore area due to groundwater flow through high permeability sediments (from Winter et al., 1999).

As an alternative to using seepage meters to monitor spring discharge, heat flow relationships can be used to quantify their discharge to surface water. Studies have shown that the interaction can be described and quantified using time series data composed of stream and underlying groundwater temperatures (Stonestrom and Constantz, 2003; Conant, 2004). Under static conditions, heat may be conducted between groundwater and surface water, but more commonly, flowing groundwater will advect heat as it moves into or out of a stream according to the prevailing hydraulic gradient. The resultant temperature distribution between groundwater and a stream (or lake) can be simulated using models that couple groundwater and heat flow (Lapham, 1989), effectively using heat as a groundwater tracer (Anderson, 2005).

Springs in Deer Lake

Because the lakes in this region are underlain by heterogeneous strata with diverse permeabilities, and because these contain sands and gravels that can conduct water rapidly, the shores of lakes are known to have areas of concentrated groundwater seepage that are locally known as “springs.” These concentrated points that can be up to a meter or more in diameter can have softer sediments than surrounding areas, can have water that is much colder than lake water (in summer) and can even show some disturbance at the water surface when lake water is calm. These “springs” are especially abundant in Deer Lake so were examined in detail. Although they are known to be found to some extent in Pokegama, a request of local residents for information on where they occur in concentration yielded no enthusiastic indication of areas of substantial concentration, so they were assumed to be of minor importance.

In Deer Lake, one very concentrated area of “springs” occurs near the Tom Nelson home (Figure 26) where ready access and on-going citizen assistance with data collection was assured, so analysis was performed on this area. Since little was known about these phenomena when the proposal was written, there was not enough funding to do a generalized study. Consequently, it was necessary to extrapolate the results from this area to the entire lake to assess whether these "springs" might contribute substantially to the lake's overall water and nutrient budget.

Because temperature differences in the substratum are the most obvious manifestations of "springs" throughout the region and because methods for estimating water flux from temperature gradients have been developed, maps of substrate temperature in a 30m X 50m section of shore were used to get an estimate of the upper limit of spring contributions to the lake's water and nutrient budget. This work was coordinated and much of it carried out by Tom Nelson, a dedicated volunteer. First, a rectangular grid was laid across a region of the shore where many springs are known to be found. This was done with a set of surveying tapes, fence posts, and ropes. The work was performed at the end of June 2012 when air and lake water temperatures were high, but water and rainfall were still plentiful. Then, temperature measurements were made using a regular 1 m^2 grid but making additional temperature measurements at points of known position where cold water could be felt in the sediments. Because there was no budget for this analysis, sediment temperature probes were crafted from inexpensive indoor-outdoor thermometers attached to sticks, placing the "outdoor" probe at the point of the stick. Devices cost approximately $8 each and were paid for by volunteers (Figure 27). A contour plot of the sediment temperature across the area was determined by a geospatial program using Krieging (Golden Software's "Surfer").

Once the locations of "springs" were known from the temperature contour plot, standard seepage meters were installed on several of them as well as several locations where sediment temperatures were relatively high. This yielded many measurements of seepage from the springs as well as estimates of background seepage. Further, minipiezometers were driven into spring and non-spring locations to estimate phosphorus concentrations.

Figure 26: Tom Nelson near the site where springs were analyzed for this study.

Figure 27: Dr. Jack Jones showing home-made sediment temperature probe.

Next, the fluxes from spring and non-spring areas were characterized by statistical analysis and the overall seepage rates determined using analyses of temperature gradients. The interaction of groundwater and surface water can be described and quantified using time series data composed of stream and underlying groundwater temperatures (Stonestrom and Constantz, 2003; Conant, 2004). Under static conditions, heat may be conducted between groundwater and surface water, but more commonly, flowing groundwater will advect heat as it moves into or out of a stream according to the prevailing hydraulic gradient. The resultant temperature distribution between groundwater and a stream (or lake) can be simulated using models that couple groundwater and heat flow (Lapham, 1989), effectively using heat as a groundwater tracer (Anderson, 2005).

To quantify the spring contribution to the lake, approximately 565 temperature measurements were made on June 30, 2012, by Tom Nelson and others in the 30m X 50m shoreline zone area near his residence. Probes from off-the-shelf, indoor/outdoor thermometers with thermistors were inserted approximately 5 cm into the sediment containing the spring. The lake temperature was approximately 25°C at that time, and ambient groundwater temperature should be approximately 4.4°C, according to the mean annual air temperature for Grand Rapids, MN. The USGS model VS2DH (Healy and Ronan, 1996) was utilized as implemented in VS2DHI v.1.3 (Hsieh et al., 2000) to simulate observed temperatures and estimate groundwater discharge and flux.

The "spring" data were extrapolated lake-wide to get an estimate of the maximum input of spring seepage water by mapping areas around the lake showing open water in winter (Figure 28) and assuming that these areas (Figure 29) had as much groundwater flow from springs as seen near the Nelson property.

Figure 28: Example of area around Deer Lake that showed open water in winter. Photo courtesy of Tom Nelson.

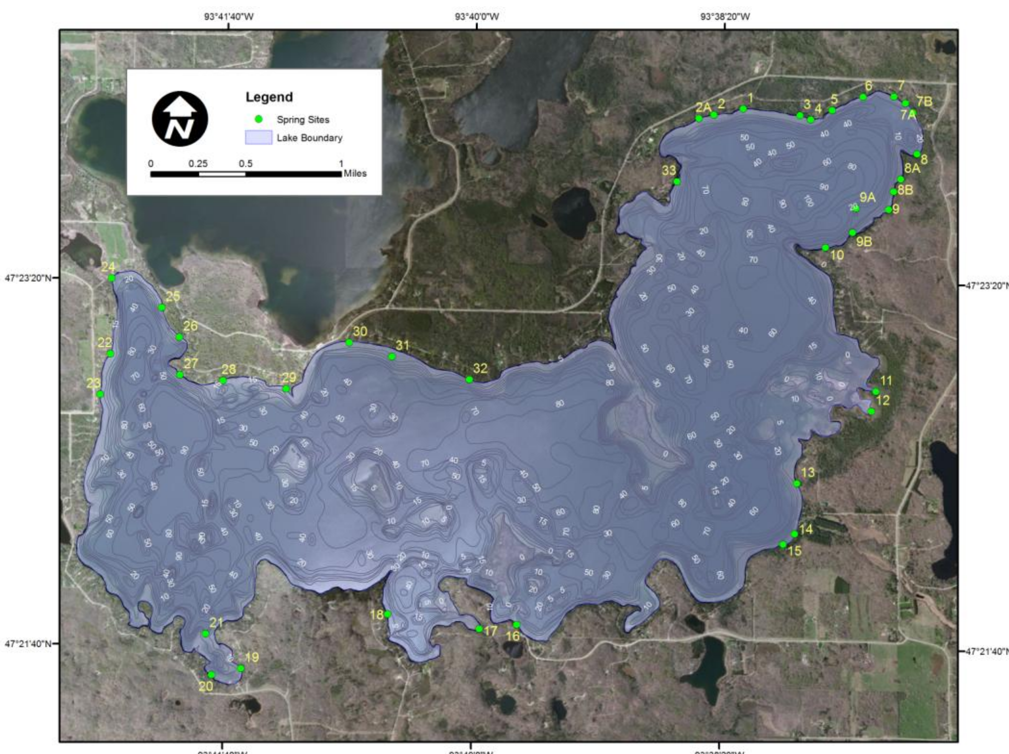


Figure 29: Potential Deer Lake spring locations determined by Tom Nelson as open water areas when the lake was mostly frozen.

Methods for the Calculation of Water and Nutrient Budgets and Export Coefficients

Water Budgets

Surface water flux was measured periodically at all substantial stream inflows. The original methods had planned to instrument the major tributaries with continuous water-level gauges (Figure 30) in order to calculate daily water flux, but equipment difficulties and low water made these data unreliable. Daily water discharges were therefore estimated between measured values by assuming a linear relationship between measured stream discharges estimated on adjacent dates. Especially in Deer Lake, a large portion of the watershed had no consolidated surface inputs so hydraulic inputs for those areas are considered to be principally via groundwater flow. Daily direct precipitation inputs to the lakes' surfaces were estimated from the Minnesota Climatology Working Group site (http://climate.umn.edu/HIDradius/radius.asp) using Deer and Pokegama lakes as target locations. Daily groundwater inputs from deep and shallow (including "springs" in Deer Lake) groundwater was estimated by dividing periodic inputs by the number of days in each period. Daily changes in lake volume (storage) were determined using hypsographic data for each lake and lake water levels measured at the outfall. When lake water levels were above those for the reference water level of bathymetric maps, the additional water volume was added as the product of the difference in lake water level from the reference level and the area of the lake at the reference water level. Water losses included outflow and surface evaporation. Daily losses discharged were estimated as the sum of interpolated flow at the outflow and evaporative loss in Deer Lake. In Pokegama, the MPCA instrumented the outfall with an acoustic Doppler current profiler (ADCP), because flows can be into or out of the lake (making use of standard rating curves impossible). The ADCP failed, however – except for a relatively short period of the study – so inflow and outflow at the normal outfall site were calculated by mass balance as the daily difference between all measured inputs and outputs. These calculations agreed well in magnitude with those that were successfully measured. Direct evaporation from the lake was estimated using the Harmon method (Harwell, 2012) because this has been shown to work well in this region (Winter et al., 1995). Data were combined to create hydraulic budgets for the lake over the sampling period. The "outfall" of Pokegama was considered to be both an outflow and a tributary, depending on the direction of flow.

Nutrient Budgets

Nutrient (P) budgets were determined for each lake from hydraulic (water) budgets weighted by the linearly interpolated total phosphorus concentrations across adjacent dates except for direct precipitation input which was not sampled as regularly. Total P of direct precipitation inputs was estimated using the average precipitation phosphorus concentrations, ignoring precipitation estimates that had obviously been contaminated with insects, particulate matter, or other adulterating substances.

Nutrient Export Coefficients of Subwatersheds

The intensity of outflow of nutrients from each subwatershed drained by surface tributaries was estimated by dividing the annual calculated efflux of nutrients by the area of the subwatershed.

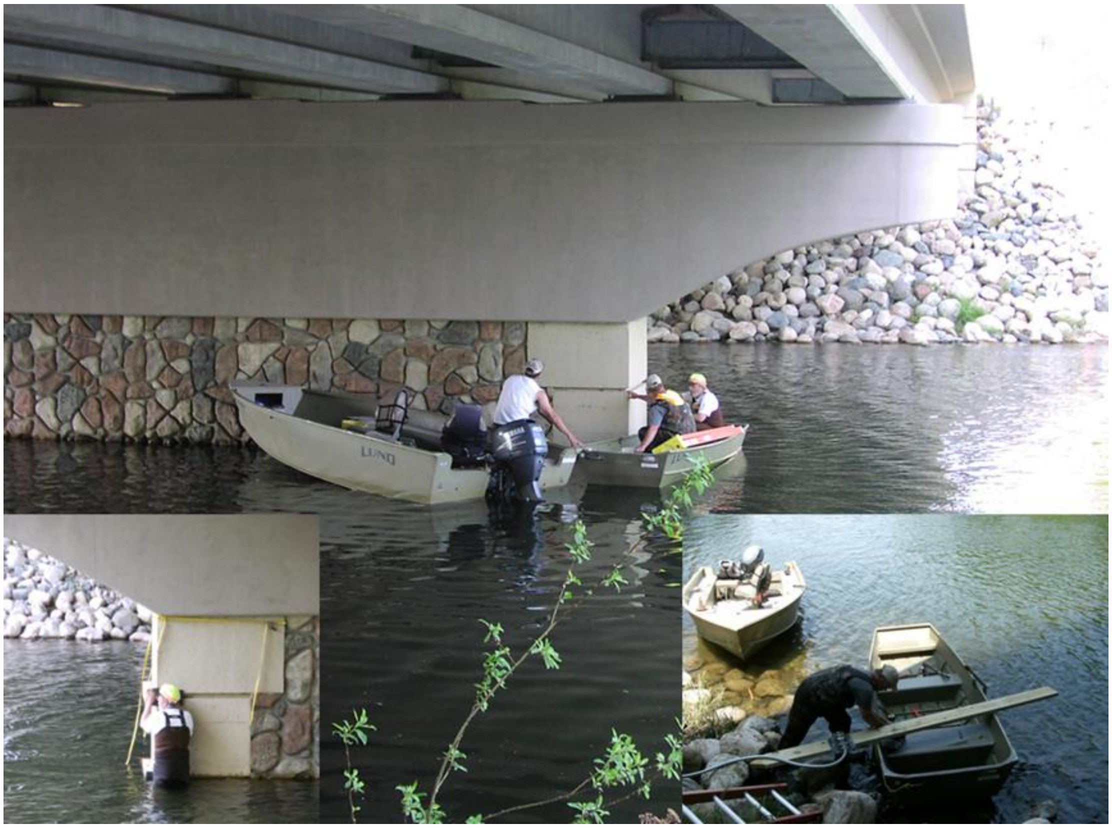


Figure 30: MPCA and ICSWCD install acoustic doppler current profiler on Pokegama outlet.

<u>Data Management and Statistics</u>

Project data was reviewed and submitted to Minnesota's Environmental Quality Information System (EQuIS) database on an annual basis. Data included lake, stream, and groundwater chemistry, stream stage, and discharge; YSI field data (temp, dissolved oxygen, specific cond, pH, and turbidity); and secchi. Precipitation data was submitted to the Minnesota Climatology Office.

In addition, data for this project have been managed and stored through cooperation with the Downing laboratory at Iowa State University. The approach used by this laboratory is to assure the security of these data by keeping all data in a controlled-access SQL server database that is backed up and secured on a regular basis. Data are provided in standard compliant formats (e.g., html and XML), as well as commonly used file formats (e.g., EXCEL, PDF, and JPG). The data query capability can provide datasets that meet custom needs.

Metadata

The Downing laboratory has developed a detailed system of data flagging that irrevocably associates data with metadata. This is imbedded in the SQL server information system. The process supports and follows limnological semantic standards for collected data. The flag system is consistent with EPA monitoring projects. The metadata are easily exchangeable. The metadata are kept in the relational database and they are updated regularly and can be corrected globally, if needed. The web-enabled relational database management system provides near real-time upload capability. The automation-capable dataflow standard operating procedures using bar-coding to document chain-of-custody facilitates both the speed and accuracy of migration with a just-in-time quality control mechanism enforced from the lab to the data repository.

Permanent Storage

The laboratory periodically formats data for upload into various government data systems for secure permanent storage.

Data Security

The laboratory is following stringent security standards over the Internet and has implemented a role-based data distribution repository. Based on the role of the users, they can access their designated area of the online data repository. The secure data portal demonstrates this practice (http://limnoweb.eeob.iastate.edu/limnoinformatics).

Information Assurance

The systems analyst (Satish Kancherla) is responsible for the secure storage and retrieval of data over this web-based system. Mr. Kancherla has extensive experience with database design and maintenance. Mr. Kancherla received a bachelors in technology degree in electronics and communications from Vellore Institute of Technology University in India. He is currently pursuing a Ph.D. degree in computer engineering at Iowa State University. Mr. Kancherla also has experience in computer programming in several languages (e.g., ASP.NET, VB.NET, C, C++, Perl scripting, and PHP) and web design.

Quality Control and Quality Assurance

The field procedures were duplicated at a rate of 10% to assess the sampler's precision, laboratory precision, and possible temporal variability. The field crews generally collected one field duplicate each day. A field duplicate includes replicating all field measurement and sample collection procedures. The duplicate was chosen randomly each day. After completing the field data sheet, both field crew technicians reviewed the data sheet for any errors and omissions. After verifying the recorded data, both field crew technicians signed the data sheet. Field crew technicians triple rinsed all sample collection equipment prior to sample collection with lake water at the site (Bartram and Balance, 1996). All bottles containing samples were labeled. The sample label included the water body code or name, the site number, the date, and time of sample collection. Field data sheets were the primary method for documenting most stream monitoring field activities. These sheets served as an initial record of any field measurements and weather conditions at the time of sampling as well as any other observations.

MPCA policy mandates that a chain of custody form be used whenever environmental samples are taken and submitted to a laboratory for analysis. Chain of custody procedures must be used to document sample possession from the time the sample is collected until it arrives at the analyzing laboratory. Any samples that were sent to PACE also require a chain of custody form.

Upon arrival at the laboratory, the conditions of the samples were determined and they were logged into the Laboratory Information Management System (LIMS). They were assigned a unique sample ID number and given barcodes. The samples were then stored in the appropriate area as determined by required storage temperature, matrix, and analyses required. The laboratory sample storage areas were monitored daily, and regular instrument/equipment testing, inspections, maintenance, and calibrations were performed as outlined in the labs QA/QC manual and SOPs. Twice a year, the lab takes proficiency tests (PT) in each certified field. Other QA/QC measures related to lab methods such as matrix spikes and running samples in triplicates can be found in the labs QA/QC manual. Refer to Tables 1 and 2 for analytical parameters and methods used. On a yearly basis, all data were uploaded to Iowa State University's data system and EQUIS.

Water Modeling Techniques

Geographic, bathymetric, hydrologic, and export data were integrated into a series of lake models to find which gave the best fit to observed values found in both Deer Lake and Pokegama lakes (Kreider, 2001; http://dnr.wi.gov/lakes/model/). This modeling was performed using a modification of the "WiLMS" Wisconsin Lake Modeling Suite (Panuska and Kreider, 2003).

The Wisconsin Lake Modeling Suite (WiLMS) model is a lake water-quality planning tool created and maintained by the Wisconsin Department of Natural Resources. It is an integration of a variety of different empirical models into a convenient computational package. The model uses an annual time step and predicts spring overturn (SPO), growing season mean (GSM), and annual average (ANN) total phosphorus concentration in lakes.

The following description is quoted from Panuska and Kreider (2003): "The WiLMS model structure is organized into four principal parts, which include the front-end, phosphorus prediction, internal loading, and trophic response. The front-end portion or model setup includes the Lake Characteristics, watershed loading calculation inputs, and the observed in-lake TP. Both the phosphorus prediction and internal load estimator use the front-end portion of the model for lake and watershed inputs. The phosphorus prediction portion contains the 13 phosphorus prediction regressions and the Uncertainty Analysis routines. The internal load estimation portion contains 4 methods to estimate and bracket a lake's internal loading. The trophic response portion of the program contains 2 levels of trophic evaluation – summary and expanded. The summary portion contains only Wisconsin trophic response relationships while the expanded contains Wisconsin regressions plus other commonly used regressions and allows for user defined regressions."

Because WiLMS uses export values in its watershed loading module, these were verified against locally measured values. The default values were found to be close to those found for Pokegama watersheds, but higher than those found around Deer Lake. As a result, P export values were reduced to half to one-third of default values used in the WiLMS default dataset. The original technical publication has also been referenced (see below). These are empirical models developed via statistical analysis of lake and reservoir ecosystems.

Canfield, D. E., and R. W Bachmann, 1981. Prediction of total phosphorus concentrations, chlorophyll-a, and Secchi depths in natural and artificial lakes. Can. J. Fish. Aquat. Sci. 38: 414-423.

Dillon, P. J., and F. H. Rigler, 1974. A test of a simple nutrient budget model predicting the phosphorus concentration in lake water. J. Fish. Res. Board Can. 31: 1771-1778.

Kirchner, W B. and P J. Dillon, 1975. An empirical method of estimating the retention of phosphorus in lakes. Water Resources Research. 11: 182-183.

Kreider, J. 2001. Wisconsin Lake Modeling Suite (WiLMS) version 3.3.18.1. Wisconsin Department of Natural Resources, Madision, Wisconsin, USA. http://www.dnr.state.wi.us/org/water/fhp/lakes/laketool.htm

Larsen D. P. and H. T. Mercier. 1976. Phosphorus retention capacity of lakes. J. Fish.Res. Board Can. 33: 1742-1750.

Nurnberg, Gertrud K. 1984. The prediction of internal phosphorus load in lakes with anoxic hypolimnia. Limnol. Oceanogr., 29 (1) 111-124.

Organisation for Economic Cooperation and Development (OECD) 1982. Eutrophication of waters: monitoring, assessment and control, Paris. 154p.

Ostrofsky, M.L., 1978. Modification of phosphorus retention models for use with low areal water loading. J. Fish Res. Board Can 35: 532-536.

Reckhow, K. H., 1977. Phosphorus models for lake management. Ph.D. dissertation, Harvard University, Cambridge, Massachusetts. Catalog No. 7731778, University Microfilms International, Ann Arbor, Michigan.

Reckhow, K. H., 1979. Uncertainty applied to Vollenweider's phosphorus criterion. J. Water Poll. Cont. Fed. 51: 2123-2128.

Walker, W W, Jr., 1977. Some analytical methods applied to lake water quality problems. Ph.D. dissertation, Harvard University.

Walker, W.W. 1984. Statistical bases for mean chlorophyll a criteria. Lake Reserv. Manage. 2:57-62.

Walker, W.W. Jr., 1985. Empirical methods for predicting eutrophication in impoundments. Report No. 3. Phase II: Model refinements. USCOE waterways experiment station technical report No. E-81-9. Vicksburg, Mississippi. 300p.

Specific Fitting Procedures

Acres of land in various land use categories and habitation densities were entered into the "non-point source" module, and default P export values were retained as they fit well with exports seen in the watersheds. Input from the Mississippi River and groundwater inputs were entered as "point-sources," because this was the simplest means of parameterizing the models. Mississippi River back-flow loads were assumed to vary by 200 kg of total P around the average load observed. For Deer Lake, only the watershed with consolidated surface tributaries was considered in surface fluxes, and direct precipitation contributions were adjusted to match values determined in the nutrient budget. WiLMS precipitation loading was adjusted to match observed values. Groundwater loading was assumed to have an uncertainty among years of about 10% around the average observed loading rates.

Lake Response Modeling

The parameterized WiLMS models were used to seek the best fitting empirical model. This model was then evaluated by increasing or decreasing P loading in percentage increments or absolute amounts to find the likely effects of changes in loading on equilibrium phosphorus concentrations. The influence on chlorophyll and Secchi disk transparency was then approximated by using known empirical relationships between P and these other variables. Relationships between phosphorus and chlorophyll were taken from extensive monitoring work performed on Itasca County lakes made under MPCA SWAG grants as well as experience with other world lake ecosystems. The relationship between Secchi transparency and chlorophyll concentrations was taken from Jones and Bachmann (1976) in preference to the relationship derived from Itasca County lakes, because the latter is heavily influenced by high levels of color seen in very small lakes, which would be irrelevant to the future conditions in Pokegama or Deer lakes.

RESULTS

Description of Project Area

Geological Setting

The geological setting of Deer and Pokegama lakes consists of deposits from multiple Wisconsinan glaciations overlying conglomerates of Cretaceous age, and granitic gneiss, greywacke, slate, and chert of Precambrian age (Figure 31). Deer Lake is underlain by Neoarchean rocks (~2.7 billion years old) consisting of granitic gneiss and foliated granitic intrusions (Meyer and Jirsa, 2005). Pokegama Lake is underlain by a basal conglomerate of the Cretaceous Coleraine Formation (~93 million years old) containing clasts of Biwabik Iron Formation. In the northwest and southeast parts of the lake, the Coleraine Formation is absent and the Paleoproterozoic Biwabik Iron and the Virginia Formations (~2.1 to 1.85 million years old), the latter containing mostly graywacke and slate, underlie glacial sediments directly. Depth to bedrock (thickness of glacial sediments) ranges from 33 to 48.7 m (100 to 160 ft) in the vicinity of Deer Lake and from 15.2 to 91.4 m (50 to 300 ft) near Pokegama Lake (Figure 32).

Two lobes of glacial ice deposited till, sand, gravel, and lake sediment at both lakes (Figure 33). The Rainy lobe was the first to enter the county from the northeast in early to middle Wisconsinan time, and it deposited a clayey to loamy textured, brown till (clay). The atypical clayey texture in the till resulted from advance over preexisting proglacial lake sediments. The till contains Precambrian igneous lithologies (basalt, gabbro), but lacks Cretaceous shale and Paleozoic carbonate clasts, thus supporting an ice source from the northeast (Lusardi, 1997; Meyer et al., 2005). Rainy lobe ice-contact sediments, consisting of sand and gravel deposited on or adjacent to glacial ice, occur at the surface along the eastern and northeastern shore of Deer Lake. These sediments likely lie in the subsurface along with Rainy Lobe till in the vicinity of Deer Lake and Pokegama Lakes (Figures 34 and 35).

The St. Louis sublobe was the next ice lobe to advance into the area during late Wisconsinan time, about 14,000 years ago (Meyer et al., 2005). Deposits from this lobe comprise the predominant surficial material at both lakes. Des Moines lobe till is loamy in texture, gray to brown, and contain Cretaceous shale and Paleozoic carbonate rocks. An ice margin marking a stopping point of this ice lobe is identified on the south and eastern sides of Deer Lake (Figure 34) and along a northeast to southwest trend across Pokegama Lake (Figure 35). The ice margin on the south side of Deer Lake is marked by a large sand and gravel delta deposit that stands out in relief over the lake. The retreat of ice back to the northwest produced large proglacial lakes whose sediments now comprise the low relief areas of lake sediments on the western side of Deer Lake (Meyer et al., 2005). Ice retreated to the north as the climate warmed and Minnesota became ice free by 11,000 years ago (Lusardi, 1997). Cross sections near both lakes show one or two till units about 20 m (66 ft) thick overlying a sand and gravel aquifer that comprises a major aquifer for private wells in the region (Figure 36).

Although their depths are similar (~38 m or 125 ft), the lakes' origins are quite different. The depth, shape, and position of Deer Lake (behind an ice margin) suggest that it was formed by melting of a large ice block. Rainy lobe ice was still present on the landscape south of the Giants Range (Figure 31), when the St. Louis sublobe advanced (Marlow et al., 2004); hence, a Rainy lobe ice block may have been buried beneath St. Louis sublobe sediment, preserving the ice as a positive feature and allowing it to melt slowly during deglaciation without filling with sediment.

Most importantly, the lake is formed entirely in glacial sediment. In contrast, Pokegama Lake lies within what is interpreted as a meltwater channel (Figure 35; Meyer et al., 2005). Channels such as this were scoured by southward-flowing meltwater streams draining lake basins to the north during ice retreat (Wright, 1972; Hobbs, 1983; Marlow et al. 2004). In contrast to Deer Lake, Pokegama Lake is set in both bedrock and glacial sediment. Contrasting settings of the lakes may influence groundwater flow and geochemistry.

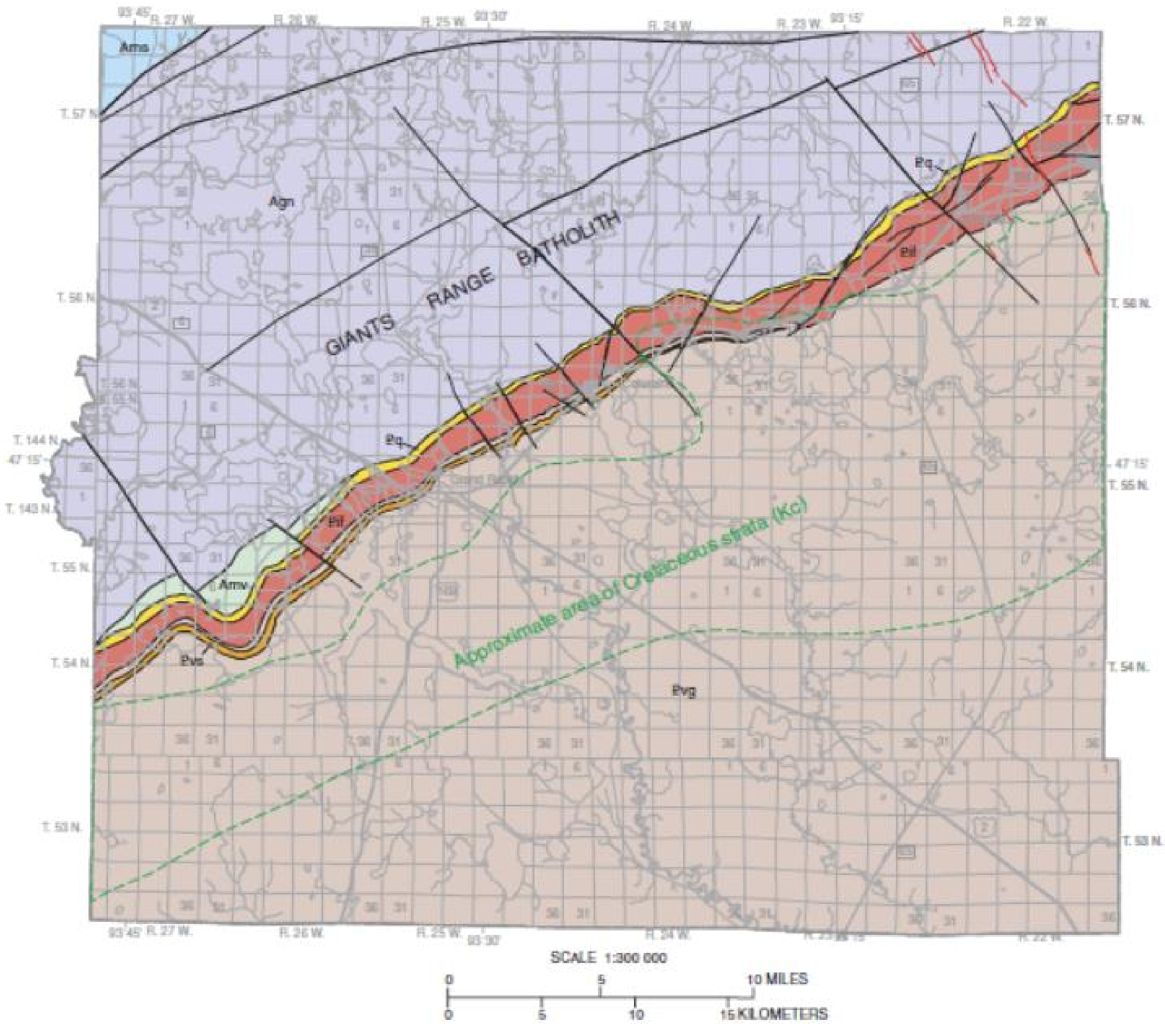


Figure 31: Map showing bedrock geology of the study area (map from Meyer and Jirsa, 2005).

Agn = Neoarchean granitic gneiss and foliated granitic intrusions; Amv = Metavolcanic rock; Pvg and Pvs = Paleoproterozoic Virginia Formation slate, greywacke and siderite; Pif = Biwabik Iron Formation; Pq = Pokegama Quartzite. Dashed green lines show extent of the Cretaceous Coleraine.

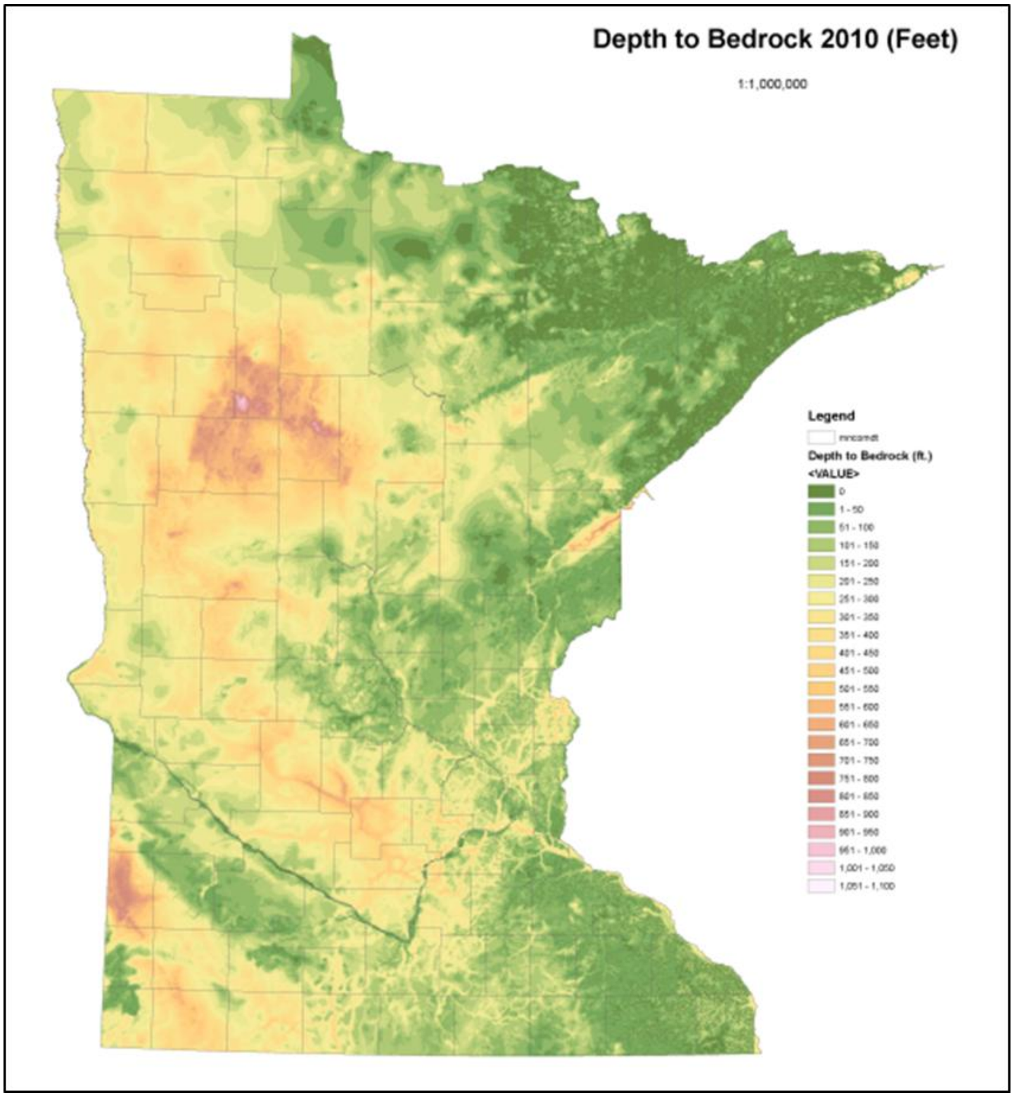


Figure 32: Map showing depth to bedrock in Minnesota.

(Created by the Minnesota Geological Survey www.mcc.mn.gov/maps.html). Depth to bedrock in the study area ranges from 33 to 91.4 m (100 to 300 ft).

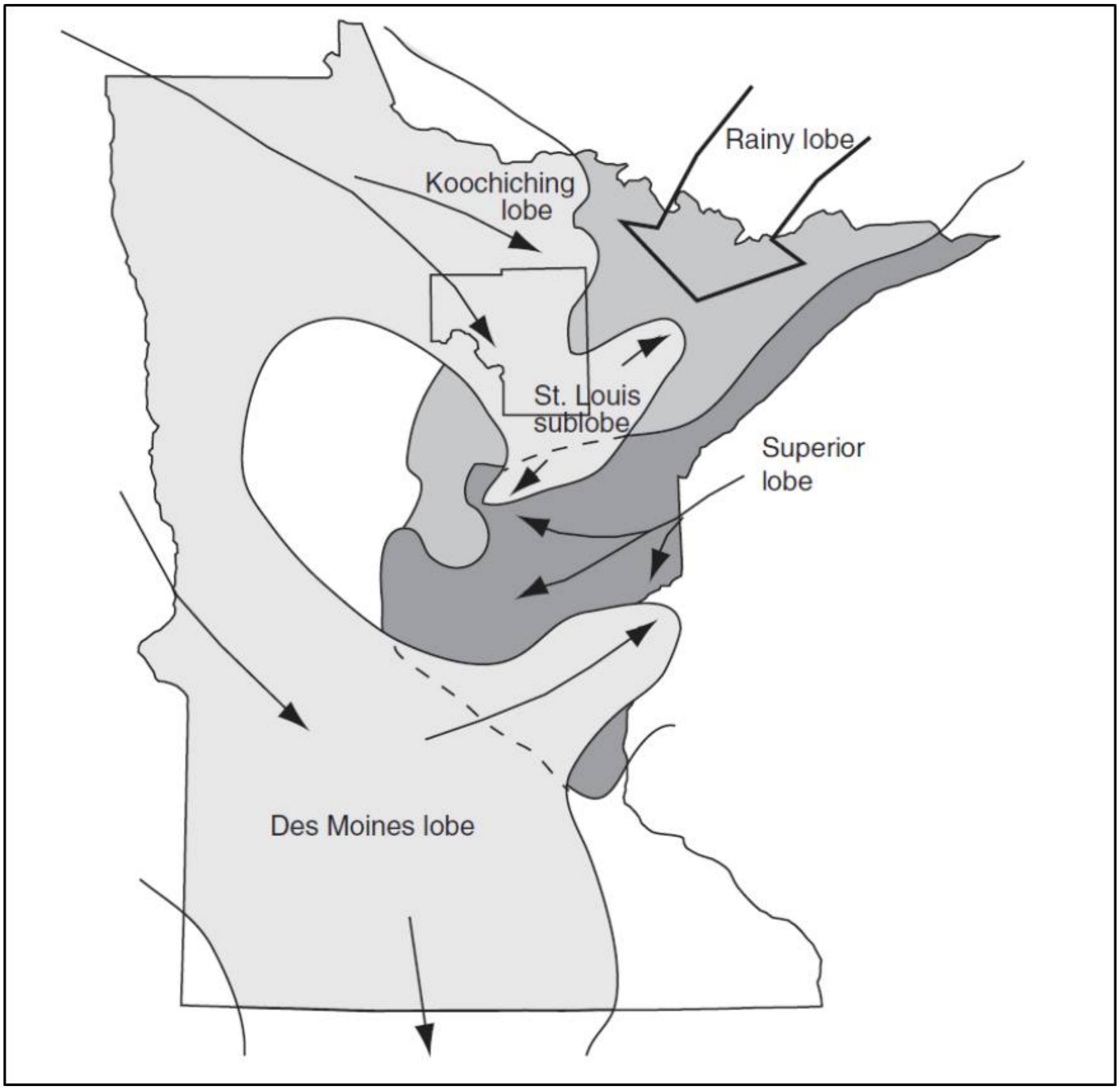


Figure 33: Map of Minnesota showing the major ice lobes that influenced Itasca County during Wisconsinan time.

The Rainy lobe advanced first into the county (shown by the box) during the early to middle Wisconsinan, followed by an advance of the St. Louis sublobe of the Des Moines Lobe from the northwest during the late Wisconsinan (map from Meyer et al., 2005).

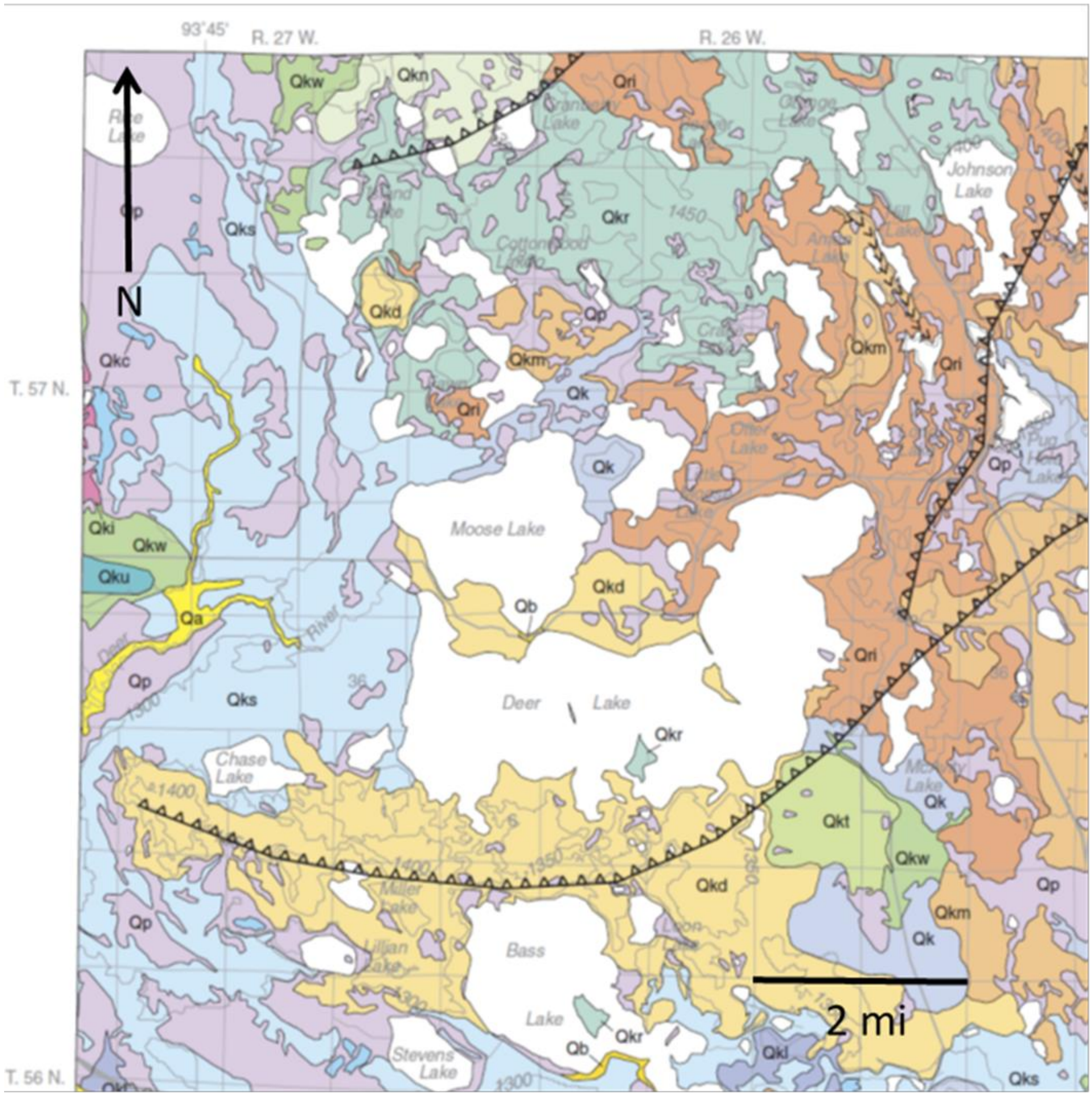


Figure 34: Surficial geologic map showing glacial sediments in the vicinity of Deer Lake.

(Map from Meyer et al., 2005). Qri = ice contact sediment of the Rainy lobe; Qkd = deltaic sediment of the St. Louis sublobe; Qks = glacial lake sediment of the St. Louis sublobe. Ice margins denoted by lines with teeth pointing up ice.

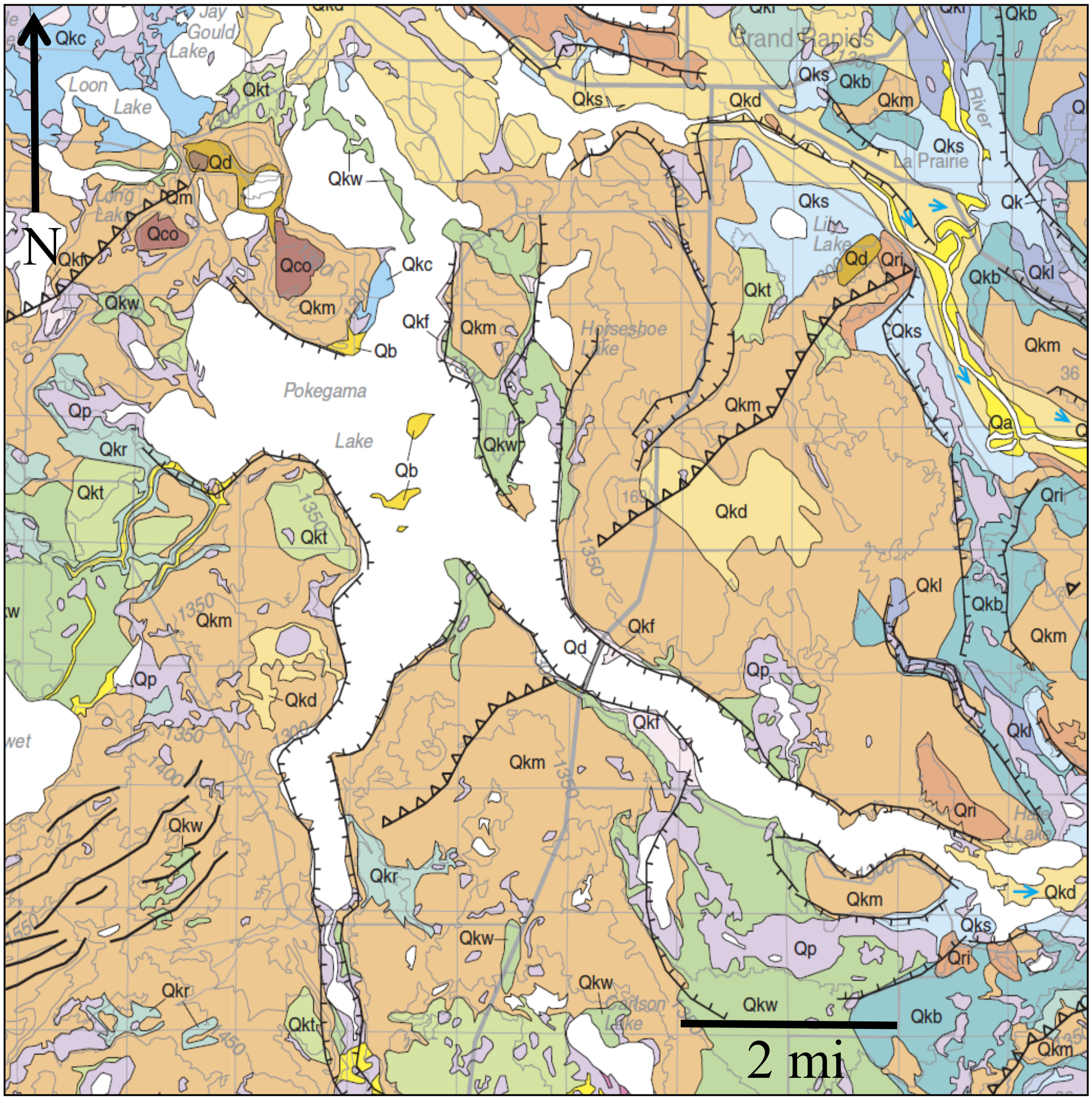


Figure 35: Surficial geologic map showing glacial sediments in the vicinity of Pokegama Lake and meltwater channels that outline the lake (lines with inward marks).

Qkm = till of the St. Louis sublobe less than 20 ft thick and underlain by Rainy-lobe sand and gravel; Qkw = till modified by water in association with glacial lakes.

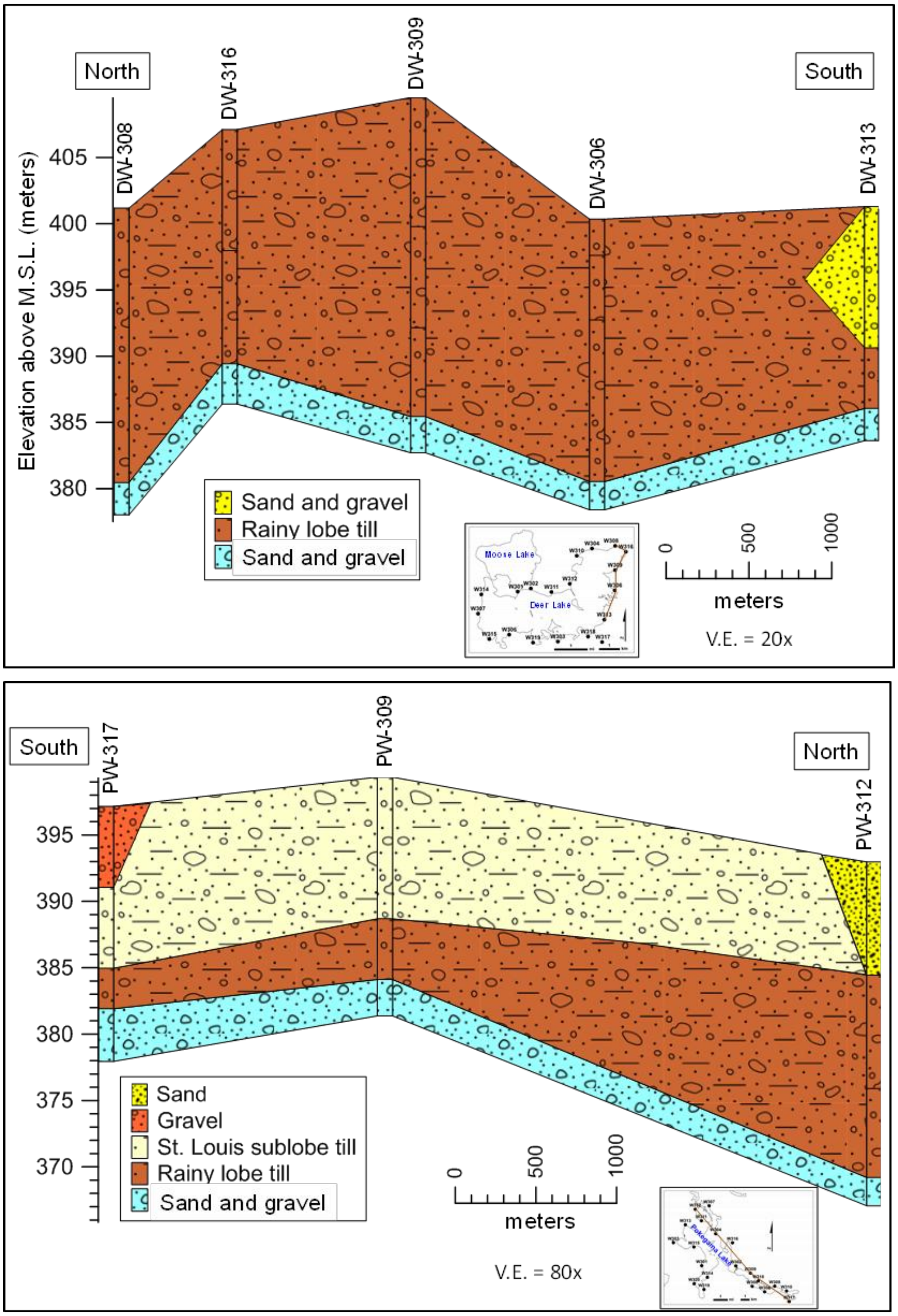


Figure 36: Cross sections showing glacial stratigraphy at Deer Lake and Pokegama Lake.

Cross sections showing glacial stratigraphy at Deer Lake (top) and Pokegama Lake (bottom). The deep sand and gravel deposit below the till units is the aquifer commonly used for drinking water from private wells. Well logs were obtained from the Minnesota County Well Index.

Local Importance of the Resources

Pokegama Lake (DNR ID#31-0532) is a 6,612-acre lake with part of the lake being within the city limits of both Grand Rapids and Cohasset. Pokegama is classified as a General Development lake. It is a large, deep lake (max depth ~110 ft), and its shoreline is primarily private and highly developed. The lake is extensively used for recreation and has seven public accesses. The US Army Corps of Engineers (USACE) utilizes Pokegama Lake as a reservoir for the Mississippi River. The USACE dam is located 3.5 river miles below the outlet of Pokegama Lake. Pokegama Lake's watershed is extensive due to its connection to the Mississippi River and includes the entire Upper Mississippi Headwaters watershed (Figure 37) north and west of Pokegama Lake. Due to the expanse of Pokegama's entire watershed, the study focused on the lake's immediate lake watershed. The lake's special features include the Bass Brook Wildlife Area, the Drumbeater Scenic and Natural Area, and the Chisholm Island Scientific and Natural Area.

Deer Lake (DNR ID#31-0719) is a 4,097-acre lake whose waters run deep (max depth ~110 feet) and clear. It is classified as a Recreational Development lake with moderate to high shoreline development and scattered rural residential development. There is one public access on its southwest shore and it experiences moderate to high recreational use during the summer months. Deer Lake's watershed is also part of the larger Upper Mississippi Headwaters watershed (Figure 37) and it lies partially within the Chippewa National Forest. Its special features include the Bear Island Wildlife Management Area (which has a conservation easement), a scientific and natural area, and an aquatic management area.

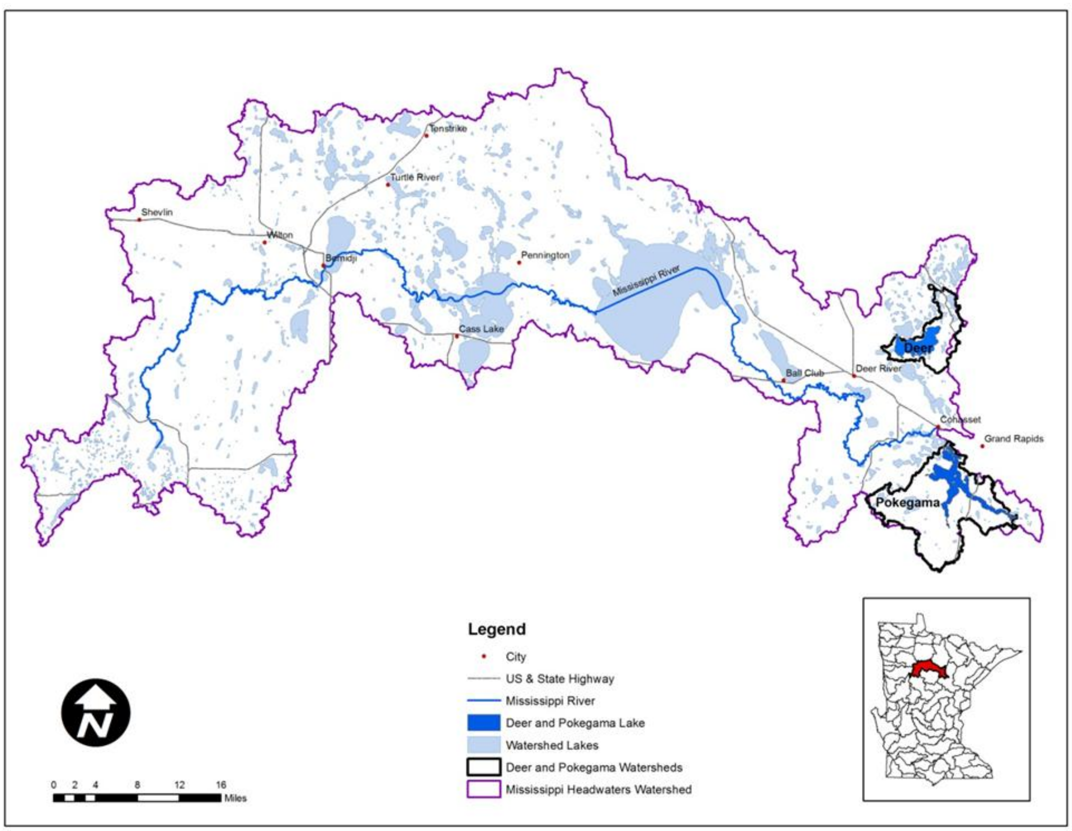


Figure 37: Mississippi Headwaters Watershed.

Social Setting

Lake Associations

Deer and Pokegama lakes both have lake associations that are active and committed to protecting the future of these two highly valued resources. Both associations have developed lake management plans and are actively implementing them and have been instrumental in assisting with monitoring and volunteer coordination for the CWP study.

The Deer Lake Association is composed of Deer Lake residents and friends. It was formed primarily to provide leadership and a collective voice for preserving and maintaining the high quality of Deer Lake's water, its surrounding land, and the community. Members value Deer Lake's fragile ecosystem, the beauty of its shoreline and islands, and the clarity and magnificent hues of its water. The association's mission is: "The Deer Lake Association will provide leadership to preserve and maintain the high quality of Deer Lake, the surrounding land, and community. Encouraging friendship and education of the community."

The purpose of the Greater Pokegama Lake Association is to: "Prevent the pollution and retard eutrophication of Pokegama Lake, including the power to do all things necessary to educate the public at large on preventing the pollution of Pokegama Lake, to obtain the necessary laws to prevent any deleterious impact, and also to engage in any studies that would provide better understanding of the dynamics of the lake and its watershed." It is also the aim of the organization to: "Maintain the desirable environmental quality of the existing lake and lakeshore area and to promote its orderly development and environmentally sound management."

Description of the Waters of Concern

Watersheds and Landuse

Pokegama Lake's watershed is 49,084 acres (including lake surface area; not including the entire upper Mississippi River watershed) in size and covers 76 square-miles. It lies on the southeastern edge of the Mississippi Headwaters Basin and is located in the Northern Lakes and Forests Ecoregion. There are 20 sub-watersheds within the Pokegama Lake watershed, 19 inlet tributaries, and the lake's direct sub-watershed. Major inlets to Pokegama include Munzer Creek (PST006) on the Wendigo Arm, Smith Creek (PST009) on the Sherry's Arm, and Sugar Brook (PST020), which flows from Sugar (Siseebakwet) Lake and enters Pokegama's Sugar Bay. Many of the other streams flowed intermittently or were ephemeral (i.e., Highway 169 north storm water pond PST002).

The National Land Cover Database 2006 (NLCD2006) was used to conduct the landuse analysis of the watershed. The 16 landuse cover classifications were condensed into 9 categories that aligned with inputs for the Wisconsin Lake Modeling Suite, which was used to model Pokegama Lake. Pokegama Lake's watershed (Figure 38) is dominated by forested cover (54%) along with open water and wetlands (30% of the total area). Pastured grasslands make up 12% of the area, and the remaining 5% contain a mix of residential and agricultural crop fields (Figure 39). Although urban and rural residential areas account for a minimal part of the watershed area, the majority of this development is located along the shores of Pokegama Lake. The land use data for each of the sub-watersheds is presented in Table 6.

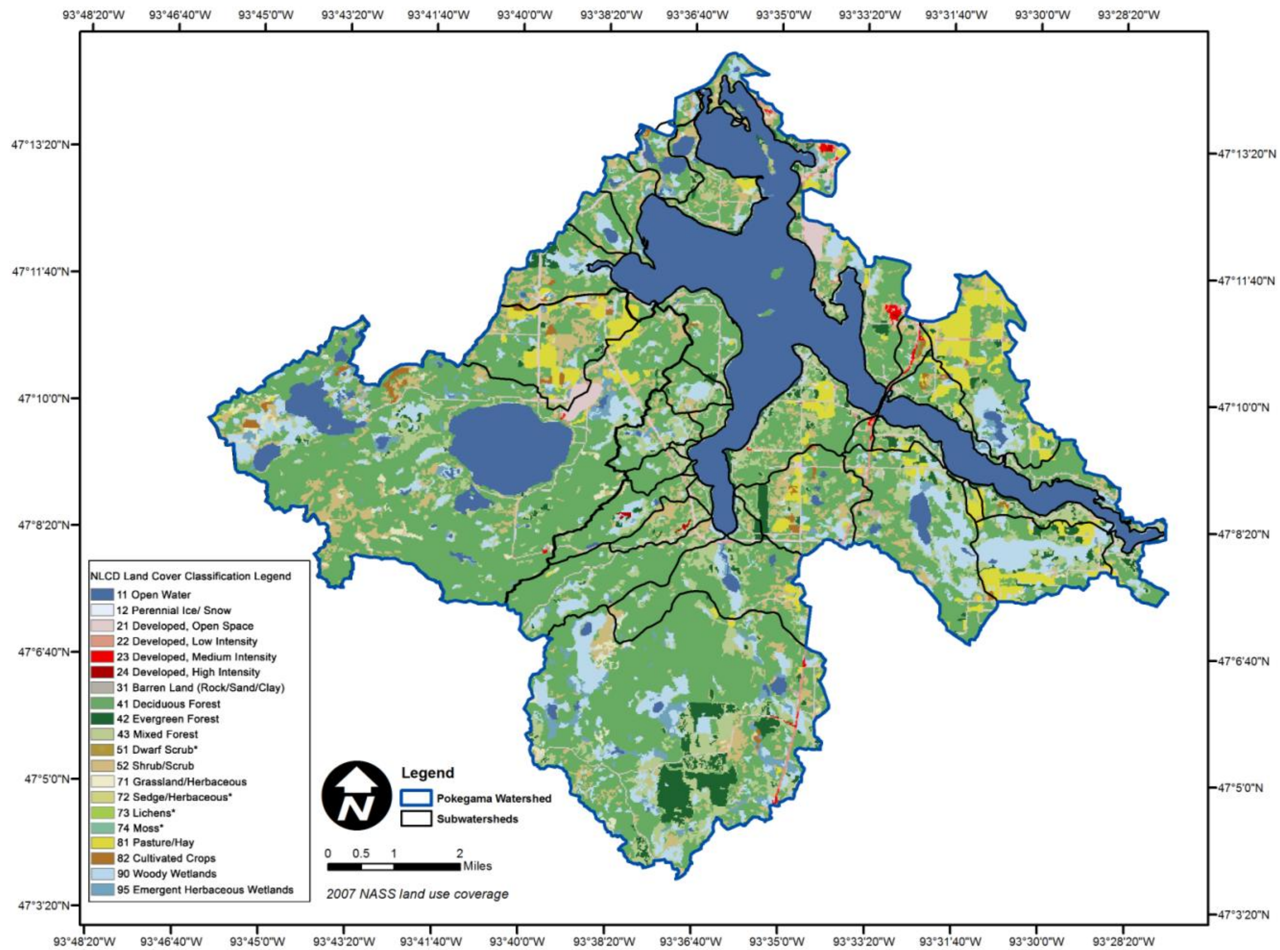


Figure 38: Landuse coverage for Pokegama Lake sub-watersheds.

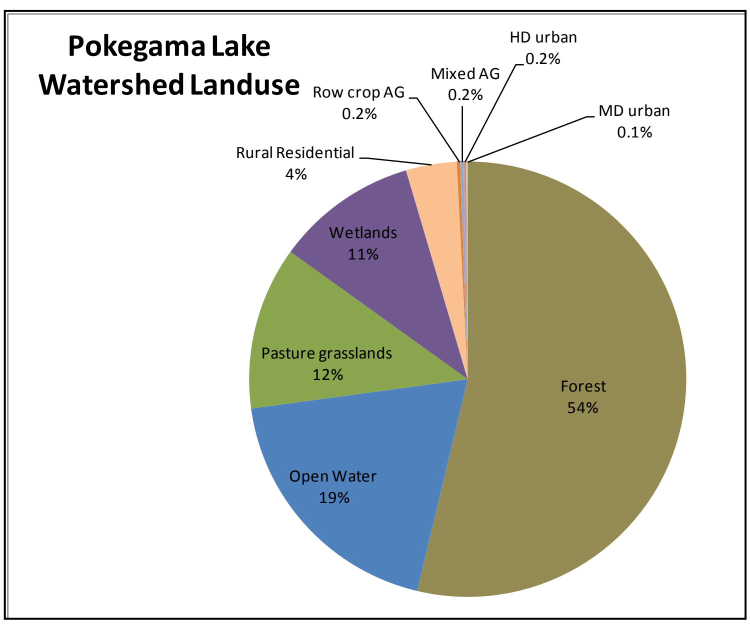


Figure 39: Pokegama watershed land use breakdown.

Subwatershed	Forest	Open Water	Pasture/ Grasslands	Wetlands	Rural Res	Row crop AG	Mixed AG	HD Urban	MD Urban	Total (acres)
Direct Wtshd	4890	313	1314	645	682	18	18	74	19	7972
2	115	--	51	6	29	6	6	--	14	226
3	762	56	663	223	91	2	2	4	1	1803
4	580	11	290	434	45	1	1	--	--	1362
5	27	--	44	2	2	--	--	--	--	75
6	1356	132	252	498	88	2	2	--	--	2329
7	61	--	7	2	18	--	--	--	6	94
8	756	22	307	99	91	17	17	--	--	1308
9	5963	124	617	1474	161	6	6	2	14	8365
10	1210	57	177	131	41	--	--	--	--	1616
11	1150	4	54	129	47	--	--	--	--	1385
12	239	--	88	8	28	--	--	6	--	370
13	492	11	40	77	15	--	--	8	--	643
14	213	--	2	6	15	--	--	--	--	236
15	361	5	36	89	22	--	--	--	--	514
16 & 17	205	--	48	71	14	--	--	--	--	338
20	6751	1813	1171	991	287	40	40	--	2	11095
21	749	2	640	120	127	26	26	--	--	1690
22	226	25	34	57	15	--	--	--	--	357
23	191	145	58	60	25	4	4	--	--	487
24	38	1	24	30	9	--	--	--	--	102
Pokegma Lake	--	6666	--	--	--	--	--	--	--	6666
Islands	38	--	8	5	--	--	--	--	--	51
Total (acres)	26372	9387	5927	5156	1851	121	121	94	56	49084

Table 6: 2006 NLCD land use areas for Pokegama Lake sub-watersheds.

Deer Lake's watershed is substantially smaller than Pokegama Lake at only 16,668 acres (including lake surface area) and covers an area of 26 square-miles along the far east edge of the Mississippi Headwaters Basin. There are 13 sub-watersheds within Deer Lake's watershed, 12 inlet tributaries, and the lake direct sub-watershed. Deer Lake tributaries are mainly small intermittent streams that are fed by wetlands, with the exception of site DST013, which is a small inlet that connects Little Deer Lake to Deer Lake.

Deer Lake is bounded on the north and south by the Marcell Moraine, which is extremely irregular in topography, ranging in elevation up to 1450 feet (lake elevation ~ 1309 ft). Due to the topography of the watershed, other research studies (Reed, 1992) had conflicting watershed boundaries and size. Further GIS analysis of the watershed and terrain confirms that a large part of the "watershed" to the north and east of Deer Lake is not directly connected to the lake via surface flow (runoff or streams) but via groundwater.

The National Land Cover Database 2006 (NLCD2006) was used and condensed like Pokegama to conduct the landuse analysis and modeling of Deer Lake's watershed. Deer Lake's watershed (Figure 40) is dominated by forested cover (44%) along with open water, which comprises 34% of the total watershed. Wetlands cover 10% of the watershed, pastured grasslands make up 8%, and the remaining 5% contains a mix of residential and agricultural crop fields (Figure 41). Like Pokegama, the majority of development is located along the shores of Deer and other lakes within the watershed. The land use data for the sub-watersheds are presented in Table 7.

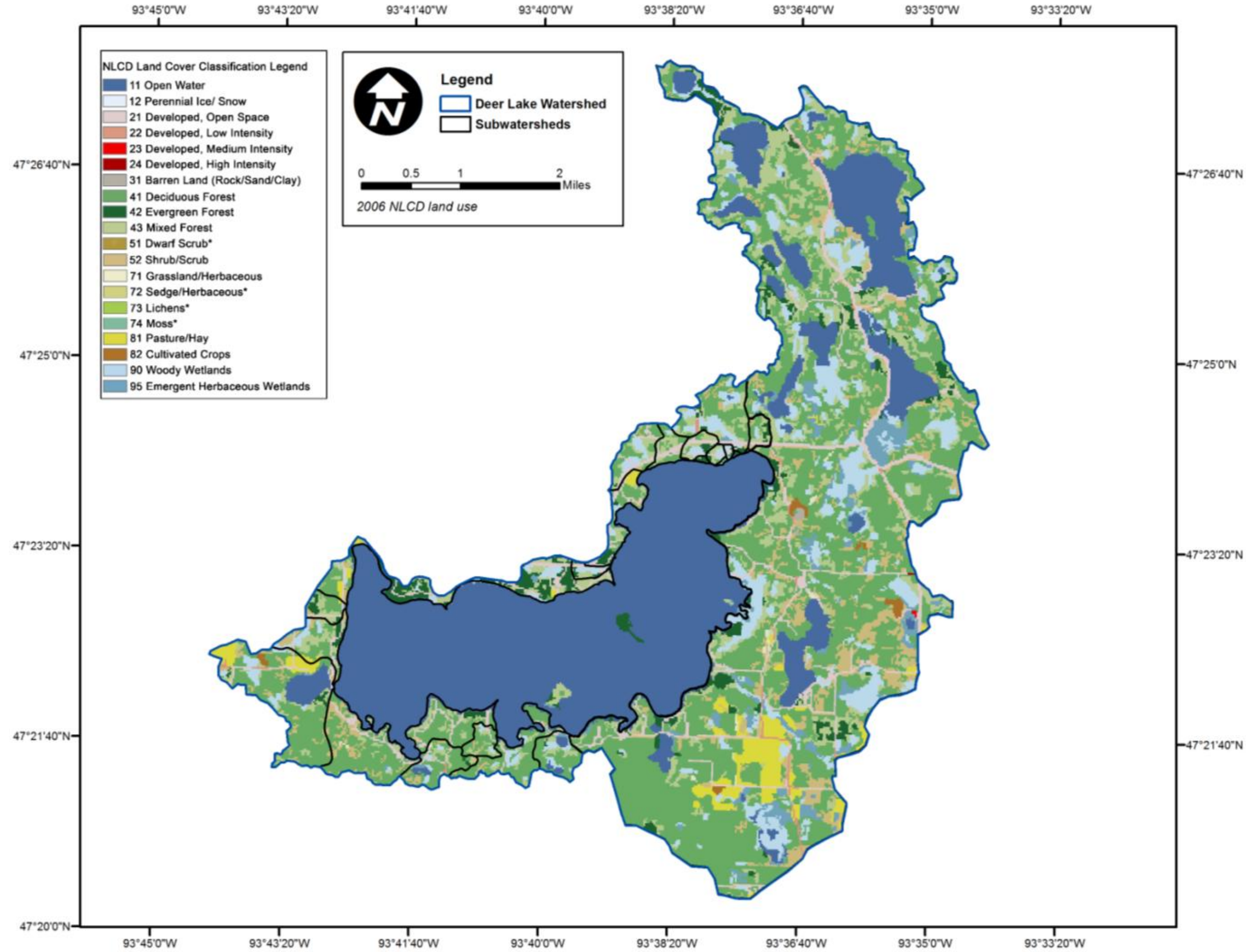


Figure 40: Land use coverage for Deer Lake sub-watersheds.

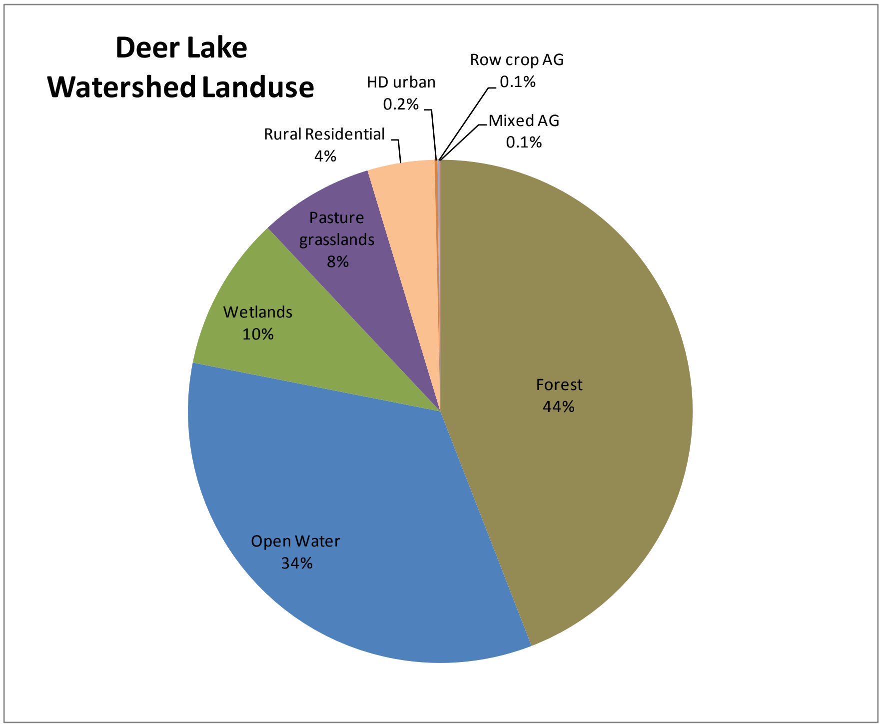


Figure 41: Deer watershed land use breakdown.

Subwatershed	Forest	Open Water	Wetlands	Pasture grasslands	Rural Residential	HD urban	Row crop AG	Mixed AG	Total
0	6458	1473	1466	1101	618	33	11	11	11174
4	13	--	10	--	6	--	--	--	30
5	71	--	21	3	19	--	--	--	114
6	27	--	7	--	12	--	--	--	46
7	10	--	5	--	2	--	--	--	18
8	2	--	4	--	2	--	--	--	7
9	145	1	59	12	13	--	--	--	230
10	32	5	3	2	--	--	--	--	42
11	46	--	4	4	3	--	--	--	57
12	85	8	11	12	12	--	--	--	128
13	302	75	36	85	22	--	3	3	526
14	49	--	1	4	6	--	--	--	59
15	69	14	18	--	2	--	--	--	104
99	--	4090	--	--	--	--	--	--	4090
999	40	--	2	--	--	--	--	--	43
Total (acres)	7349	5666	1648	1224	717	33	14	14	16668

Table 7: 2006 NLCD land use areas for Deer Lake sub-watersheds.

Lake Water Quality

Deer Lake – Trophic State and Seasonal Patterns

Based on surface samples (mixed layer measured at 6 sites) from summers 2011 and 2012 the trophic state of Deer Lake (Table 8) would be classified as oligotrophic. Geometric mean concentrations of total phosphorus (9 µg/L), total nitrogen (305 µg/L), and algal chlorophyll (0.99 µg/L) were below the widely accepted limits used to separate oligotrophic from mesotrophic lakes (Nürnberg, 1996). These concentrations suggest the average ratio of total nitrogen-to-total phosphorus was about 34, which is consistent with phosphorus limitation of phytoplankton. This ratio matches values found in lakes of the Northern Lakes and Forests ecoregion of northwestern Minnesota (NLF, Heiskary and Wilson, 2008, their Table 4). The ratio of chlorophyll-to-total phosphorus was 0.11, which is about half of the expected value for a temperate lake with this phosphorus content (Jones and Bachmann, 1976, and others) and may indicate strong grazing pressure from zooplankton (Carpenter et al., 1985). Small differences in nutrients and algal biomass between the two summers (Table 8) are consistent with temporal variation measured in other lake systems (Knowlton and Jones, 2006, and references therein).

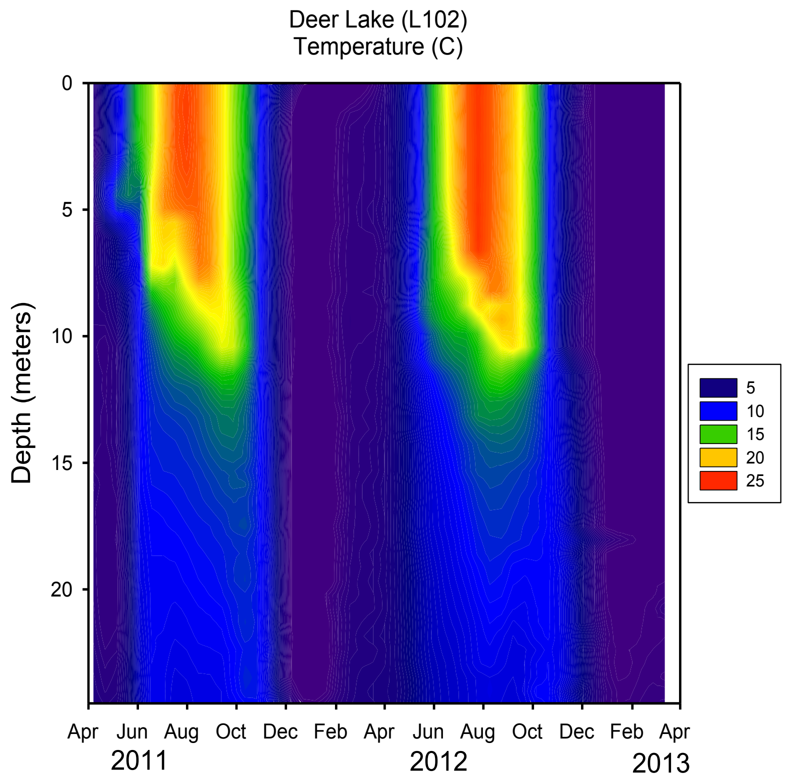
Summer Secchi transparency averaged 5 m in Deer Lake, which is consistent with water clarity in oligotrophic systems (Nürnberg, 1996). Transparent lake waters are a consequence of low algal biomass and low values of mineral and organic suspended solids (generally < 1 mg/L, Table 8). Alkalinity and conductivity (94 mg/L and 227 µmhos/cm, respectively, Table 8) are within the upper end of the interquartile range found among lakes in the NLF ecoregion (Heiskary and Wilson 2008, their Table 4). These values likely reflect the carbonate materials in local geology and the groundwater influence in Deer Lake. Most pH measurements during summer were between 8.0 and 8.5 (Table 8). These values are near the upper quartile measured in NLF lakes and may be a result of low organic color (acids), phytoplankton productivity, and productivity of the expansive macrophyte beds that cover the sediments within the photic zone of Deer Lake. Dissolved oxygen measurements in the surface layer were mostly near saturation and support the hypothesis of active productivity within the photic zone.

Figure 42: Students from Itasca Community College work on lake sampling.

Deer Lake showed dimictic stratification (Figure 43a) with a classic epilimnion (a warm, circulating surface layer) that formed in early summer to a depth of 6 to 8 m and warmed to >25 C. This layer deepened and then cooled by late summer. The metalimnion, located below to a depth of about 12 m was characterized by temperatures of about 15 C. The water column cooled during fall and showed holomictic mixing. The lake was covered with ice during winter. Ice-off varies; it was recorded on April 1, 2012, but was delayed until May 18, 2013. Spring overturn is a warming period that ends with formation of the summer epilimnion.

Oxygen depletion, measured as concentration and percent saturation, occurred in Deer Lake during summer stratification (Figure 43 b and c); the deepest areas of the water column were devoid of oxygen by late summer with much of the hypolimnion showing hypoxia (<2 mg/L). Oligotrophic lakes are known to show some oxygen depletion (Nürnberg, 1996) but the low concentrations and oxygen depletion in most of hypolimnetic volume of Deer Lake is surprising. A reasonable hypothesis is that groundwater devoid of oxygen entered the hypolimnion and contributed to oxygen depletion attributed to decomposition of autochthonous organic matter. Oxygen depletion also occurred during winter stratification (Figure 43 b and c), but was less complete (measured as concentration and saturation) and included a smaller volume of water than summer. Low pH values and increased conductivity in the bottom waters coincided with zones of oxygen depletion during seasonal stratification (Figure 43 d and e). Low pH and increased conductivity are consistent with carbon dioxide release concurrent with decomposition and increased levels of calcium bicarbonate and other ions. Values of pH and conductivity were nearly uniform during spring and fall periods of holomixis.

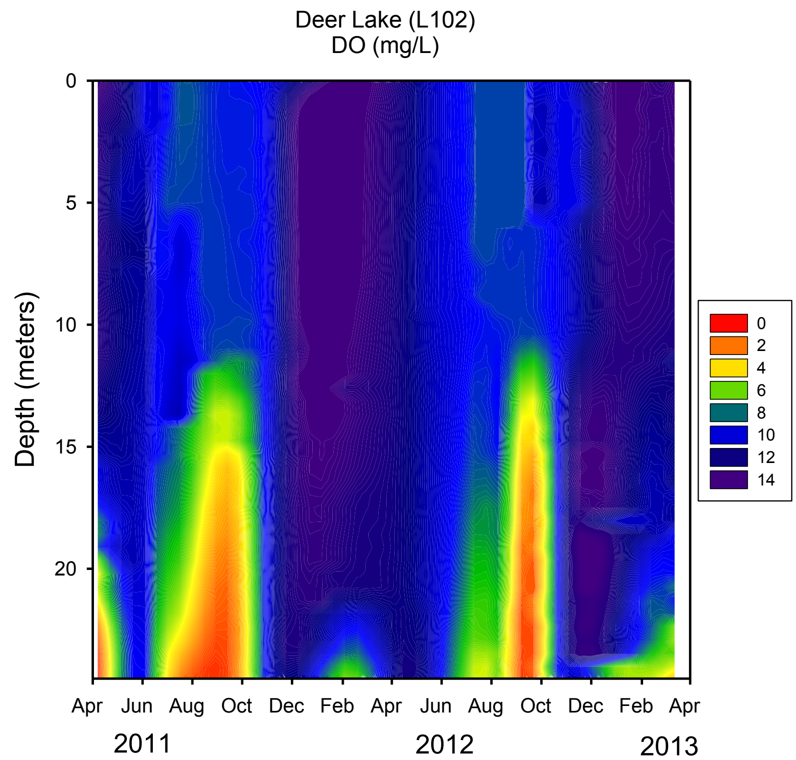
Nutrient chemistry and transparency in Deer Lake reflect the seasonal pattern found in dimictic lakes. The annual mean and overall mean values for water chemistry metrics differ only slightly from summer measurements and are a consequence of seasonal fluctuations (Tables 8 and 9). Transparency was at a minimum in late summer (Figure 44) at about 3 m and was at maximum during the clear-water phase of spring (8.9 m). This pattern is typical of temperate lakes and reflects maximum algal biomass during summer and zooplankton grazing in the water column during spring. Total phosphorus and nitrogen in the water column of Deer Lake show nearly uniform concentrations with depth during periods of holomixis. During summer stratification, there was a slight increase in total phosphorus with depth that likely resulted from release from organic materials during decomposition and mobilization of this element under anoxic conditions (Figure 45). In contrast, total nitrogen concentrations decreased in the summer hypolimnion, presumably this reflects denitrification during periods of anoxia. The deep-water sample collected in November 2011 shows extreme concentrations of phosphorus and nitrogen and may reflect conditions in the interstitial water of the sediments rather than conditions within the deep zone of the water column.



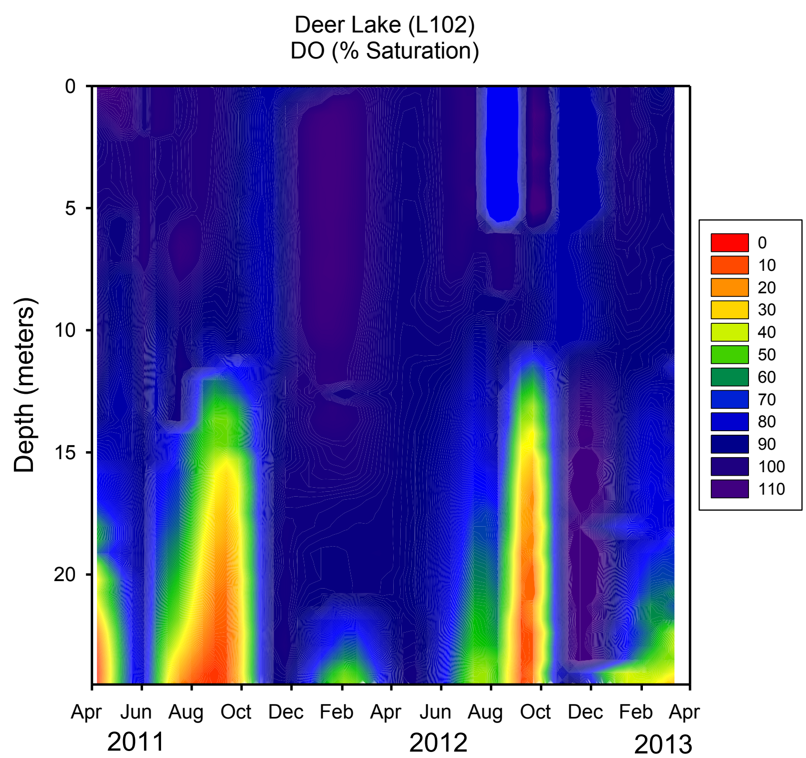
Isopleth diagrams are time and depth depictions of conditions in the water column. Temporal patterns were similar at the other sampling sites (data not shown).

Temperature (43 a)

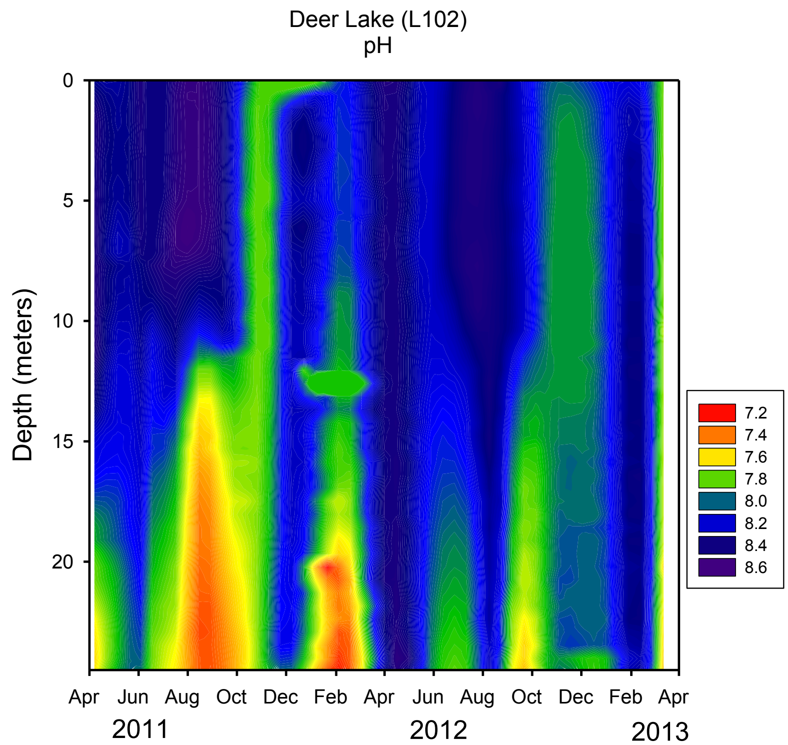
Figure 43 a-e: Isopleth diagrams based on data collected from Deer Lake (L 102) during 2011 to 2012.



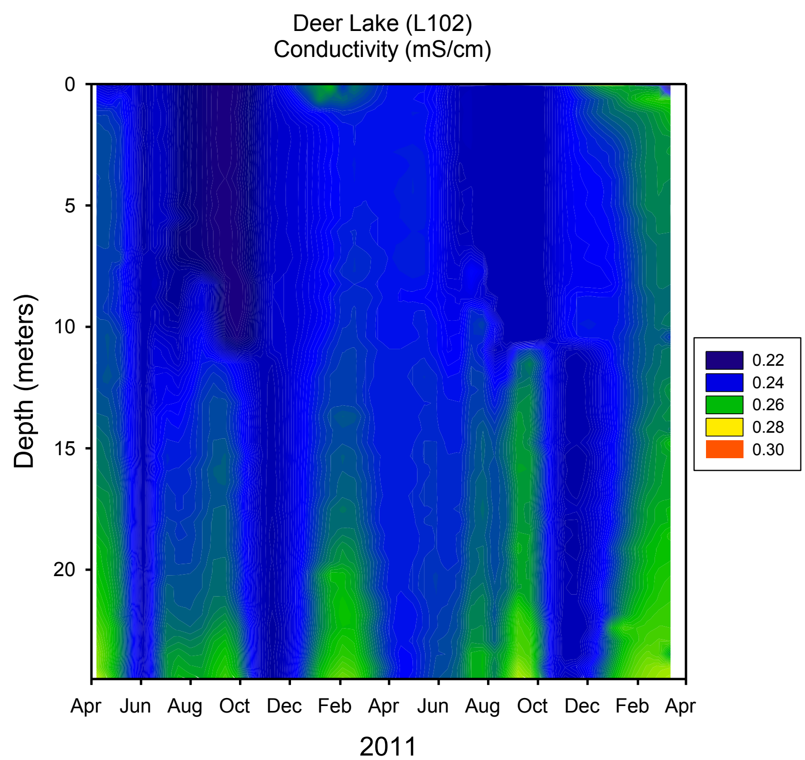
Dissolved oxygen concentration (43 b)



Dissolved oxygen saturation (43 c)



pH (43 d)



Conductivity (43 e)

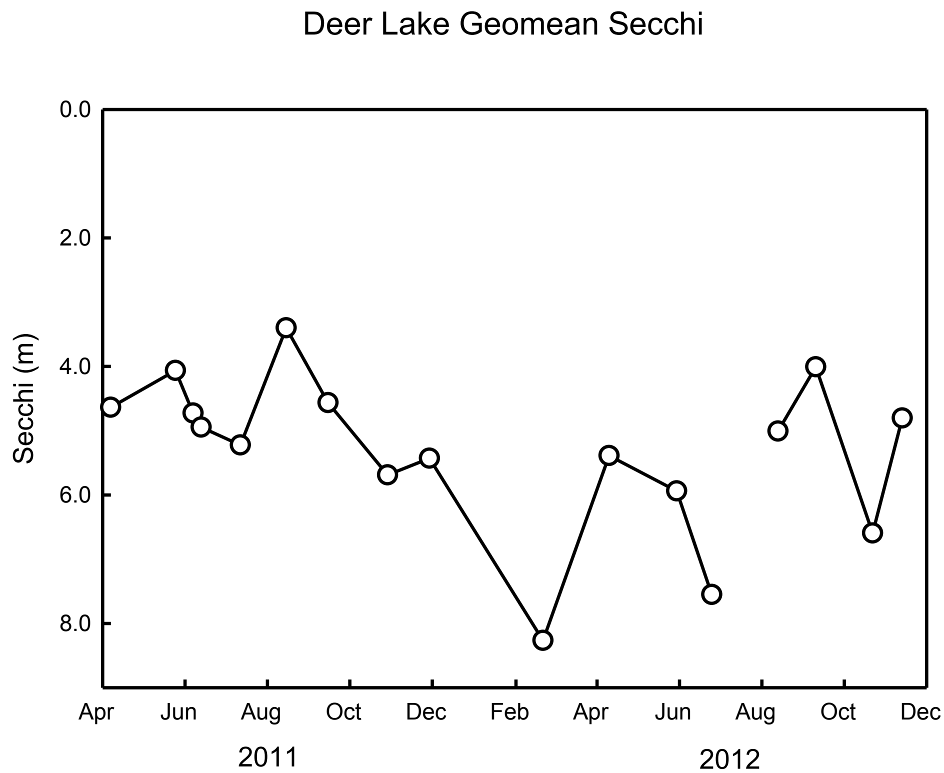
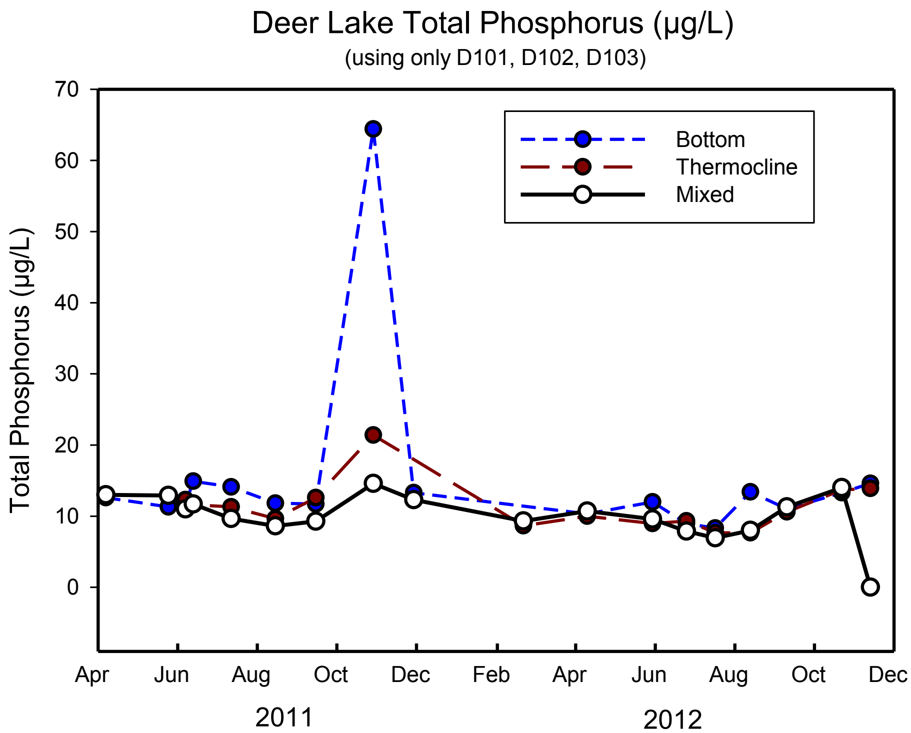


Figure 44: Transparency in Deer Lake during 2011 to 2012 measured with a Secchi disk.

Data are the geometric mean of collections from 6 sampling sites.



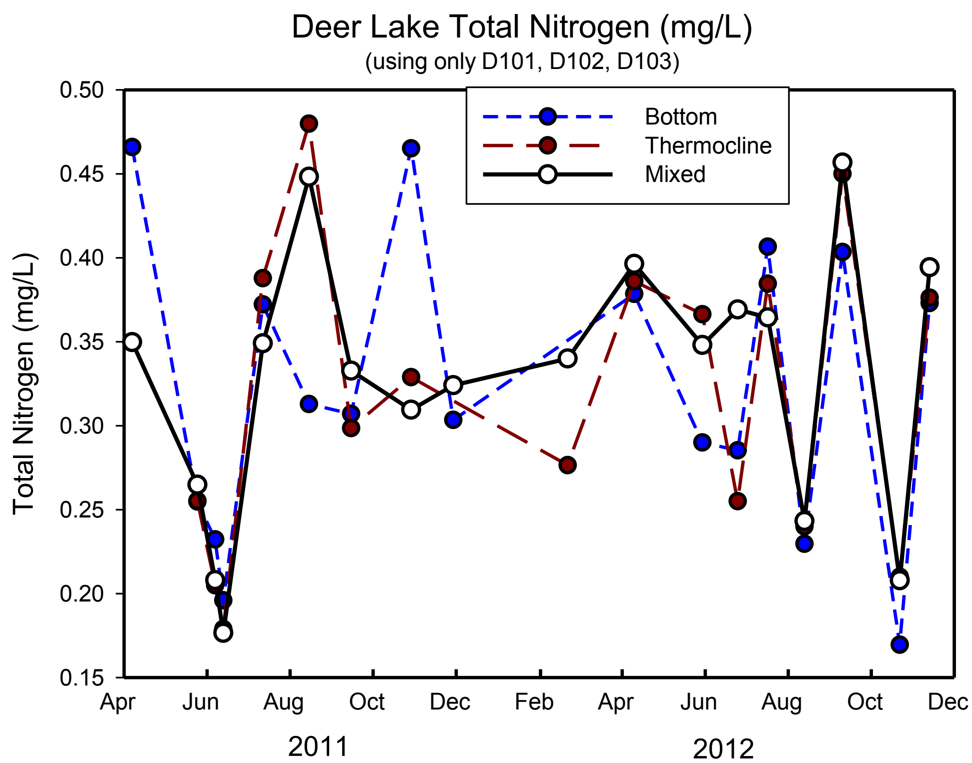


Figure 45: Total phosphorus and total nitrogen values from Deer Lake during 2011 to 2012

Data show the temporal pattern in both nutrients in the mixed layer (surface), mid water column, and at depth. Data are the geometric averages from the 3 deepest locations (L 101, 102, and 103).

Pokegama Lake – Trophic State and Seasonal Patterns

Based on surface samples (mixed layer measured at 6 sites) from summers 2011 and 2012, the trophic state of Pokegama Lake (Table 8) is mesotrophic. Geometric mean concentrations of total phosphorus (16 µg/L), total nitrogen (473 µg/L), and algal chlorophyll (3.6 µg/L) are within the range generally accepted for mesotrophic lakes (Nürnberg, 1996). These concentrations suggest the average ratio of total nitrogen-to-total phosphorus was about 30, which is consistent with phosphorus limitation of phytoplankton. This ratio matches the mid-range of values reported from lakes of the Northern Lakes and Forests ecoregion of northwestern Minnesota (NLF, Heiskary and Wilson 2008, their Table 4). The ratio of chlorophyll-to-total phosphorus was 0.22, which is slightly below the expected value for a temperate lake with this phosphorus content (0.29, Jones and Bachmann, 1976, and others), but within the range of normal variation. Differences in nutrients and algal biomass between the two summers (Table 8) were quite small and may reflect the riverine influence of this impounded lake.

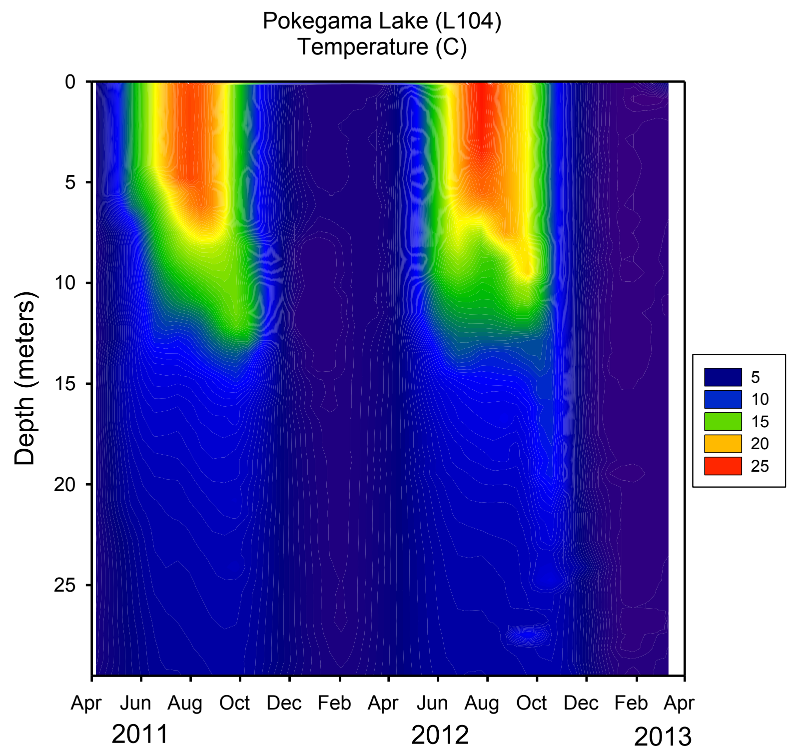
Summer Secchi transparency averaged 3.7 m in Pokegama Lake, which is consistent with water clarity in mesotrophic systems (Nürnberg, 1996). Transparency of lake water is determined by scattering absorption of light by particles (algal cells and suspended solids, both mineral and organic), dissolved organics, and the water molecule. An empirical relationship between Secchi transparency and algal chlorophyll developed for temperate lakes (Jones and Bachmann, 1978) predicts transparency in Pokegama Lake at 3.0 m (versus an average of 3.7 m). This finding suggests moderate influences of suspended solids (generally < 2 mg/L, Table 8) and dissolved organics in this lake. Alkalinity and conductivity (129 mg/L and 260 µmhos/cm, respectively, Table 8) are within the upper end of the interquartile range found among lakes in the NLF ecoregion (Heiskary and Wilson, 2008, their Table 4). These values likely reflect the carbonate materials in the watershed and groundwater influences. Most pH measurements during summer were between 8.0 and 8.5 (Table 8). These values are near the upper quartile measured in NLF lakes and may be a result of low organic color (acids) and suggest the release of hydroxyl ions as a consequence of productivity by phytoplankton and macrophytes within the photic zone of Pokegama Lake. Dissolved oxygen measurements in the surface layer were at saturation and support the hypothesis of active productivity within the photic zone.

Pokegama Lake is dimictic (Figures 47 a and b). A classic epilimnion (a warm, circulating surface layer) formed in early summer to a depth of about 7 to 8 m and this layer subsequently warmed to >25C. The epilimnion cooled and deepened in late summer prior to the transition to homothermal circulation during fall, which is the pattern in dimictic lakes. The summer metalimnion (beneath the epilimnion), located to a depth of about 12 m, was characterized by temperatures of around 15 C. At the deepest sites in the western side of the main basin temperatures below the metalimnion were about 12 C. At the deepest sites toward the western side of the lake (L 102 in Sugar Bay and L 104 in Sherry Arm Bay). Temperatures in the water column declined with depth, which is consistent with the classic pattern in dimictic lakes, and the summer temperature profile at these sites showed a true hypolimnion (Figure 47a). In contrast, temperature profiles from a deep sampling location on the western side of the lake (L 105 south of King Bay, Figure 47b) showed metalimnetic temperatures extending to 20 m, or greater, during both summers of this study. At this location the hypolimnion was truncated in summer 2011 and not clearly defined in summer 2012 (Figure 47b); the metalimnion extended to the sediments at this location. Such sharp differences in temperature profiles between sites within a single lake basin are uncommon. It likely results from physical factors that involve lake morphology and prevailing wind directions. It seems wind-driven internal waves trap warm water in the narrow arm of the lake that extends to the southeast of Pokegama Lake. Conditions in the southern end of Poole Bay (L103, data not shown) were intermediate between these extremes. This study was designed to detect these patterns, but not address the factors that account for atypical stratification in Pokegama Lake. The information gathered provides the basis for further study of this finding. During fall, the lake demonstrated holomictic circulation at all sampling sites and progressive cooling over time. Ice covered the lake during winter. Following ice-off in the spring the lake underwent spring holomixis and warming that resulted in summer stratification.

Oxygen depletion, measured as concentration and percent saturation (Figures 47 b and c), occurs in the hypolimnion during summer with values <2 mg/L at the bottom of the water column (Figures 47 c and d). Oxygen depletion in the hypolimnion was greater in summer 2012 than 2011 (lower concentrations) and was more extensive (low values in a larger volume of the water column). In both summers there was oxygen depletion within the metalimnion of this mesotrophic lake (Figures 47 b and c), but oxygen concentration was > 5 mg/L in the metalimnion during summer 2011 and <5 mg/L in 2012. For many warm-water fish species, optimal conditions broadly include temperatures cooler than 24 C with dissolved oxygen > 5 mg/L (Matthews et al. 1985) and the metalimnion of Pokegama Lake would not have provided an ideal refuge from the warm epilimnetic temperatures of mid-summer 2012 (Figures 47 a and c). On the western side of the lake the entire water column below a depth of 5 m had oxygen concentrations <5 mg/L during mid-summer (L 105 south of King Bay, Figure 47d) and would not have been suitable habitat for warm-water fishes in 2012. It is common for mesotrophic lakes to show oxygen depletion (Nürnberg, 1996) as a consequence of decomposition of autochthonous and allochthonous organic matter. Groundwater, devoid of oxygen, may have also contributed to the oxygen pattern in this lake. Oxygen depletion also occurred during winter stratification (Figure 47 b, c, and d), but was less complete and included a smaller volume of water than summer. This seasonal difference in oxygen is common and is a consequence of less organic production during winter and cold temperatures that slow bacterial decomposition of organic matter. Low pH values and increased conductivity in the bottom water coincided with zones of oxygen depletion during stratification (Figures 47 e and f). Low pH and increased conductivity are consistent with carbon dioxide release during decomposition and the subsequent increase in calcium bicarbonate and other ions. Values of pH and conductivity were nearly uniform during spring and fall periods of holomixis.

Nutrient chemistry and transparency in Pokegama Lake reflect the seasonal pattern of dimictic lakes. The annual mean and overall mean values for water chemistry metrics differed only slightly from the summer averages (Tables 8 and 9). Transparency was at a minimum during summer, at about 3 m and the maximum value of 7.7 m was collected in early-summer 2012 (Figure 48, Tables 8 and 9). Temperate lakes often show maximum transparency during spring as a consequence of seasonal zooplankton grazing of algal cells from the water column. Total phosphorus in the water column of Pokegama Lake showed nearly uniform concentrations with depth during most sampling periods (Figure 49). Nitrogen concentrations were more variable with depth than. Samples from summer 2012 consistently showed less nitrogen in samples from the thermocline and near-bottom, which likely reflects denitrification in zones of anoxia. A sharp decline in the total nitrogen concentration of Pokegama Lake in June 2012 coincided with an increase in lake level in response to riverine inflow (Figure 49); concurrently there was a small increase in total phosphorus (Figure 49). This event demonstrates the influence of riverine inflow on the nutrient budget of this lake. High concentrations of total phosphorus and nitrogen in a bottom sample from fall 2011 and a bottom sample from winter 2012 suggest these collections may have included interstitial water from the surface sediments.

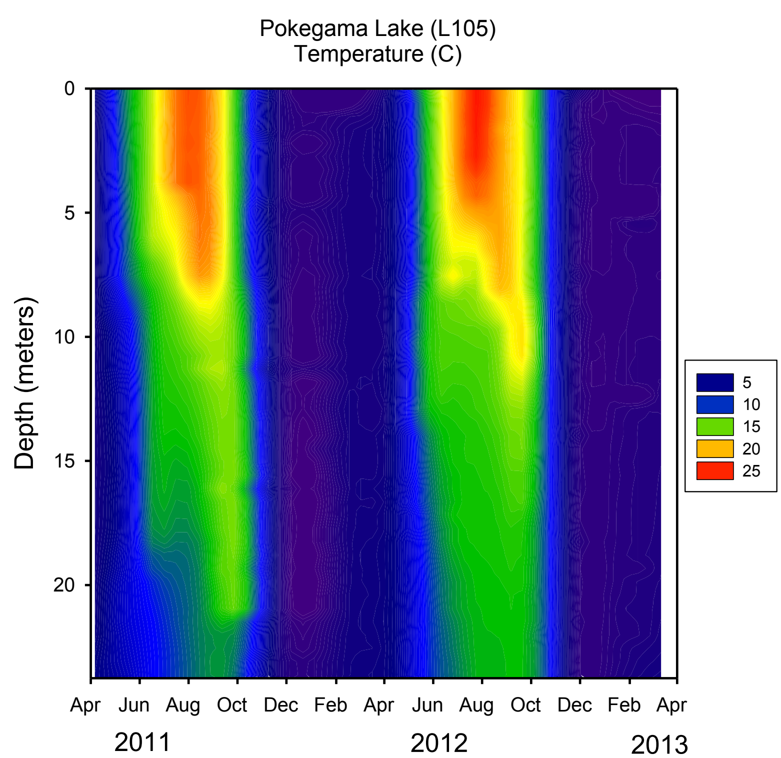
Figure 46: Matt Johnson (ICSWCD) winter lake monitoring.



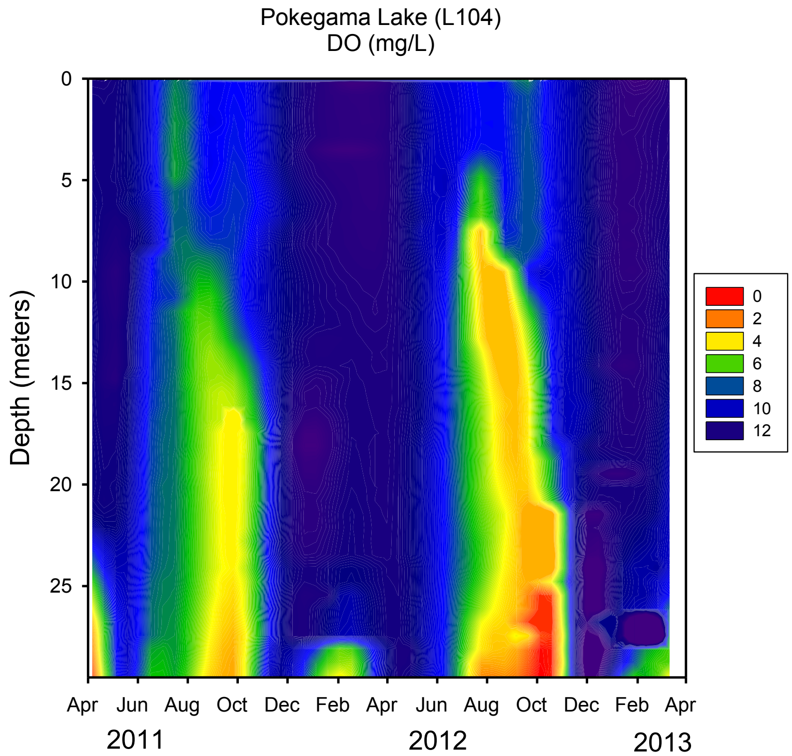
Isopleth diagrams are time and depth depictions of conditions in the water column. Temporal patterns were similar at the other deep-water sampling site on the western side of the lake (L 102, data not shown). Temperature (40 b) and oxygen concentration (40 e) from site L 105 on Pokegama Lake are included to illustrate spatial variation in this lake.

Temperature (47a)

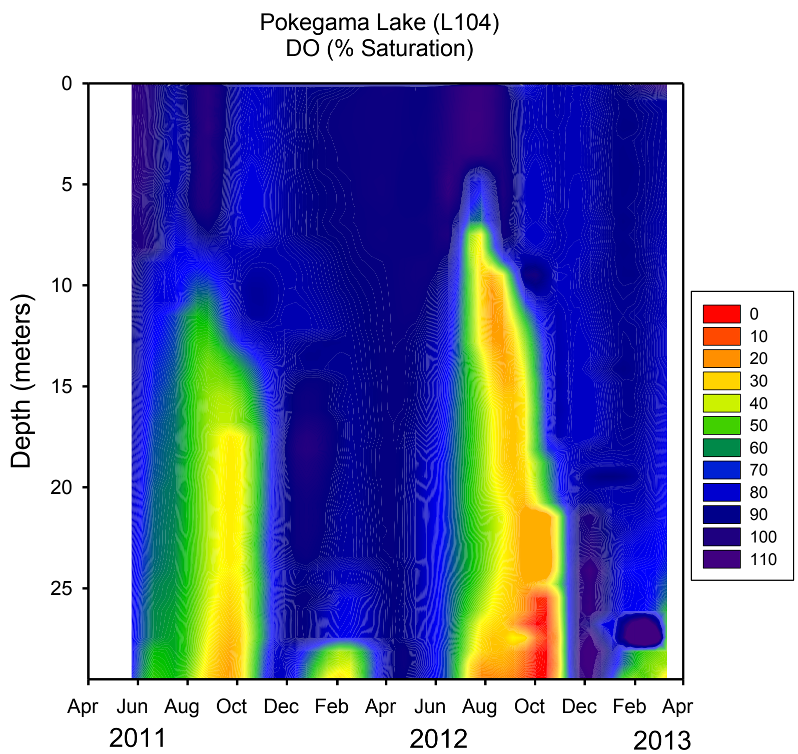
Figure 47 a-g: Isopleth diagrams based on data collected from Pokegama Lake (L 104) during 2011 to 2012.



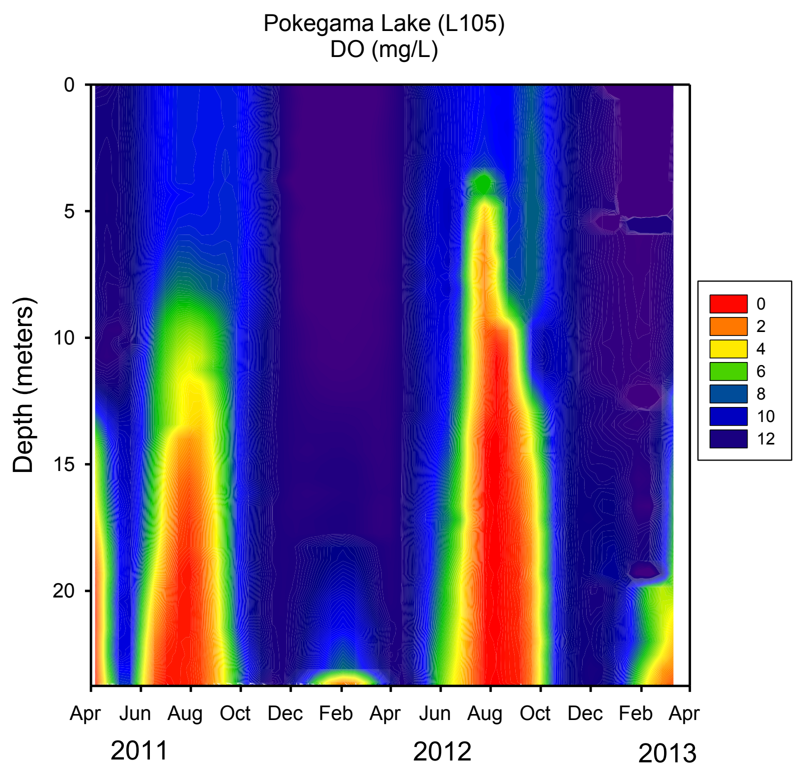
Temperature (47b)



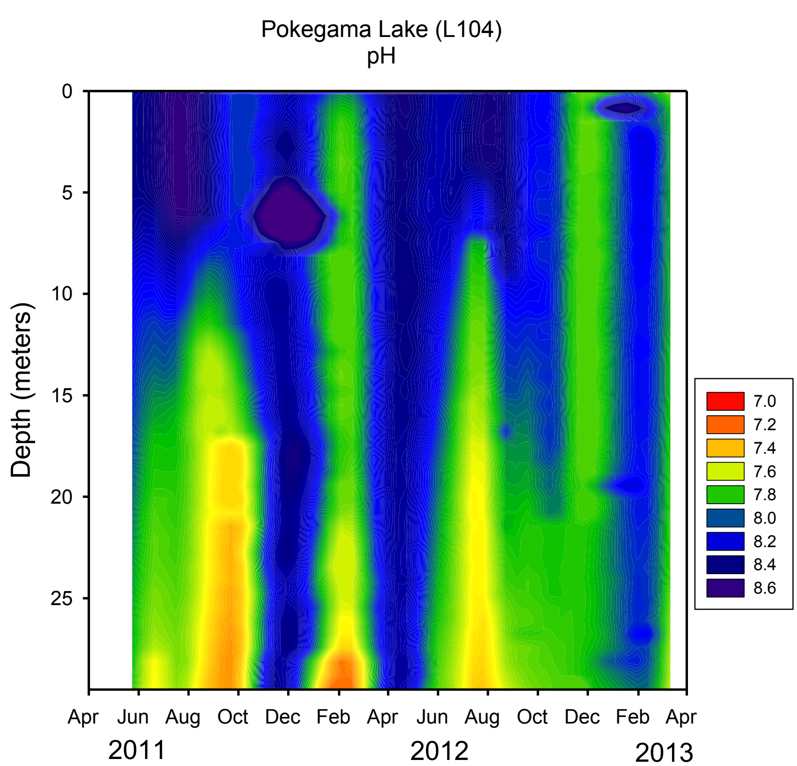
Dissolved oxygen concentration (47c)



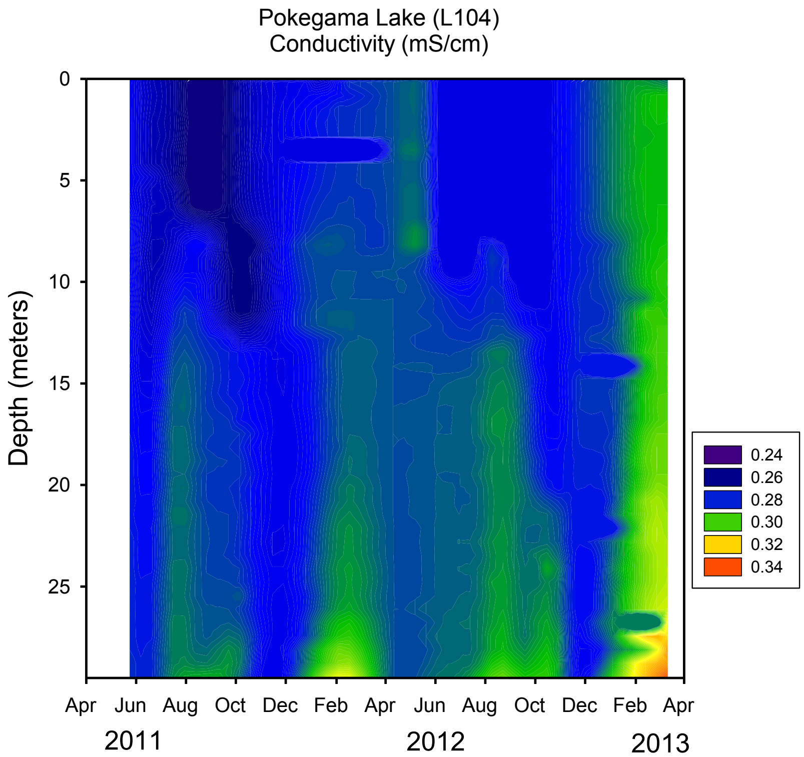
Dissolved oxygen concentration (47d)



Dissolved oxygen concentration (47e)



pH (47f)



Conductivity (47g)

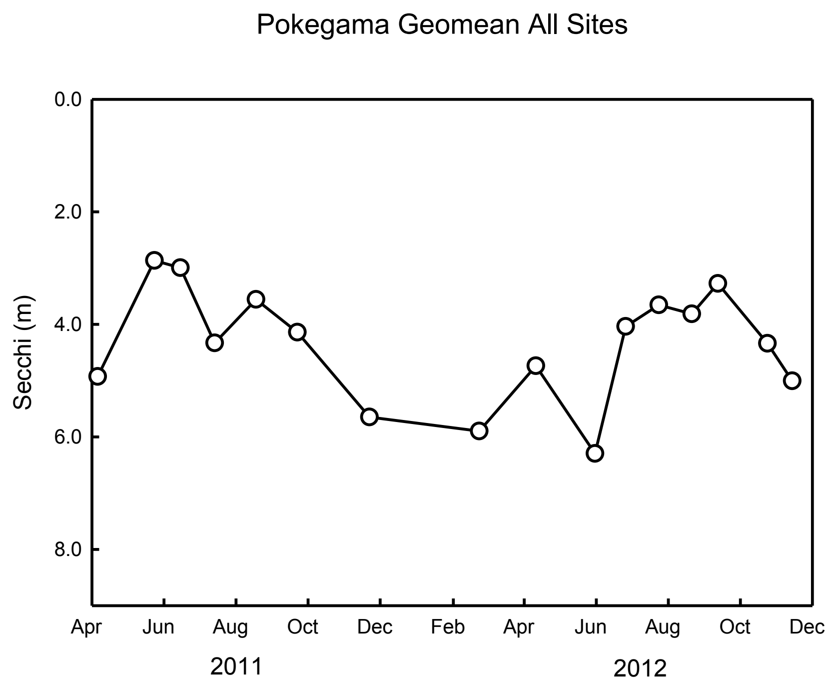


Figure 48: Transparency in Pokegama during 2011 to 2012 measured with a Secchi disk.

Data are the geometric mean of collections from 6 sampling sites.

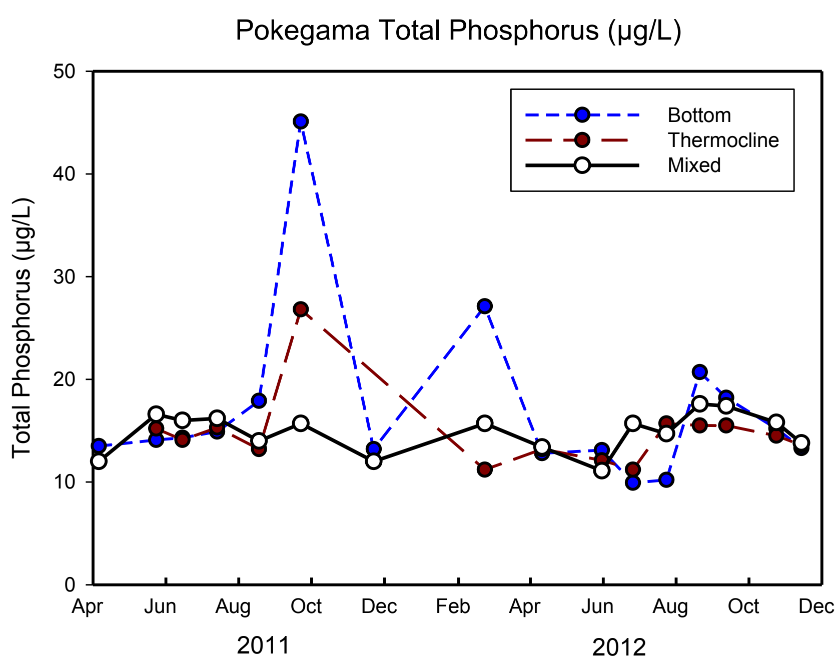


Figure 49: Total phosphorus and total nitrogen values from Pokegama Lake during 2011 to 2012.

Data show the temporal pattern in both nutrients in the mixed layer (surface), mid water column, and at depth. Data are the average of all 6 sites.

SUMMER DATA ONLY (June, July, August)			TP	TN	Chl	Secchi	TSS	NVSS	VSS	Alk	Cond	pH	DO Conc	DO % Sat
Deer Lake	2011	**N**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**
		Geomean	10	296	1.27	4.51	0.99	1.05	0.97	78.795	0.228	8.45	9.30	100.26
		Median	10	328	1.50	4.70	1.00	0.90	0.90	116.000	0.230	8.45	9.32	101.90
		Minimum	7	123	0.50	3.10	0.50	0.90	0.90	5.000	0.220	8.34	7.31	85.23
		Maximum	12	508	2.00	7.30	3.39	3.00	2.25	121.100	0.240	8.56	10.86	103.96
	2012	**N**	**18**	**18**	**18**	**12**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**
		Geomean	8	316	0.71	6.15	0.73	0.85	0.90	120.110	0.225	8.36	8.49	97.43
		Median	8	310	0.50	6.25	0.50	0.90	0.90	120.450	0.230	8.40	8.65	100.64
		Minimum	6	190	0.50	4.75	0.50	0.40	0.90	115.700	0.180	7.97	5.59	64.96
		Maximum	10	430	1.22	8.40	1.40	0.90	0.90	124.300	0.240	8.46	9.67	105.37
	Total	**N**	**42**	**42**	**42**	**36**	**42**	**42**	**42**	**42**	**42**	**42**	**42**	**42**
		Geomean	9	305	0.99	5.00	0.87	0.96	0.94	94.398	0.227	8.41	8.94	99.04
		Median	8	310	1.16	4.90	1.00	0.90	0.90	117.000	0.230	8.43	8.85	101.61
		Minimum	6	123	0.50	3.10	0.50	0.40	0.90	5.000	0.180	7.97	5.59	64.96
		Maximum	12	508	2.00	8.40	3.39	3.00	2.25	124.300	0.240	8.56	10.86	105.37
Pokegama Lake	2011	**N**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**
		Geomean	15	458	3.23	3.59	1.94	0.94	1.07	128.238	0.260	8.48	8.89	99.17
		Median	16	460	3.41	3.33	2.00	0.90	0.90	128.000	0.260	8.47	8.83	99.65
		Minimum	13	334	2.35	2.85	1.40	0.90	0.90	117.100	0.240	8.33	7.33	84.97
		Maximum	20	564	4.80	5.25	2.59	1.19	2.20	132.300	0.280	8.61	9.76	103.70
	2012	**N**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**17**	**17**	**17**	**17**
		Geomean	16	489	4.04	3.83	2.00	0.89	1.47	129.295	0.260	8.33	8.87	101.42
		Median	15	500	4.23	3.75	2.25	0.90	1.88	129.750	0.260	8.41	8.80	103.26
		Minimum	13	320	2.59	3.10	1.00	0.80	0.90	124.000	0.250	7.64	8.26	92.25
		Maximum	22	690	5.29	4.70	2.80	0.90	2.59	134.800	0.270	8.49	9.54	111.09
	Mean	**N**	**36**	**36**	**36**	**36**	**36**	**36**	**36**	**36**	**35**	**35**	**35**	**35**
		Geomean	16	473	3.61	3.71	1.97	0.91	1.25	128.766	0.260	8.41	8.88	100.26
		Median	16	488	3.59	3.70	2.00	0.90	0.90	129.050	0.260	8.43	8.80	100.08
		Minimum	13	320	2.35	2.85	1.00	0.80	0.90	117.100	0.240	7.64	7.33	84.97
		Maximum	22	690	5.29	5.25	2.80	1.19	2.59	134.800	0.280	8.61	9.76	111.09

Table 8: Summary data from summer samples during 2011 and 2012 collected from Deer and Pokegama lakes.

Data are presented as the geometric mean, median, minimum and maximum from the 6 sites on each lake. The averages of all summer samples from this study are presented as the mean. Total phosphorus (TP), total nitrogen (TN) and algal chlorophyll (Chl) are as µg/L. Secchi transparency is in meters. Total suspended solids (TSS), Non-volatile suspended solids (VSS), volatile suspended solids (VSS), and dissolved oxygen (DO) are as mg/L. Alkalinity (Alk) is mg/L $CaCO_3$. Conductivity (Cond) is µmhos/cm. Dissolved oxygen saturation (% Sat) is percentage of saturation at the measured water temperature.

ALL DATA USED			**TP**	**TN**	**CHL**	**Secchi**	**TSS**	**NVSS**	**VSS**	**Alk**	**Cond**	**pH**	**DO Conc**	**DO % Sat**
Deer Lake	2011	**N**	**54**	**54**	**48**	**53**	**42**	**42**	**42**	**48**	**54**	**54**	**54**	**54**
		Geomean	11	303	1.94	4.69	0.93	1.00	0.94	98.3	0.234	8.31	9.77	93.59
		Median	11	314	1.64	4.83	1.00	0.90	0.90	118.0	0.230	8.38	9.71	98.80
		Minimum	7	123	0.50	3.10	0.50	0.80	0.90	5.0	0.220	7.79	7.31	56.62
		Maximum	20	508	9.11	7.30	3.39	3.00	2.25	127.5	0.270	8.56	13.31	103.96
	2012	**N**	**54**	**54**	**54**	**47**	**48**	**48**	**48**	**54**	**50**	**50**	**49**	**49**
		Geomean	10	332	1.47	5.75	1.07	0.91	0.90	124.4	0.234	8.23	9.66	93.65
		Median	10	345	1.42	5.55	1.19	0.90	0.90	123.7	0.240	8.30	9.54	96.95
		Minimum	6	160	0.50	3.45	0.50	0.40	0.90	115.7	0.180	7.76	5.59	60.47
		Maximum	15	460	9.20	8.90	2.90	1.59	0.90	135.8	0.270	8.55	13.49	105.37
	Total	**N**	**108**	**108**	**102**	**100**	**90**	**90**	**90**	**102**	**104**	**104**	**103**	**103**
		Geomean	10	317	1.68	5.16	1.00	0.95	0.92	111.3	0.234	8.27	9.72	93.62
		Median	11	322	1.56	5.01	1.00	0.90	0.90	120.9	0.230	8.35	9.64	97.49
		Minimum	6	123	0.50	3.10	0.50	0.40	0.90	5.0	0.180	7.76	5.59	56.62
		Maximum	20	508	9.20	8.90	3.39	3.00	2.25	135.8	0.270	8.56	13.49	105.37
Pokegama Lake	2011	**N**	**42**	**42**	**30**	**41**	**30**	**30**	**30**	**30**	**36**	**36**	**42**	**36**
		GeoMean	15	437	3.37	3.92	1.80	0.92	1.11	129.7	0.266	8.39	9.47	95.61
		Median	15	431	3.64	3.96	1.80	0.90	0.90	129.0	0.270	8.43	9.15	99.19
		Minimum	10	315	0.50	2.45	1.20	0.90	0.90	117.1	0.240	7.77	6.80	76.91
		Maximum	20	637	5.85	6.25	2.60	1.19	2.60	139.2	0.280	8.63	12.53	105.56
	2012	**N**	**54**	**54**	**54**	**53**	**50**	**50**	**50**	**54**	**52**	**52**	**52**	**52**
		Geomean	15	474	3.76	4.46	1.60	0.90	1.17	136.2	0.272	8.18	9.81	92.96
		Median	15	495	4.40	4.30	1.70	0.90	0.90	135.0	0.270	8.23	9.80	93.70
		Minimum	10	320	1.33	3.10	0.50	0.80	0.90	124.0	0.250	7.64	7.30	77.88
		Maximum	26	900	8.72	7.70	3.00	1.09	2.59	152.7	0.310	8.53	12.73	111.09
	Mean	**N**	**96**	**96**	**84**	**94**	**80**	**80**	**80**	**84**	**88**	**88**	**94**	**88**
		Geomean	15	457	3.61	4.22	1.67	0.91	1.15	133.9	0.270	8.26	9.65	94.03
		Median	15	445	3.99	4.08	1.80	0.90	0.90	131.4	0.270	8.37	9.54	95.18
		Minimum	10	315	0.50	2.45	0.50	0.80	0.90	117.1	0.240	7.64	6.80	76.91
		Maximum	26	900	8.72	7.70	3.00	1.19	2.60	152.7	0.310	8.63	12.73	111.09

Table 9: Summary data from all samples from 2011 and 2012 collected from Deer and Pokegama lakes.

Data are presented as the geometric mean, median, minimum and maximum from the 6 sites on each lake. The averages of all samples from this study are presented as the mean. Total phosphorus (TP), total nitrogen (TN) and algal chlorophyll (Chl) are as µg/L. Secchi transparency is in meters. Total suspended solids (TSS), Non-volatile suspended solids (VSS), volatile suspended solids (VSS), and dissolved oxygen (DO) are as mg/L. Alkalinity (Alk) is mg/L $CaCO_3$. Conductivity (Cond) is µmhos/cm. Dissolved oxygen saturation (% Sat) is percentage of saturation at the measured water temperature.

Groundwater Inputs

Groundwater Discharge from the Shallow Aquifer

Groundwater discharge from the shallow aquifer into Deer and Pokegama lakes was estimated using seepage meters and Darcy's Law (Tables 10 and 11). Positive seepage fluxes in the meters along with primarily upward gradients in minipiezometers at both lakes suggest that groundwater flows into both lakes and hence are discharge lakes. At Deer Lake, annual groundwater discharge ranged from a low of 14,239 m^3 at Zone F to 249,244 m^3 at Zone D in 2011, with a similar trend in 2012. Deltaic deposits associated with an ice margin of the St. Louis sublobe at Site D, in addition to the greater topographic relief driving more groundwater flow into the south side of the lake, are likely responsible for the higher values in this zone in both years. The smaller seepage values are generally related to shoreline areas containing lacustrine silt and clay. Springs, discussed elsewhere in this report, occur in Zone A and elsewhere in Deer Lake and also indicate groundwater inflow to the lake. They likely represent shallow subcrops of subsurface sand units whose interconnectedness upgradient is not known. Seepage values in Deer Lake appear to respond to rainfall events, which yields assurance that seepage meters recorded real events (Figure 50).

Groundwater discharge into Pokegama Lake was generally higher than into Deer Lake, with values ranging from 53,163 m^3 at Site D to 611,446 m^3 at Site A and a similar range (but slightly lower values) in 2012 (Table 11). Both of these zones include areas mapped as till of the St. Louis sublobe, so materials alone may not account for differences in discharge and other more local factors may be involved. Total annual groundwater discharge at Pokegama Lake is more than double that of Deer Lake (Table 10). Although there are some differences in the surficial materials between the two lakes, specifically the lake sediment on the west and northwest sides of Deer Lake, it is likely the greater topographic relief at Pokegama that causes this overall difference in discharge. Seepage fluxes at Pokegama Lake also vary due to its function as a controlled reservoir, so seepage fluxes are sensitive to dramatic changes in lake level – most notably in Zone G nearest the dam. As an example of this effect, in 2012 after a series of intense rainfall events during the last two weeks of June, water was held back from the Mississippi River causing the lake level to rise approximately 0.9 m (3 ft). Lake water was forced outward into the shallow aquifer, yielding a short-term negative seepage flux from in the seepage meters. The relationship between the reservoir pool elevation and surrounding groundwater has been a concern in the region and is the subject of a report by Jones (2005). In general, however, groundwater inflow from the shallow aquifer to Pokegama Lake was dominant during the study.

Groundwater Discharge from the Deep Aquifer

Darcy's Law (See Methods) was used to estimate groundwater discharge (Q) to the lakes using the deep aquifer that provides drinking water to private wells. Water levels in all the private wells were above their respective lake level, indicating groundwater flow into the lakes (Figure 51). Estimates of transmissivity (T) ranged from a geometric mean of 1×10^{-4} m^2/s (N=19) in aquifers near Deer Lake to 3×10^{-4} m^2/s (N=14) in aquifers near Pokegama Lake. Based on the assumed thickness of the deposits, equivalent values of hydraulic conductivity (K) were 5×10^{-5} m/s and 8×10^{-5} m/s, respectively, for the aquifer near the two lakes. These values compare favorably to the $K = 3 \times 10^{-4}$ m/s used in a groundwater model of the region by Jones (2004) and are within the accepted range of K values for clean to silty sand (Freeze and Cheery, 1979). Periods were established to represent each of the measurements so that they could be summed to an annual value (Table 12). Hydraulic gradients typical for horizontal flow conditions in high K sand and gravel aquifers were shown by the data we collected (Table 13). Annual groundwater discharge (Q) to the lake from the deep aquifer reached values of 1.58 x 10^6 m^3 in 2011 and 1.90 x 10^6 m^3 in 2012 for Deer Lake, while Pokegama was characterized by slightly higher values of 1.72 x10^7 and 8.70 x10^6 m^3 in 2011 and 2012, respectively. This difference may not be significant due to the simplifying assumptions that we made about unit thicknesses and aquifer perimeter. Nevertheless, discharge from the deep aquifer is greater than that estimated from seepage meter data by about a factor of two for Deer Lake and a factor of nearly 10 in Pokegama Lake, suggesting that the deep aquifer has a greater influence on lake hydrology than the shallow aquifer.

Nutrient and Chloride Loads from the Shallow Aquifer

Nutrients and chlorides can be viewed as indicators of human impact and phosphorus loads are needed to calculate nutrient inflows and inflows. Groundwater samples taken from minipiezometers and seepage fluxes from seepage meters were used in combination to estimate nutrient and chloride flux from the shallow aquifer system at each lake (Table 14). At Deer Lake, NO_3-N concentrations were below the analytical detection limit of 0.1 mg/L, with only one sampling event yielding a measureable concentration (Zone B on 7/1/13 with a concentration of 0.54 mg/L). Total dissolved phosphorus (TDP) concentrations ranged from 5.0 µg/L to 322.0 µg/L. Zone F contributed the most TDP with a 2011-2012 mean concentration of 283 µg/L – a high concentration for the region and a cause for concern to the effect of P on the lake. Chloride concentrations ranged from about 1 to 116.4 mg/L, and Zone F contained the highest concentration with a combined 2011-2012 mean value of 104.9 mg/L. Such values generally imply a Cl source from de-icing salt or septic tank effluent, both of which are also causes for concern. Zone F is adjacent to County Road 19, which is a possible source of de-icing salt. Zones A-E, and G were two to three orders of magnitude lower in the concentrations of TDP and Cl (Table 14). Zone A was not sampled for nutrients in 2011 due to lack of water production from the minipiezometer. The total nutrient load from the groundwater is provided in Table 16. Nutrient loads via shallow groundwater were larger in 2012 than in 2011 due to both an increase groundwater flow and discharge and an increase in nutrient and Cl concentrations in some zones (e.g., zones D and F; Table 16).

At Pokegama Lake, NO_3-N concentrations ranged from 0.1 to 2.6 mg/L, which is generally higher than at Deer Lake (Table 15). Site C showed the highest mean concentration in 2012 of 1.7 mg/L. Concentrations of TDP range from 3.7 to 481.5 µg/L, with the highest mean and maximum concentrations at Site F. Chloride concentrations ranged from 1.3 to 242.7 mg/L with a hotspot at Site C where the mean concentration was 196.9 mg/L. The causes for these high concentrations are not well understood; however, it is likely that septic tank effluent and de-icing salt are also sources for the TDP and Cl in Pokegama Lake. Nutrient and Cl loads at Pokegama Lake were two to three times higher in 2011 and 2012 than in Deer Lake (Table 16).

Nutrient and Chloride Loads from the Deep Aquifer

Loads from the deep aquifer system were calculated by combining Darcy's Law with water quality data from private wells, as shown above. Mean concentration values were used to determine the load produced per period (kg/period; Table 17) and these values were then summed to produce annual loads from 2011 and 2012 (Table 18). Not surprisingly, annual loads to Pokegama Lake from the deep aquifer are up to 10 times greater than those at Deer Lake, partly due to the greater groundwater discharge coming into Pokegama Lake. In any case, annual P loads to either lake and chloride loads of 60-75,000 kg are of concern for the health the lakes.

Summary of Groundwater Discharge and Load Estimates

Annual groundwater discharge and nutrient/Cl loads from the shallow and deep aquifer systems are summarized in Tables 19 and 20. The data indicate that the deep aquifer generally provides more groundwater discharge to the lake than the shallow aquifer, sometimes by an order of magnitude. If there are multiple deep aquifers involved in the region that intersect the lakes (see Jones, 2004; 2005), then the groundwater and load contributions of the deep aquifer are likely underestimated as presented here. The implementation section outlines additional analyses that could delineate these aquifers and their hydraulic head relationships with the lakes.

Year	Site/Zone	Mean seepage flux (cm/d)	Zone length (m)	Zone width (m)	Annual discharge Q (m^3)
2011	A	0.33	6447	30	141134.46
	B	0.23	5465	30	86375.12
	C	0.08	4610	30	24171.50
	D	0.49	8292	30	249243.88
	E	0.11	2782	30	22048.57
	F	0.05	3630	30	14573.16
	G	0.12	2493	30	24186.05
	Total				561732.74
2012	A	0.15	6447	30	80557.46
	B	0.79	5465	30	236813.22
	C	0.11	4610	30	30954.47
	D	0.65	8292	30	361194.45
	E	0.12	2782	30	22917.53
	F	0.05	3630	30	13375.80
	G	0.06	2493	30	14239.76
	Total				760052.68

Table 10: Mean seepage flux (cm/d) and estimated groundwater discharge for zones at Deer Lake in 2011 and 2012 from seepage meter data.

Year	Site/Zone	Mean seepage flux (cm/d)	Zone length (m)	Zone width (m)	Annual discharge Q (m^3)
2011	A	0.49	19156	30	611445.71
	B	0.72	10397	30	489412.40
	C	0.09	8616	30	54148.77
	D	0.05	13742	30	53163.35
	F	0.35	19195	30	443053.46
	H	0.36	10961	30	247270.64
	Total				1898494.33
2012	A	0.21	21141	30	409797.99
	B	0.34	10397	30	327097.74
	C	0.14	8616	30	66459.66
	D	0.05	13742	30	48909.41
	F	0.60	13582	30	497151.70
	G	1.13	5667	30	245033.03
	H	0.27	8976	30	208427.92
	Total				1802877.45

Table 11: Mean seepage flux and estimated groundwater discharge for zones at Pokegama Lake in 2011 and 2012 from seepage meter data.

Period	Start date	End date	Relative discharge
D1	January 1, 2011	March 31, 2011	Low
D2	April 1, 2011	Sept. 30, 2011	High
D3	October 1, 2011	December 31, 2012	Low
D4	January 1, 2012	March 31, 2012	Low
D5	April 1, 2012	Sept. 30, 2012	High
D6	October , 2012	January 1, 2013	Low

Table 12: Periods used for the Deep aquifer discharge calculations.

Lake	Period	N	Mean hydraulic head difference (m)	Mean distance to lake (m)	Mean *grad h* (unitless)	T * I (m^2/s)	Aquifer perimeter (m)	Q (m^3/period)	Total Annual Q (m^3)
Deer	D1	X	X	X	0.015	1.80 x 10^{-6}	25589.6	3.51 x 10^5	
	D2	14	0.68	48.09	0.02	2.19 x 10^{-6}	25589.6	8.68 x 10^5	
	D3	15	0.54	46.50	0.015	1.81 x 10^{-6}	25589.6	3.60 x 10^5	1.58 x10^6
	D4	X	X	X	0.015	1.80 x 10^{-6}	25589.6	3.55 x 10^5	
	D5	19	1.12	81.55	0.02	2.99 x 10^{-6}	25589.6	1.18 x 10^6	
	D6	X	X	X	0.015	1.80 x 10^{-6}	25589.6	3.59 x 10^5	1.90 x10^6
Pokegama	D1	X	X	X	0.02	4.96 x 10^{-6}	52153.4	1.97 x 10^6	
	D2	11	1.08	58.57	0.02	5.58 x 10^{-6}	52153.4	4.51 x 10^6	
	D3	11	1.17	65.78	0.02	4.98 x 10^{-6}	52153.4	2.02 x 10^6	1.72 x10^7
	D4	X	X	X	0.02	4.96 x 10^{-6}	52153.4	1.99 x 10^6	
	D5	14	1.20	61.49	0.02	5.82 x 10^{-6}	52153.4	4.70 x 10^6	
	D6	X	X	X	0.02	4.96 x 10^{-6}	52153.4	2.01 x 10^6	8.70 x10^6

Table 13: Example Q calculations for each of the six periods in Table 12 above, including total annual Q.

The mean winter gradient measured in Period D3 was applied to unmeasured winter periods. Annual Q values correspond to 2011 (Periods D1-D3).

Zone A	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	-	-	-
Std. Dev.	-	-	-
Median	-	-	-
Max	-	-	-
Min	-	-	-
N	-	-	-
2012			
Mean	<0.1	4.9	12.0
Std. Dev.	-	3.19	1.47
Median	-	4.6	11.8
Max	-	11.9	14.9
Min	-	0.5	9.9
N	11	11	11

Zone B	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	<0.1	7.0	2.5
Std. Dev.	-	2.27	0.15
Median	-	6.5	2.5
Max	-	11.8	2.8
Min	-	5.0	2.3
N	8	8	10
2012			
Mean	<0.1	4.9	3.80
Std. Dev.	-	3.19	0.65
Median	-	4.6	3.59
Max	-	11.9	4.79
Min	-	0.5	2.98
N	11	11	12

Zone C	NO3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	<0.1	16.26	1.7
Std. Dev.	-	-	0.15
Median	-		1.7
Max	-		1.8
Min	-		1.6
N	1	1	2
2012	<0.1	6.0	3.2
Mean	-	0.01	0.59
Std. Dev.	-	6.0	3.1
Median	-	6.0	2.6
Max	-	12	11
Min	-	6.0	4.6
N	12	6.0	3.2

Zone D	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	<0.1	10.5	1.2
Std. Dev.	-	2.25	0.11
Median	-	10.7	1.3
Max	-	13.9	1.4
Min	-	6.8	1.0
N	6	12	10
2012			
Mean	<0.1	11.8	1.6
Std. Dev.	-	5.55	0.24
Median	-	9.8	1.5
Max	-	20.5	2.0
Min	-	6.4	1.3
N	13	13	13

Zone E	NO3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	<0.1	6.2	7.6
Std. Dev.	-	1.01	1.18
Median	-	5.8	7.3
Max	-	8.1	9.1
Min	-	5.4	5.8
N	10	10	10
2012			
Mean	<0.1	6.3	10.7
Std. Dev.	-	0.18	1.18
Median	-	6.3	10.4
Max	-	6.5	13.1
Min	-	6.1	9.2
N	13	13	11

Zone F	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	<0.1	251.1	104.4
Std. Dev.	-	47.74	5.28
Median	-	246.2	104.2
Max	-	322.0	112.2
Min	-	194.5	101.9
N	10	10	10
2012			
Mean	<0.1	315.2	105.3
Std. Dev.	-	21.59	8.14
Median	-	320.6	105.0
Max	-	337.1	116.4
Min	-	269.9	93.2
N	13	13	12

Zone G	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	<0.1	6.4	1.6
Std. Dev.	-	0.35	0.16
Median	-	6.4	1.5
Max	-	6.8	1.8
Min	-	6.1	1.3
N	10	10	10
2012			
Mean	<0.1	6.4	2.1
Std. Dev.	-	0.99	0.32
Median	-	6.2	2.0
Max	-	8.2	2.8
Min	-	5.3	1.7
N	13	13	11

Table 14: Summary table for nutrient and Cl data obtained from groundwater sampled from minipiezometers at Deer Lake.

Data sorted by zone.

Zone A	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	<0.1	8.4	1.7
Std. Dev.	-	2.14	0.40
Median	-	7.9	1.7
Max	-	13.4	2.7
Min	-	5.9	1.3
N	8	9	10
2012			
Mean	<0.1	16.7	3.8
Std. Dev.	-	6.16	1.51
Median	-	13.9	3.5
Max	-	26.4	6.6
Min	-	7.5	1.8
N	11	12	12

Zone D	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	<0.1	7.9	29.1
Std. Dev.	-	1.88	6.74
Median	-	8.1	29.0
Max	-	10.1	40.2
Min	-	3.7	19.9
N	8	10	10
2012			
Mean	<0.1	24.4	32.5
Std. Dev.	-	3.84	7.69
Median	-	25.1	35.3
Max	-	30.7	42.6
Min	-	16.0	13.1
N	14	14	14

Zone B	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	0.3	5.8	2.7
Std. Dev.	0.09	0.35	0.54
Median	0.3	5.8	2.6
Max	0.4	6.2	3.7
Min	0.2	5.3	1.9
N	8	5	10
2012			
Mean	<0.1	7.0	3.1
Std. Dev.	-	1.49	0.95
Median	-	7.0	2.8
Max	0.0	10.3	5.7
Min	0.0	5.1	2.4
N	10	11	11

Zone F	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	<0.1	439.8	3.7
Std. Dev.	-	36.92	0.75
Median	-	444.4	3.6
Max	-	481.5	4.8
Min	-	359.6	2.2
N	8	10	10
2012			
Mean	<0.1	342.7	5.2
Std. Dev.	-	146.01	0.91
Median	-	398.2	5.3
Max	-	467.4	6.6
Min	-	45.3	3.9
N	12	12	12

Zone C	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	<0.1	91.8	34.0
Std. Dev.	-	47.42	26.45
Median	-	87.9	26.8
Max	-	165.0	79.8
Min	-	11.9	7.3
N	8	10	10
2012			
Mean	1.7	26.9	196.9
Std. Dev.	0.75	6.05	33.56
Median	1.8	29.6	204.3
Max	2.6	33.9	242.7
Min	0.2	16.5	117.6
N	10	10	10

Zone G	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	-	-	-
Std. Dev.	-	-	-
Median	-	-	-
Max	-	-	-
Min	-	-	-
N	-	-	-
2012			
Mean	0.7	22.1	6.5
Std. Dev.	0.43	4.56	1.04
Median	0.7	21.7	6.6
Max	1.2	28.2	8.2
Min	0.3	15.4	4.2
N	13	13	12

Zone H	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2011			
Mean	<0.1	8.7	2.8
Std. Dev.	-	1.64	0.98
Median	-	8.0	2.6
Max	-	13.0	4.5
Min	-	7.0	1.4
N	8	10	10

Zone H	NO_3-N (mg/L)	TDP (µg/L)	Cl (mg/L)
2012			
Mean	<0.1	12.2	4.6
Std. Dev.	-	2.26	1.5
Median	-	11.4	5.1
Max	-	17.1	7.0
Min	-	9.0	2.7
N	11	11	11

Table 15: Summary table for nutrient and Cl data obtained from groundwater sampled from minipiezometers at Pokegama Lake.

Data sorted by zone.

Lake	Year	Site/Zone	NO_3-N load (kg)	TDP load (kg)	Cl load (kg)
Deer	2011	A	7.06	0.72	444.57
		B	4.32	0.58	215.94
		C	1.21	0.08	77.35
		D	12.46	2.48	312.34
		E	1.10	0.12	168.47
		F	0.73	3.76	1507.12
		G	1.21	0.11	37.30
		Total	28.09	7.84	2763.10
Deer	2012	A	4.03	0.39	958.44
		B	19.09	1.00	904.91
		C	1.55	0.11	97.54
		D	18.06	3.61	527.89
		E	1.15	0.08	246.89
		F	0.67	3.88	1402.77
		G	0.71	0.07	26.28
		Total	45.25	9.15	4164.74
Pokegama	2011	A	30.57	5.18	1066.18
		B	78.33	2.51	1278.16
		C	2.71	4.69	2171.54
		D	2.66	0.42	1524.33
		F	22.15	197.47	1588.84
		H	12.36	2.22	671.23
		Total	148.78	212.48	8300.29
Pokegama	2012	A	20.49	4.94	1099.55
		B	46.06	1.89	959.93
		C	72.74	3.38	9035.81
		D	2.45	0.83	1456.70
		F	24.86	166.73	2351.28
		G	36.74	5.40	1576.25
		H	10.42	2.16	775.37
		Total	213.76	185.33	17254.88

Table 16: Annual groundwater nutrient and Cl loads into Deer and Pokegama lakes as estimated by seepage meters and minipiezometers.

Data sorted by site/zone.

Lake	Period	N	Mean NO_3-N (mg/L)	Mean TDP (ug/L)	Mean Cl (mg/L)	NO_3-N load (kg/period)	TDP load (kg/period)	Cl load (kg/period)
Deer	D1	X	0.055	12.77	6.71	19.29	4.48	2353.27
	D2	15	0.055	14.7	6.1	43.38	12.75	5292.04
	D3	15	0.055	14.69	7.13	19.81	5.29	2568.66
	D4	X	0.055	12.77	6.71	19.50	4.53	2379.42
	D5	23	0.06	8.92	6.89	71.08	10.57	8162.40
	D6	X	0.055	12.77	6.71	19.72	4.58	2405.56
Pokegama	D1	X	0.11	6.18	7.75	216.66	12.17	15264.37
	D2	14	0.10	4.50	10.03	450.79	20.29	45213.83
	D3	11	0.11	8.55	6.95	222.28	17.28	14044.11
	D4	X	0.11	6.18	7.75	219.06	12.31	15433.97
	D5	20	0.12	5.49	6.27	563.94	25.80	29466.09
	D6	X	0.11	6.18	7.75	221.47	12.44	15603.58

Table 17: Groundwater nutrient and Cl concentrations and loads/period flowing into Deer and Pokegama Lakes from the deep aquifer.

Data sorted by period.

Lake	Year	NO_3-N load (kg)	TDP load (kg)	Cl load (kg)
Deer	2011	82.48	22.52	10213.96
	2012	110.30	19.67	12947.37
Pokegama	2011	889.72	49.73	74522.31
	2012	1004.48	50.55	60503.64

Table 18: Annual groundwater nutrient and Cl loads entering Deer and Pokegama lakes from deep aquifer.

Lake	Year	Annual volume from shallow aquifer (m^3)	Annual volume from deep aquifer (m^3)	Total volume from shallow and deep aquifers (m^3)
Deer	2011	5.62×10^5	1.58×10^6	2.14×10^6
	2012	7.60×10^5	1.90×10^6	2.66×10^6
Pokegama	2011	1.89×10^6	1.72×10^7	1.91×10^7
	2012	1.80×10^6	8.70×10^6	1.05×10^7

Table 19: Summary of annual volume totals for shallow and deep aquifers individually and their combined volume contribution to the lakes.

Lake	Year	Parameter	Load from shallow aquifer (kg)	Load from deep aquifer (kg)	Load from shallow and deep aquifers (kg)
Deer	2011	NO_3-N	28.09	82.48	110.57
		TDP	7.84	22.52	30.36
		Cl	2763.1	10213.96	12977.1
	2012	NO_3-N	45.25	110.30	155.55
		TDP	9.15	19.67	28.82
		Cl	4164.7	12947.37	17112.1
Pokegama	2011	NO_3-N	148.78	889.72	1038.5
		TDP	212.48	49.73	262.21
		Cl	8300.29	74522.31	82822.6
	2012	NO_3-N	213.76	1004.48	1218.24
		TDP	185.33	50.55	235.88
		Cl	17254.88	60503.64	77758.52

Table 20: Summary of annual load totals for shallow and deep aquifers and their combined load contribution to the lakes.

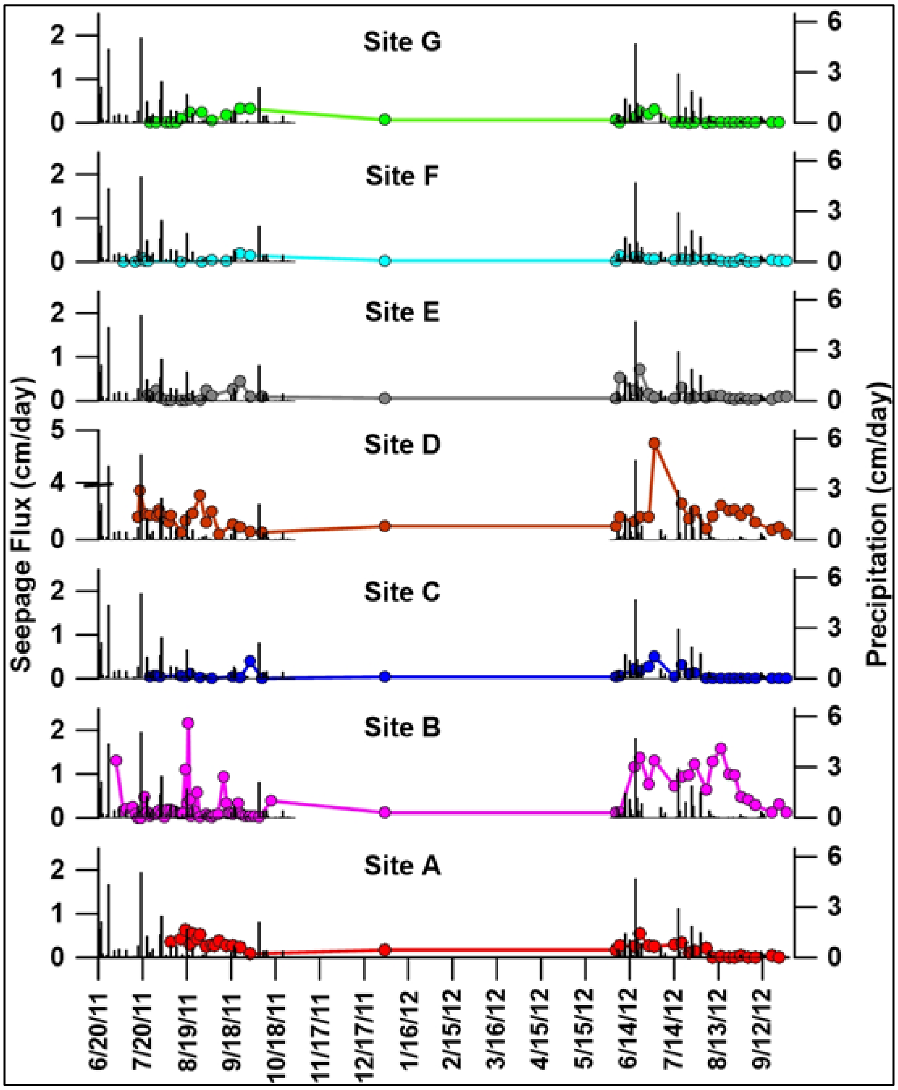
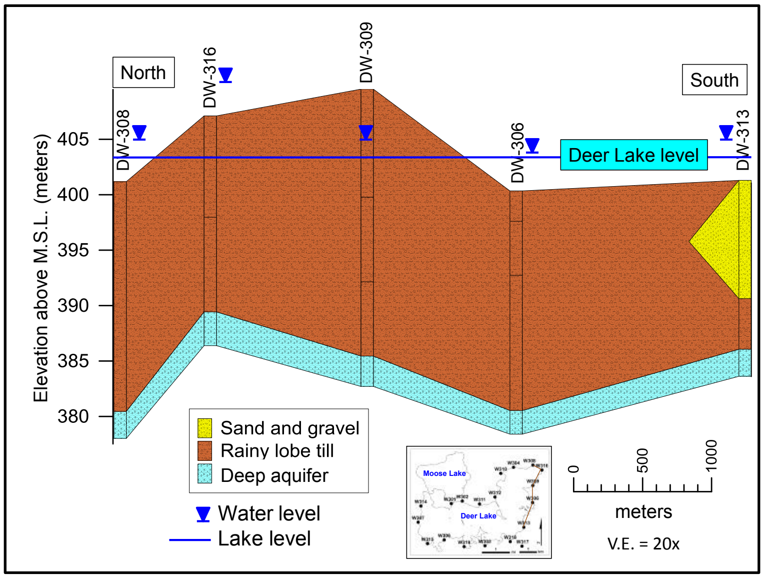


Figure 50: Time series plots of seepage flux in cm/d showing meter flux response to precipitation.

Time series plots of seepage flux in cm/d showing meter flux response (leftmost Y axis) to precipitation (rightmost Y axis). Data suggest an increase in seepage flux occurs with increased precipitation, presumably due to an increase in hydraulic gradients driving more groundwater into the discharge zone along the shoreline.



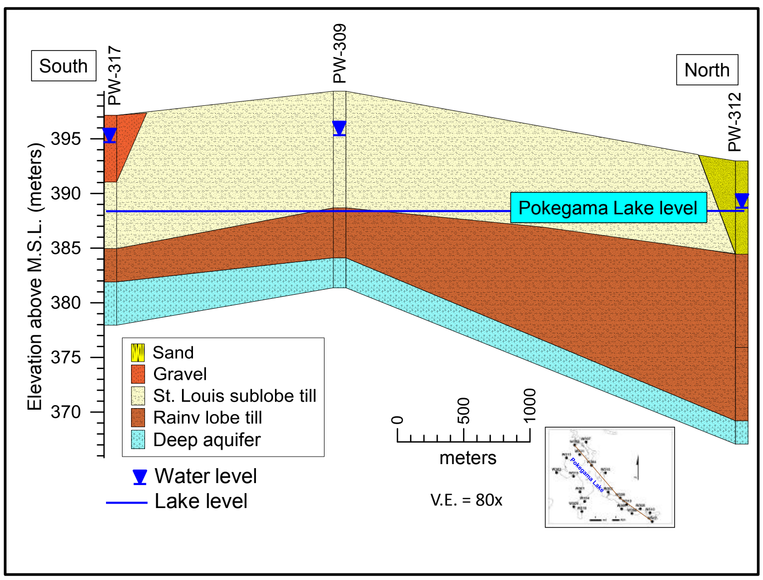


Figure 51: Cross sections showing relationship of lake levels to hydraulic heads measured in the deep aquifer.

Hydraulic heads are higher than lake levels in all cases, indicating a potential for flow of groundwater from the aquifer into the lake.

Hydrogeochemistry of Groundwater in the Deep Aquifer

The hydrogeochemistry of groundwater in the deep aquifer was investigated using the previously used private wells at Deer (20) and Pokegama (19) Lakes. Results in Tables 21, 22, and 23 indicate that groundwater in this aquifer at both lakes is a $CaCO_3$-type water that is low in dissolved O_2 (overall mean 0.88 mg/L), essentially devoid of NO_3-N, and showing Fe concentrations as high as 8.78 mg/L (DW311) with an overall mean of 1.49 mg/L. Although the overall mean SO_4 concentration is 11 mg/L, some samples lie below the detection limit (DW319). Anecdotal evidence from homeowners and notes during sampling indicate an H_2S smell to well water, Fe-oxide accumulations near the wells, and small bubble formation suggestive of dissolved methane. These data, in addition to the presence of measureable NH_3-N concentrations (overall mean of 0.26 mg/L), suggest a strongly reducing geochemical environment in the deep aquifer, perhaps capable of producing methane. The presence of high concentrations of DOC (overall mean of 23 mg/L), particularly in wells closer to Pokegama Lake (maximum value of 138.7 mg/L), suggests the geochemical system is driven by a labile C source. After using up O_2, alternate electron acceptors oxidize DOC and end with CO_2 reduction, producing methane as the final step (Stumm and Morgan, 1981; Simpkins and Parkin, 1993). The geochemical environment is important to document because P may travel unimpeded and reach large concentrations in reducing groundwater environments because a predominant receptor for P, Fe^{3+}, exist in its reduced form of Fe^{+2} (Rodvang and Simpkins, 2001). The source of the TDP and its transport in the groundwater here is not well understood and should be a focus of future research in the region. This need is also expressed in the implementation part of this report.

Geochemical Parameter	Mean Value/ Concentration
pH	7.51
Temp ºC	8.49
Diss O_2 (mg/L)	0.88
Specific Conductance (ms/cm)	0.602
Specific Condutance (µs/cm)	602
Total Alkalinity (mg/L $CaCO_3$)	248
Ca (mg/L)	66.2
Mg (mg/L)	18.3
Na (mg/L)	11.4
K (mg/L)	2.2
Fe (mg/L)	1.49
Mn (mg/L)	0.24
Sr (mg/L)	0.17
Si (mg/L)	7.82
HCO_3 (mg/L)	303
Cl (mg/L)	8.0
SO_4 (mg/L)	11.0
TDP (µg/L)	5.71
NO_3+NO_2-N (mg/L)	0.04
NH_3+NH_4-N (mg/L)	0.26
DOC (mg/L)	23.2

Table 21: Mean values for all geochemical analyses for groundwater sampled from private wells (N=39).

Sampled in Summer 2012. Data are preliminary and have not been checked for charge balance errors.

Well ID	pH	Temp C	Diss. O2	SPC ms	SPC us	Total Alk. (CaCO3)	Ca	Mg	Na	K	Fe	Mn	Sr	Si	HCO3	Cl	SO4	TDP (µg/L)	NO3 -N	NH3 -N	DOC
DW301	7.89	11.34	0.68	0.461	461	249	42.6	10.8	44.4	3.3	0.07	0.06	0.25	6.41	303.5	7.0	3.2	17.07	<0.10	0.82	24.7
DW302	7.31	9.00	0.51	0.744	744	374	70.9	25.7	53.9	3.6	0.15	0.24	0.35	7.28	455.8	8.8	46.0	19.41	<0.10	0.66	67.6
DW303	7.26	11.57	<2	0.505	505	253	65.4	21.2	6.7	3.3	2.30	0.23	0.24	8.17	309.1	3.7	20.6	<5.00	<0.10	0.37	32.3
DW304	7.18	7.54	1.96	0.560	560	278	82.9	20.5	5.3	2.1	0.01	0.02	0.10	8.18	339.5	11.8	9.2	<5.00	<0.10	0.05	35.7
DW305	7.30	8.47	0.59	0.504	504	276	74.2	18.0	4.7	2.3	3.23	0.20	0.14	9.36	337.2	1.5	5.0	<5.00	<0.10	0.20	34.3
DW306	7.76	7.59	0.44	0.408	408	274	59.7	14.0	6.7	2.6	1.25	0.30	0.24	7.36	333.9	<1	<0.14	57.19	<0.10	0.37	28.1
DW307	7.04	9.46	3.78	0.911	911	NA	98.2	51.5	12.8	2.9	1.83	0.27	0.36	11.65	NA	1.5	13.9	<5.00	<0.10	0.23	62.3
DW308	7.46	7.83	0.51	0.340	340	183	53.4	9.4	2.9	1.7	2.94	0.39	0.08	8.12	223.5	<1	<0.14	6.22	<0.10	0.42	14.5
DW309	7.33	7.76	0.64	0.387	387	209	61.4	10.0	3.6	1.7	3.91	0.70	0.09	7.99	254.5	1.4	<0.14	<5.00	0.23	0.35	31.3
DW310	7.52	8.53	0.60	0.402	402	223	61.2	13.4	4.1	2.5	0.60	0.16	0.10	8.46	272.4	<1	3.3	<5.00	<0.10	0.06	44.9
DW311	6.94	9.56	0.60	1.090	1090	NA	132.0	48.4	12.7	3.6	8.78	0.14	0.38	12.94	NA	77.3	24.9	<5.00	<0.10	0.48	138.7
DW312	7.76	7.98	0.58	0.494	494	280	65.5	17.0	12.9	3.4	1.65	0.32	0.28	7.14	341.2	1.1	0.5	<5.00	<0.10	1.06	11.4
DW313	7.40	8.48	0.67	4.620	4620	255	74.0	13.4	2.7	1.4	2.43	0.22	0.08	8.96	311.3	2.6	3.6	<5.00	<0.10	0.25	9.6
DW314	7.66	8.04	0.61	0.684	684	397	82.2	25.5	30.1	2.8	0.72	0.08	0.41	7.80	483.9	1.8	0.7	38.94	<0.10	0.88	20.7
DW315	7.63	7.93	0.91	0.450	450	242	59.8	17.7	9.2	2.7	0.18	0.06	0.19	7.11	294.9	1.4	11.2	23.86	<0.10	0.20	7.4
DW316	8.07	9.09	0.53	0.439	439	219	66.2	11.6	5.5	2.3	4.01	0.38	0.09	8.14	267.4	2.1	0.4	<5.00	<0.10	0.08	7.6
DW317	8.03	8.26	0.30	0.439	439	250	73.1	10.4	3.6	1.3	1.11	0.59	0.09	10.12	305.1	4.7	3.5	<5.00	<0.10	0.10	12.9
DW318	8.07	8.25	0.34	0.365	365	224	54.1	10.6	3.6	1.5	<0.02	<0.01	0.06	8.70	272.9	11.8	0.5	<5.00	<0.10	0.31	7.3
DW319	8.03	8.82	0.54	0.415	415	259	65.0	10.6	3.1	1.3	5.80	0.09	0.08	9.37	316.5	1.3	<0.14	<5.00	<0.10	0.44	3.5
Mean																					
N=19	7.56	8.71	0.78	0.75	748.32	261.46	70.62	18.93	12.03	2.43	2.16	0.23	0.19	8.59	318.99	8.73	7.72	8.56	0.01	0.39	31.31

Table 22: Results of geochemical analyses for groundwater sampled from private wells near Deer Lake in Summer 2012.

All values in mg/L except where noted. Data are preliminary and have not been checked for charge balance errors. SPC is specific conductance.

Well ID	pH	Temp C	Dis. O_2	SPC ms	SPC us	Total Alk. (CaCO3)	Ca	Mg	Na	K	Fe	Mn	Sr	Si	HCO3	Cl	SO4	TDP (µg/L)	NO3-N	NH3-N	DOC
PW301	7.22	7.43	0.52	0.489	489	246	68.8	19.4	2.9	1.2	0.73	0.18	0.08	8.04	300.1	7.7	13.4	<5.00	<0.10	<0.027	12.9
PW302	7.29	8.06	3.95	0.575	575	265	74.8	19.5	17.5	1.2	0.01	0.02	0.08	8.47	323.8	23.8	17.8	<5.00	1.2	<0.027	33.2
PW303	7.68	7.26	0.38	0.438	438	245	57.5	18.1	8.6	2.1	0.15	0.13	0.17	7.42	298.4	1.4	1.3	27.06	<0.10	0.14	12.3
PW304	7.73	8.54	0.60	0.485	485	243	48.9	19.5	23.8	3.2	1.12	0.24	0.45	4.28	295.9	10.1	8.8	<5.00	<0.10	0.45	13.2
PW305	7.63	8.80	0.84	0.337	337	167	52.3	10.8	3.2	0.7	0.22	0.10	0.07	6.70	203.5	1.3	17.7	<5.00	<0.10	<0.027	4.5
PW306	7.62	8.80	0.78	0.391	391	NA	50.0	14.9	8.7	2.2	2.54	0.25	0.26	7.26	NA	1.4	<0.14	<5.00	<0.10	0.88	49.4
PW307	7.50	8.86	0.64	0.593	593	236	74.6	22.9	10.0	2.0	0.42	0.14	0.09	6.62	287.3	45.1	21.1	5.05	<0.10	<0.027	48.5
PW308	7.28	8.80	0.52	0.452	452	229	67.0	16.9	2.6	1.4	0.83	0.13	0.07	5.50	279.3	4.5	16.8	<5.00	<0.10	<0.027	4.7
PW309	7.32	7.51	4.40	0.429	429	221	65.4	15.4	2.9	1.7	0.30	0.13	0.07	4.82	269.3	1.5	14.9	<5.00	<0.10	<0.027	33.1
PW310	7.10	8.84	0.58	0.42	420	141	53.1	13.1	6.8	1.2	1.49	2.11	0.09	8.35	172.1	10.6	18.6	9.15	<0.10	<0.027	3.6
PW311	7.63	8.86	0.74	0.41	410	203	57.9	16.2	4.1	2.3	0.15	0.13	0.10	7.34	247.3	2.1	21.6	5.05	<0.10	0.03	6.1
PW312	7.41	9.24	0.52	0.595	595	328	77.4	25.2	11.1	2.7	2.65	0.13	0.26	8.82	399.6	1.2	7.0	<5.00	<0.10	0.34	9.5
PW313	7.27	8.31	2.83	0.51	510	276	73.9	19.2	7.3	1.3	0.14	0.09	0.08	7.92	337.0	13.2	13.6	<5.00	0.21	<0.027	10.2
PW314	7.42	7.95	0.53	0.44	440	239	NA	NA	NA	NA	NA	NA	NA	NA	291.8	1.3	9.0	<5.00	<0.10	0.07	10.0
PW315	7.38	8.64	NA	0.482	482	242	74.1	16.8	2.7	1.3	0.52	0.16	0.08	5.71	295.2	3.1	23.6	<5.00	<0.10	<0.027	7.4
PW316	8.03	8.33	0.43	0.478	478	243	26.7	13.3	73.1	3.6	1.15	0.02	0.37	5.32	295.9	8.9	27.5	<5.00	<0.10	0.53	10.3
PW317	7.29	8.04	0.48	0.463	463	254	67.4	20.1	2.8	1.4	2.43	0.25	0.08	8.48	310.1	1.2	18.0	<5.00	<0.10	0.15	14.1
PW318	7.67	7.55	0.46	0.414	414	240	58.8	16.7	5.8	2.6	0.18	0.46	0.12	7.50	292.3	<1	9.1	8.13	<0.10	0.06	6.8
PW319	7.29	8.13	0.27	0.451	451	235	60.3	17.4	4.8	1.5	0.80	0.15	0.14	7.61	286.3	1.9	11.4	7.06	<0.10	0.04	10.2
PW320	7.36	7.55	0.22	0.426	426	230	63.6	18.6	5.2	2.5	1.25	0.19	0.16	7.66	281.1	1.2	11.3	6.66	<0.10	0.07	10.6
Mean																					
N=20	7.46	8.28	1.04	0.46	463.90	235.82	61.7	17.58	10.74	1.91	0.90	0.26	0.15	7.04	287.70	7.45	14.13	3.41	0.07	0.14	15.5

Table 23: Results of geochemical analyses for groundwater sampled from private wells near Pokegama Lake in Summer 2012.

All values in mg/L except where noted. Data are preliminary and have not been checked for charge balanced errors. SPC is specific conductance.

Stable Isotopes in Deep and Shallow Groundwater

Stable isotopes of oxygen and hydrogen were sampled and analyzed from precipitation, lake water, and groundwater to determine its source and age and help us understand the larger regional picture of groundwater flow around the two lakes. A local meteoric (precipitation) water line was developed for the area using 28 precipitation samples collected between July 19, 2011 and July 26, 2012. Rainfall events amounting to 158 mm were captured during the summer parts of that period. The equation of the regression line through the points is:

$$\delta^2H = 7.95\ \delta^{18}O + 11.44‰$$

which shows an R^2=0.99 and significance at the $p<0.01$ level (Figure 52). This represents the Local Meteoric Water Line (LMWL) for the study area and is quite close to the global meteoric water line of Craig (1961), which is $\delta^2H = 8\ \delta^{18}O + 10‰$. Mean values for $\delta^{18}O$ and δ^2H are -9.71 and -65.72 ‰, respectively, while precipitation weighted mean values are -7.16 and -46.09 ‰, respectively. Although precipitation-weighted mean values are generally used to estimate the meteoric water input (Simpkins, 1995), the lack of winter snowmelt data on the LMWL "levers" these values towards enriched (less negative) isotopic values. Given the mean annual temperature of the region, the $\delta^{18}O$ composition should be between -14 and -12 ‰ (Dutton et al., 2005).

In addition to being a conservative tracer that moves with the water molecule, stable isotopes of hydrogen and oxygen are also subject to preferential removal (fractionation) of the lighter isotope (i.e., ^{16}O and H) from open-water surfaces. Because fractionation affects $\delta^{18}O$ more strongly than δ^2H, the result of fractionation is an isotopic composition that falls along a slope near 5.0, below the LMWL (Clark and Fritz, 1997). Knowledge of the lake end member of the isotopic enrichment makes it possible to assess the movement and mixing of lake water into groundwater, thus providing a separate approach to tracing groundwater flow in an aquifer (Krabbenhoft et al., 1990; Rosenberry et al., 2011; Jones et al., 2013). This technique is particularly useful in our study because, without a groundwater monitoring network, we could not access hydraulic head data to map the regional direction of groundwater flow. As a first step, samples of lake water were taken in summer and fall 2011 from Deer Lake (N=83) and Pokegama Lake (N=54) and analyzed for $\delta^{18}O$ and δ^2H. The results indicate that the mean composition of the lakes is significantly different, with samples from Deer Lake showing a more isotopically enriched signature for $\delta^{18}O$ and δ^2H (-4.96‰, -47.51‰) than means from samples in Pokegama Lake, whose values are -7.17‰ and -60.00‰, respectively (Figure 53). We defined an evaporation line for both lakes together with the equation:

$$\delta^2H = 5.19\ \delta^{18}O - 23.04‰$$

with an R^2=0.99 and significance at the $p<0.01$ level. The intersection of this line with the LMWL ($\delta^{18}O$ = -12.60‰, δ^2H = -88.43‰) defines the approximate starting point of the lake water prior to evaporation and is consistent with the predicted regional meteoric (precipitation) input (Dutton et al, 2005). Values from Deer Lake also lie farther up the evaporation line, suggesting greater evaporation than at Pokegama Lake. Greater evaporation could be related to water residence time in the lakes - i.e., longer residence time equals more opportunity for evaporation – a situation that would favor Deer Lake.

Thirty-nine groundwater samples from private wells near Dear Lake and Pokegama Lake (summer 2012 samples) were analyzed for stable isotopes and plotted against the LMWL (Figure 54). The mean $\delta^{18}O$ and $\delta^{2}H$ composition of 19 samples from Deer Lake is -10.33 and -76.92‰ and for Pokegama Lake is -11.71 and -83.77‰, respectively. Ten of 19 samples from Deer Lake and 18 of 20 samples from Pokegama Lake lie on the LMWL between $\delta^{18}O$ and $\delta^{2}H$ compositions of -11 and -13‰ and -76 and -86‰, respectively. These samples probably represent groundwater of meteoric origin that has entered the system under the present climate. At Deer Lake, deep groundwater samples from DW303, 304, 306, 309, 310, 311, 312, 313, 314, and 316, showed values more enriched (less negative) than the -11‰ and -76‰ isotopic compositions and are interpreted to be on the evaporation line. Enriched values occur in wells in the northeast part of the lake (Figure 55), and we initially hypothesized that this pattern indicated lake water outflow and mixing with groundwater there; however, subsequent evaluation of hydraulic data (see earlier part of this section) indicated that this hypothesis was not correct. It is more likely that groundwater in this area is mixing with isotopically enriched water from lake water up-gradient from Deer Lake as part of a regional groundwater flow system. At Pokegama Lake, groundwater from wells PW303 and PW306 showed $\delta^{18}O$ compositions of -9.41 and -8.91‰, respectively, and did not show a pattern like that of Deer Lake (Figure 56). In some cases, the wells are close enough to the shoreline that they may draw in lake water during pumping, which could cause mixing of meteoric and lake water. It is interesting to note that the isotopic composition of Deer Lake is more enriched than at Pokegama Lake, which is consistent with the groundwater data.

We plotted the isotopic data versus well screen elevation in attempt to see trends within the aquifers (Figure 57). Most of our samples come from an upper sand and gravel aquifer (Aquifer 1) between 363 and 395 m elevation. Samples from this aquifer show a large variation in isotopic composition, with the more up-gradient wells at Deer Lake showing evaporation-driven isotopic enrichment (samples to the right of the dashed blue line; Figure 57) and the others with meteoric signatures more reflective of the present input. With the exception of one well near Pokegama Lake, most of this groundwater in deeper aquifers (Aquifers 2 and 3) shows meteoric water signatures.

We also took samples from minipiezometers (adjacent to the seepage meters) to characterize the isotopic composition of the shallow groundwater. In general, isotopic values from this aquifer are about 1‰ more enriched than the deep aquifer. At Deer Lake, thirty one samples taken from minipieozmeters in 2011 and 2012 showed mean values of -9.79 and -72.68‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively. At Pokegama Lake, mean values for $\delta^{18}O$ and $\delta^{2}H$ from shallow groundwater were -10.63 and -77.23‰, respectively. We calculated mean values for each site/zone and plotted those against the LMWL, excluding data from July and August 2012 at Pokegama Lake due to the high water levels in the reservoir. As was the case for the deep groundwater samples, some samples fell on LMWL and some fell on the same evaporation line defined for the deep groundwater samples (Figure 58). Plan view maps show slightly different results than those for deep groundwater. For Deer Lake, there are many more sites/zones that show mixing with lake water, based on the same $\delta^{18}O$= -11‰ and $\delta^{2}H$= -76‰ cutoff used for deep groundwater (Figure 59). At Pokegama Lake, the patterns are more similar deep groundwater there and show mostly meteoric water compositions (Figure 60). At both sites, the overall enrichment of isotopes could be due to mixing of lake water along the unsealed annulus of the minipiezometer or through the sampling process. However, that process should occur equally at both sites. More enrichment in shallow groundwater at Deer Lake than at Pokegama Lake may suggest a different source of water at Deer Lake, such as evaporated water from surrounding wetland areas. Further investigation is needed to understand these differences. In general, however, groundwater appears to be mixtures of percolated precipitation and lake water that has been exposed, long-term, to evaporative loss.

Tritium Age-Dating in Deep Groundwater

A student research grant from the Geological Society of America allowed us to analyze eight deep groundwater at both lakes for enriched tritium (^3H), expressed in tritium units (TU). Wells whose stable isotope values did not show evidence of evaporative enrichment were chosen (Table 24), that is, those that were not principally composed of lake water. Values ranged from $<0.8 \pm 0.3$ to 17.2 ± 1.3 TU and span a range of ages from before the 1963 bomb pulse to potentially recent, based on radioactive decay data from Ames, Iowa and the Midwest (Simpkins, 1995). Plots of the data in plan view (Figures 61 and 62) and against well-screen elevation (Figure 63) indicate no clear trends in age with depth or position. Other parameters that might indicate a recent groundwater age, such as Cl and DOC, were not helpful. With the exception of DW302 and PW304, Cl concentrations are near background, suggesting that these waters are not receiving de-icing salt and probably not recent in age. The concentrations of DOC also show no clear pattern, with very deep wells often showing higher concentrations than shallower wells. The lack of relationships between these parameters and the spread of tritium ages suggests that the regional groundwater flow systems feeding the lakes are likely complex. Although a few wells indicated that the water was older than 50-60 years, many of the wells had tritium signatures consistent with much more recent rainfall as a source.

Summary and Conclusions

Stable isotopes of water ($\delta^{18}O$ and δ^2H) in deep and shallow groundwater were helpful in understanding the regional picture of groundwater flow in the vicinity of the two lakes, specifically the regional groundwater flow into the northeast portion of Deer Lake. The data also showed more isotopic enrichment at Deer Lake than at Pokegama Lake, which is reflected in the more enriched composition of lake water in Deer Lake than in Pokegama Lake. The radioactive isotope tritium (^3H) in deep groundwater suggests a range of groundwater from pre-1963 to perhaps recent. However, the lack of any relationship of ^3H with Cl and DOC data suggest that the groundwater is not very recent in age. In short, groundwater flow systems in these aquifers deserve more investigation if their relationship to the lakes is to be understood. This is why the implementation part of this report suggests that more substantial investigation of the region's groundwater be undertaken to serve better surface water management.

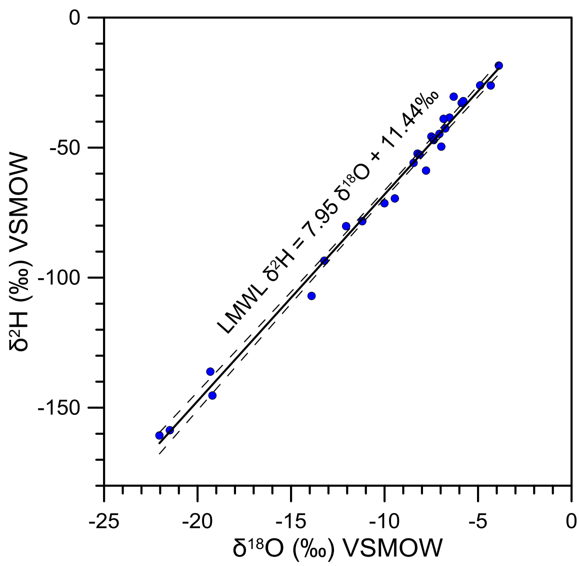


Figure 52: LMWL for the study area based on 28 precipitation samples taken during the summer months of 2011 and 2012.

The combined uncertainty (analytical uncertainty and average correction factor) for all samples in this study is ± 0.11‰ and ± 0.42‰ (VSMOW) for $\delta^{18}O$ and $\delta^{2}H$, respectively. Dashed lines indicate 95% confidence bands.

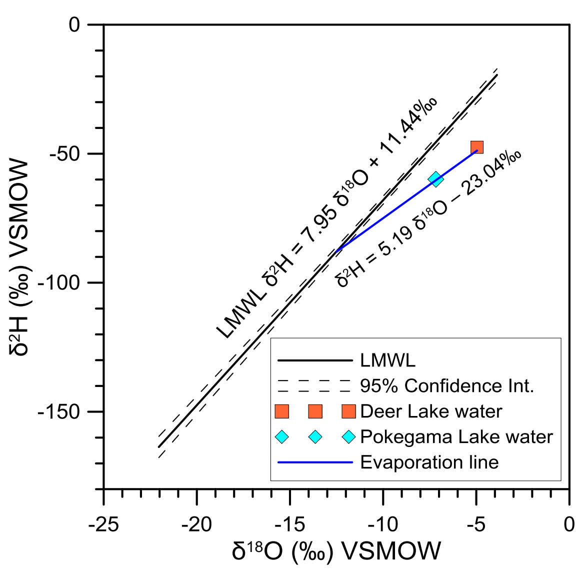


Figure 53: Plot showing the mean isotopic composition of Deer and Pokegama Lake water and the evaporation line of slope 5.19 fit to those points.

Analytical uncertainly is ± 0.11‰ and ± 0.42‰ (VSMOW) for $\delta^{18}O$ and $\delta^{2}H$, respectively.

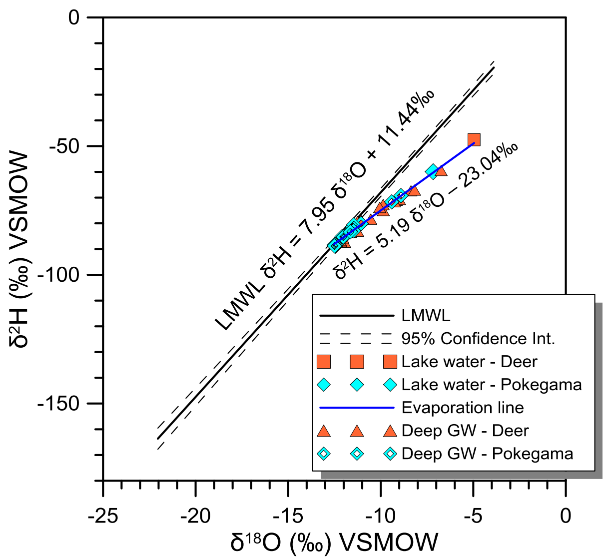


Figure 54: Plot showing the mean isotopic composition of Deer and Pokegama Lake water and deep groundwater samples from private wells (summer 2012 data).

Mixing of meteoric groundwater and evaporated groundwater is indicated by samples plotting on the evaporation line. Analytical uncertainty is ± 0.11‰ and ± 0.42‰ (VSMOW) for $\delta^{18}O$ and $\delta^{2}H$, respectively.

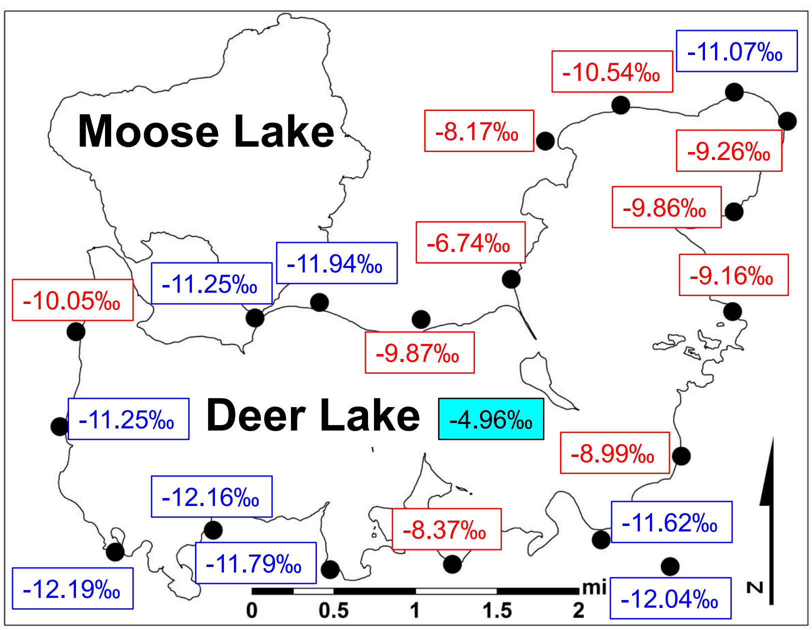


Figure 55: Map of Deer and Moose lakes showing δ18O composition of deep groundwater sampled from private wells (summer 2012 data).

Blue boxes indicate groundwater of meteoric origin and red boxes show groundwater that has probably mixed with lake-evaporated water. The extent of evaporated water signatures in deep groundwater in the northeast part of the lake suggests that this is an area receiving recharge from lakes up-gradient of Deer Lake. The mean $\delta^{18}O$ composition of Deer Lake is -4.96 ‰. Analytical uncertainty is ± 0.11‰ and ± 0.42‰ (VSMOW) for $\delta^{18}O$ and $\delta^{2}H$, respectively.

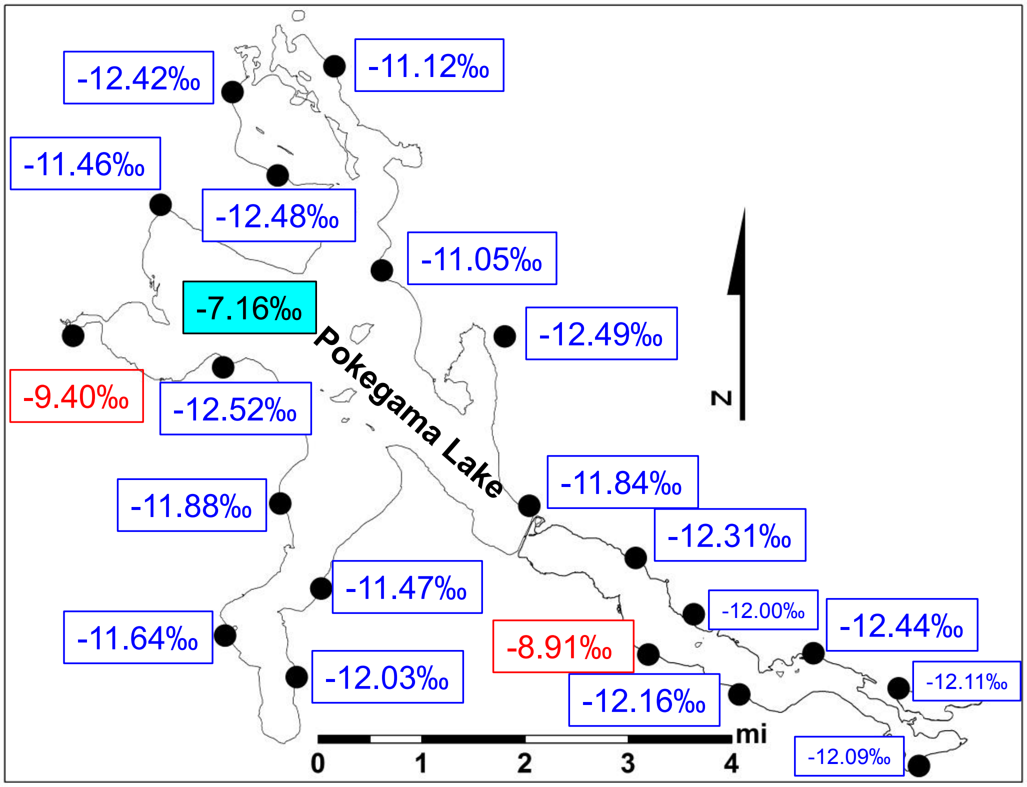


Figure 56: Map of Pokegama Lake showing δ18O composition of deep groundwater sampled from private wells.

Blue boxes indicate groundwater of meteoric origin and red boxes show groundwater that has probably mixed with lake-evaporated water. In contrast to Deer Lake, most groundwater appears to be of direct meteoric origin. Evidence of lake water is limited to two wells that could be drawing water directly from the lake. The mean $\delta^{18}O$ composition of Pokegama Lake is -7.16 ‰. Analytical uncertainty is ± 0.11‰ and ± 0.42‰ (VSMOW) for $\delta^{18}O$ and $\delta^{2}H$, respectively.

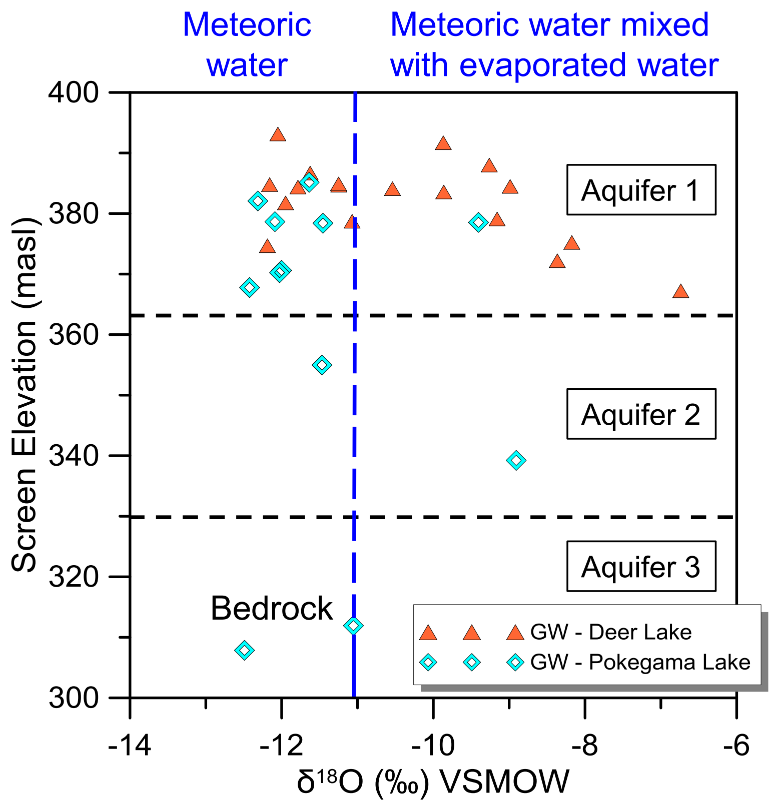


Figure 57: Relationship of δ18O composition and elevation of screened interval in private wells for data shown in plan view in Figures 55 and 56.

Samples taken from Aquifer 1, a sand and gravel aquifer that is tapped for private wells at both Deer and Pokegama Lakes, shows a large variation in isotopic composition depending on whether the source is purely meteoric water or meteoric water that has been subjected to lake evaporation. Aquifer 2 is a deeper sand and gravel aquifer and Aquifer 3 is in fractured Precambrian bedrock near Pokegama Lake. Lake elevations are 399 m and 388 m and for Deer and Pokegama Lakes, respectively. The mean $\delta^{18}O$ composition of Deer and Pokegama Lakes is -4.96 ‰ and -7.16 ‰, respectively. Analytical uncertainty is ± 0.11‰ and ± 0.42‰ (VSMOW) for $\delta^{18}O$ and $\delta^{2}H$, respectively.

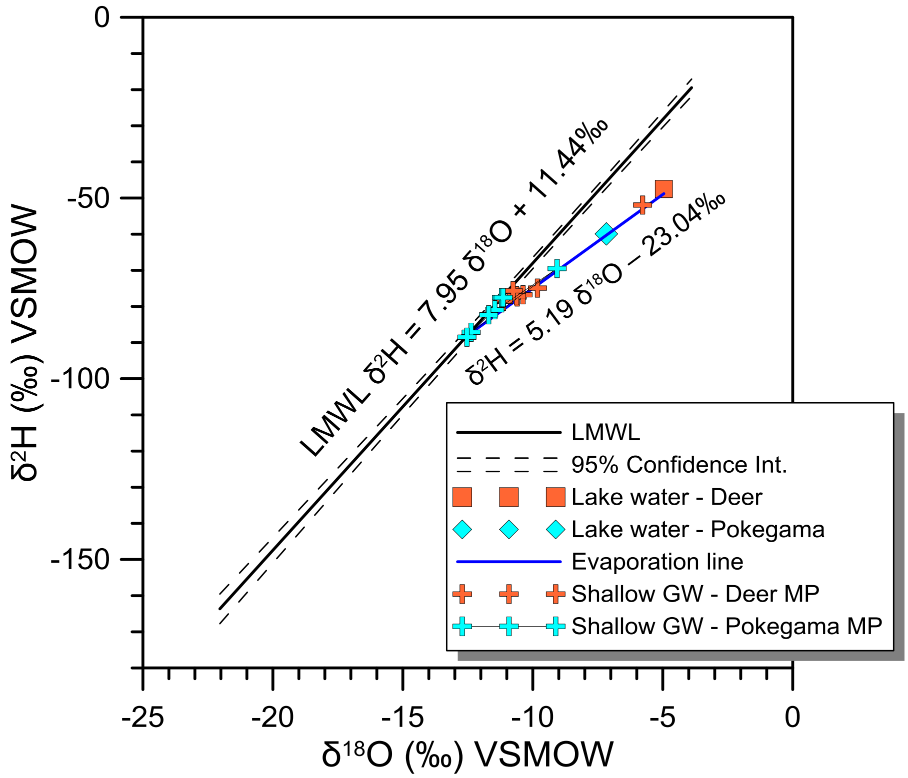


Figure 58: Plot showing the mean isotopic composition of Deer and Pokegama lake water and mean values from shallow groundwater samples in minipiezometers.

Mixing of meteoric groundwater and evaporated groundwater is indicated by samples plotting on the evaporation line and with compositions more enriched than -10 and -68‰ for $\delta^{18}O$ and $\delta^{2}H$‰, respectively. Analytical uncertainty is ± 0.11‰ and ± 0.42‰ (VSMOW) for $\delta^{18}O$ and $\delta^{2}H$, respectively

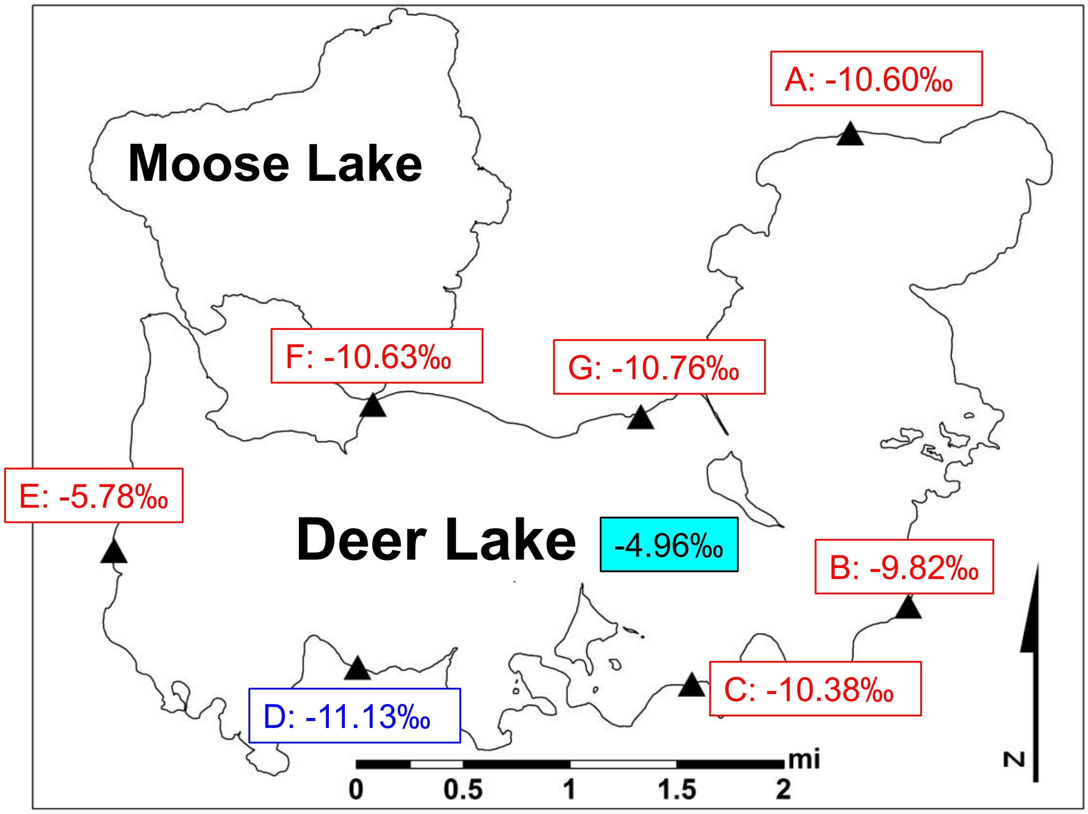


Figure 59: Map of Deer and Moose Lakes showing δ18O composition of shallow groundwater sampled from minipiezometers (2011-2012 data).

Blue boxes indicate groundwater of meteoric origin and red boxes show groundwater that has probably mixed with lake-evaporated water based on a cut-off value of -11 and -68‰. The extent of evaporated water signatures is larger than that for deep groundwater, suggesting greater interaction with lake water. The mean $\delta^{18}O$ composition of Deer Lake is -4.96 ‰. Analytical uncertainty is ± 0.11‰ and ± 0.42‰ (VSMOW) for $\delta^{18}O$ and $\delta^{2}H$, respectively.

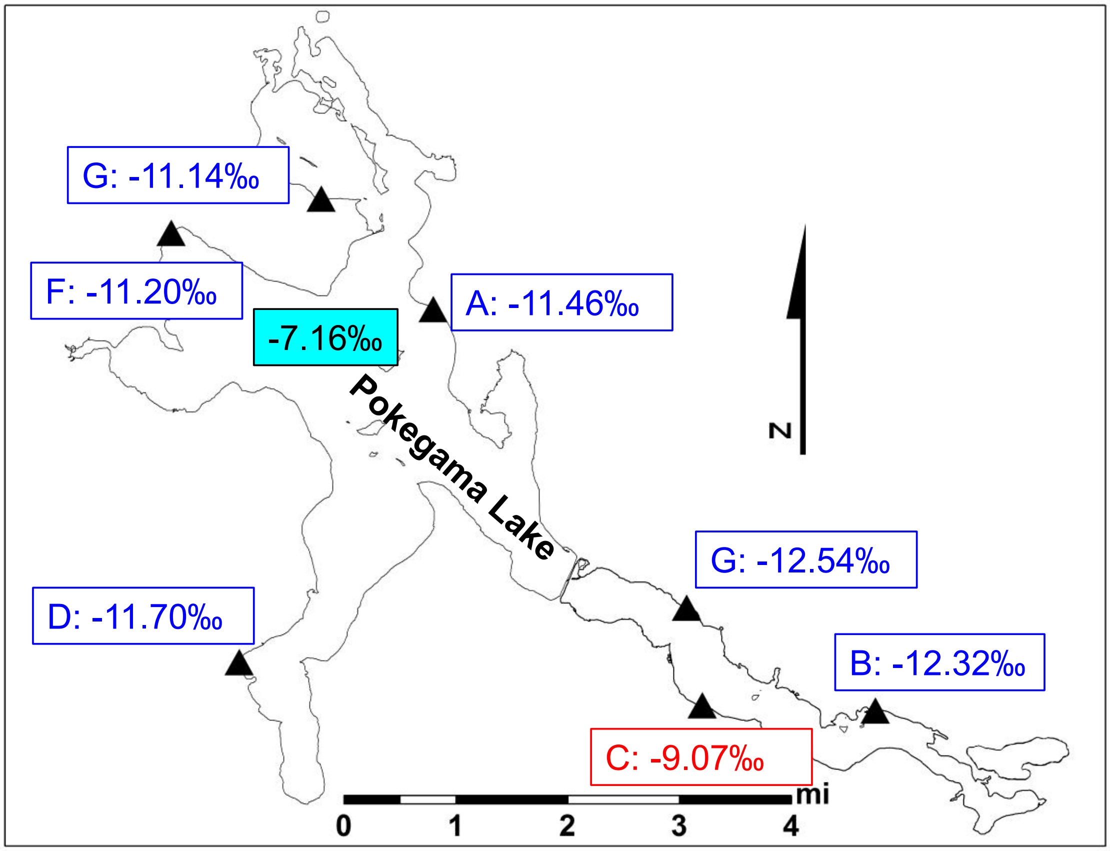


Figure 60: Map of Pokegama Lake showing δ18O composition of deep groundwater sampled from minipiezometers (2011-2012).

Blue boxes indicate groundwater of meteoric origin and red boxes show groundwater that has probably mixed with lake-evaporated water. In contrast to Deer Lake, the isotopic composition of the shallow groundwater shows little evidence of mixing with lake water and is very similar to the deep groundwater. The mean $\delta^{18}O$ composition of Pokegama Lake is -7.16 ‰. Analytical uncertainty is ± 0.11‰ and ± 0.42‰ (VSMOW) for $\delta^{18}O$ and $\delta^{2}H$, respectively.

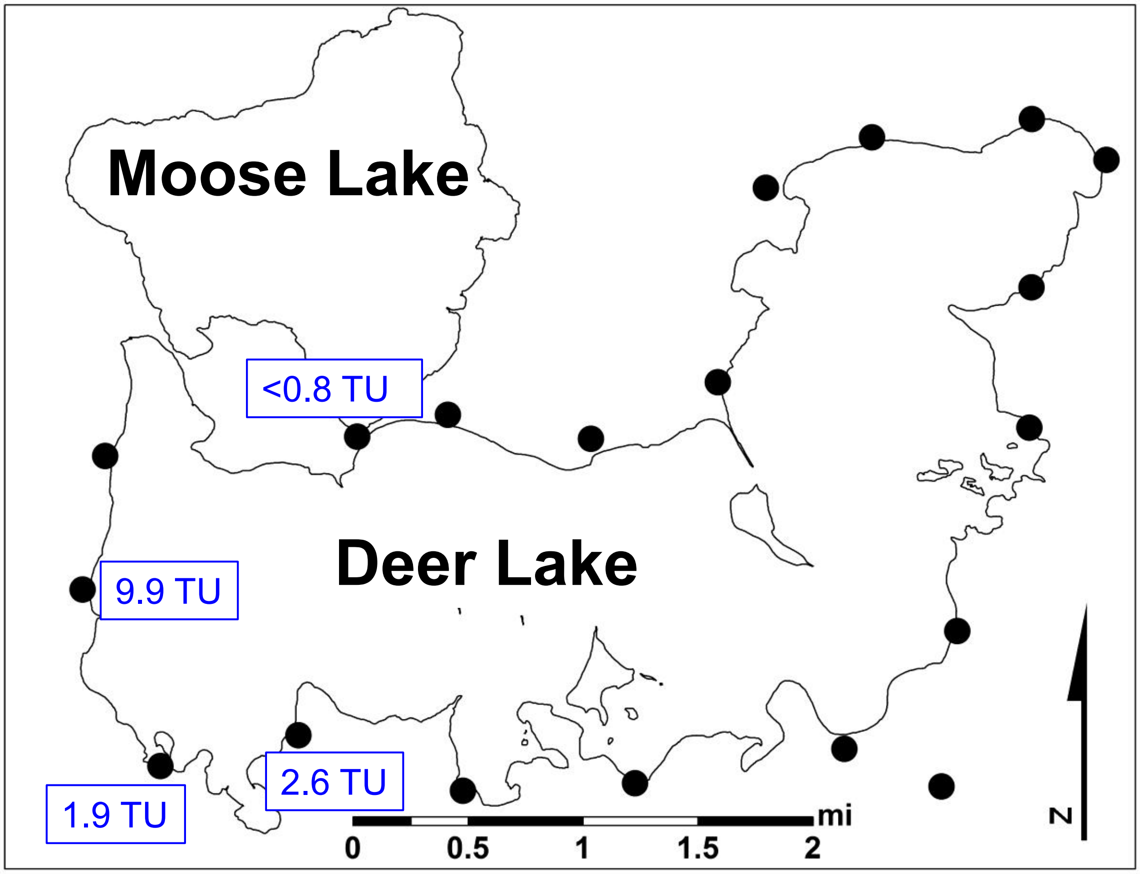


Figure 61: Map of Deer and Moose lakes showing 3H activities in deep groundwater.

Activities suggest groundwater ages ranging from pre-1963 to mixtures of water of different ages.

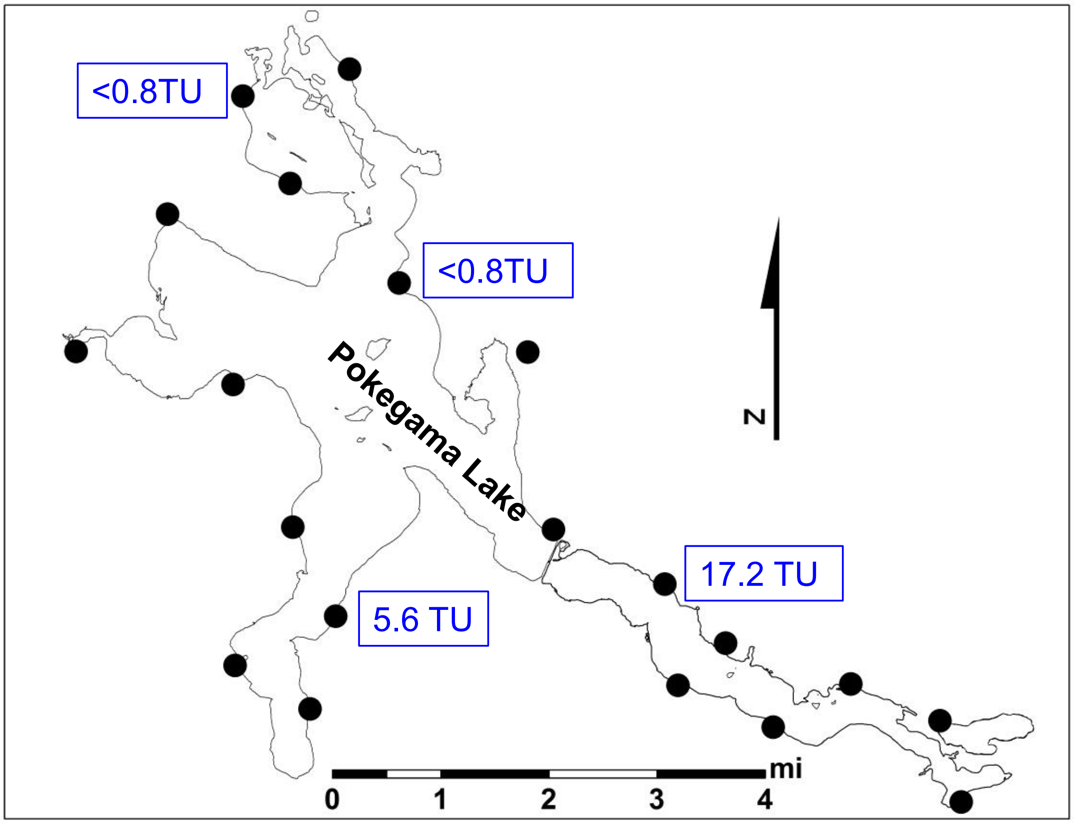


Figure 62: Map of Pokegama Lake showing 3H activities in deep groundwater.

Activities suggest groundwater ages ranging from pre-1963 to mixtures of water of different ages.

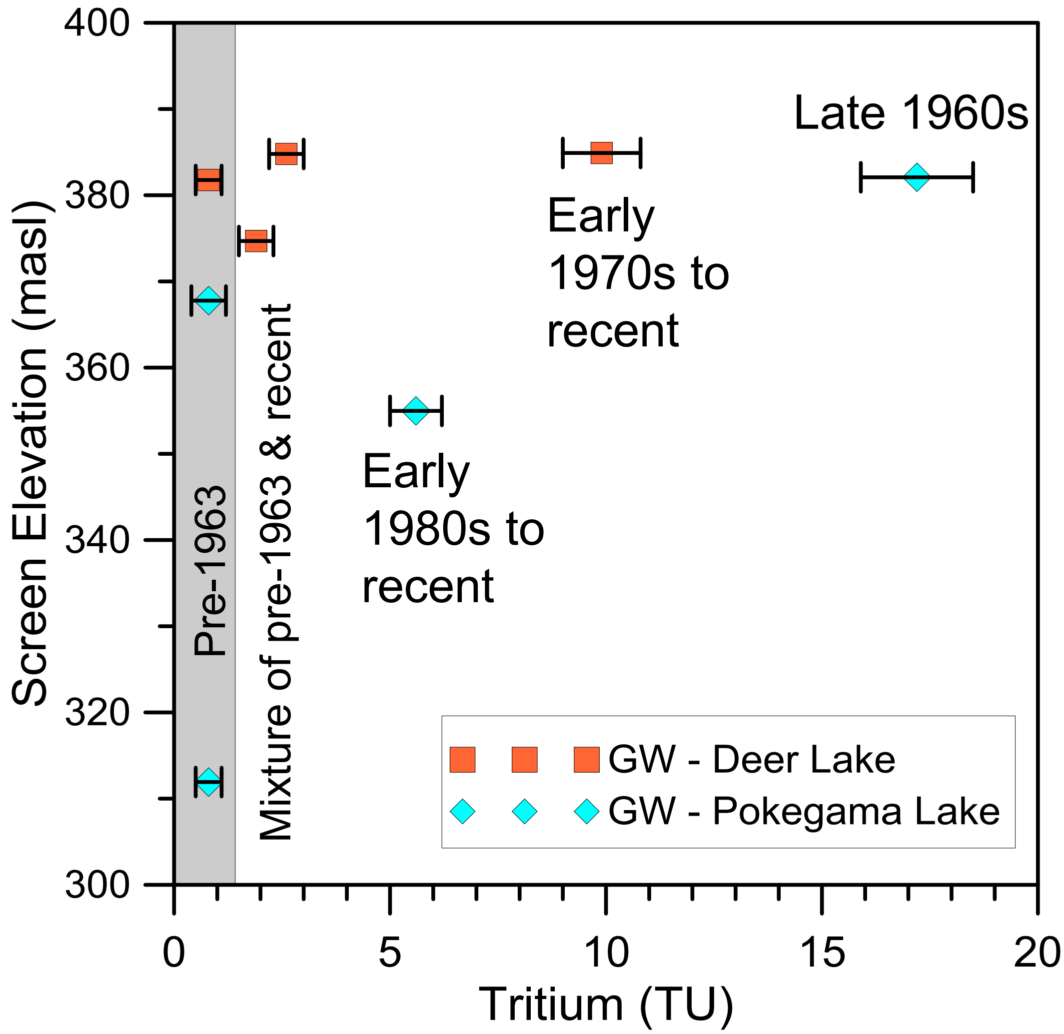


Figure 63: Plot of 3H activities sampled in deep groundwater versus well screen elevation.

Activities suggest groundwater ages ranging from pre-1963 to mixtures of water of different ages.

Well ID	Screen depth (m)	^3H (TU)	$\delta^{18}O$‰	Cl (mg/L)	DOC (mg/L)	Age Interpretation
DW302	29.0	<0.8 ± 0.3	-11.9481	8.8	67.6	Pre-bomb, older than 1963
DW305	22.3	2.6 ± 0.4	-12.1586	1.5	34.3	Mixture of pre-bomb and recent
DW307	18.3	9.9 ± 0.9	-11.2493	1.5	62.3	Early 1970s to recent
DW315	30.5	1.9 ± 0.4	-12.1876	1.4	7.4	Mixture of pre-bomb and recent
PW304	94.5	<0.8 ± 0.3	-11.0536	8.8	13.2	Pre-bomb, older than 1963
PW309	18.0	17.2 ± 1.3	-12.3141	1.5	33.1	Late 1960s
PW312	25.9	<0.8 ± 0.4	-12.4232	1.2	9.5	Pre-bomb, older than 1963
PW314	38.7	5.6 ± 0.6	-11.4674	1.3	10	Early 1980s to recent

Table 24: Tritium activities, Cl, and DOC concentrations in deep groundwater near Deer and Pokegama lakes.

Tritium interpretation based on data from the Midwest and Ames, Iowa (Simpkins, 1995). With the exception of DW302 and PW304, Cl concentrations are near background, suggesting that these waters are not very recent. DOC values are highly variable.

Springs Analysis

Temperature Patterns in Areas with Springs

In the part of Deer Lake with concentrated "spring" inputs in shallow seepage, temperatures beneath the sediment surface were quite low in localized spots, suggesting some areas of concentrated groundwater input (Figure 64). Cool temperatures approached but did not descend to those expected for pure groundwater (around 4.4 degrees C).

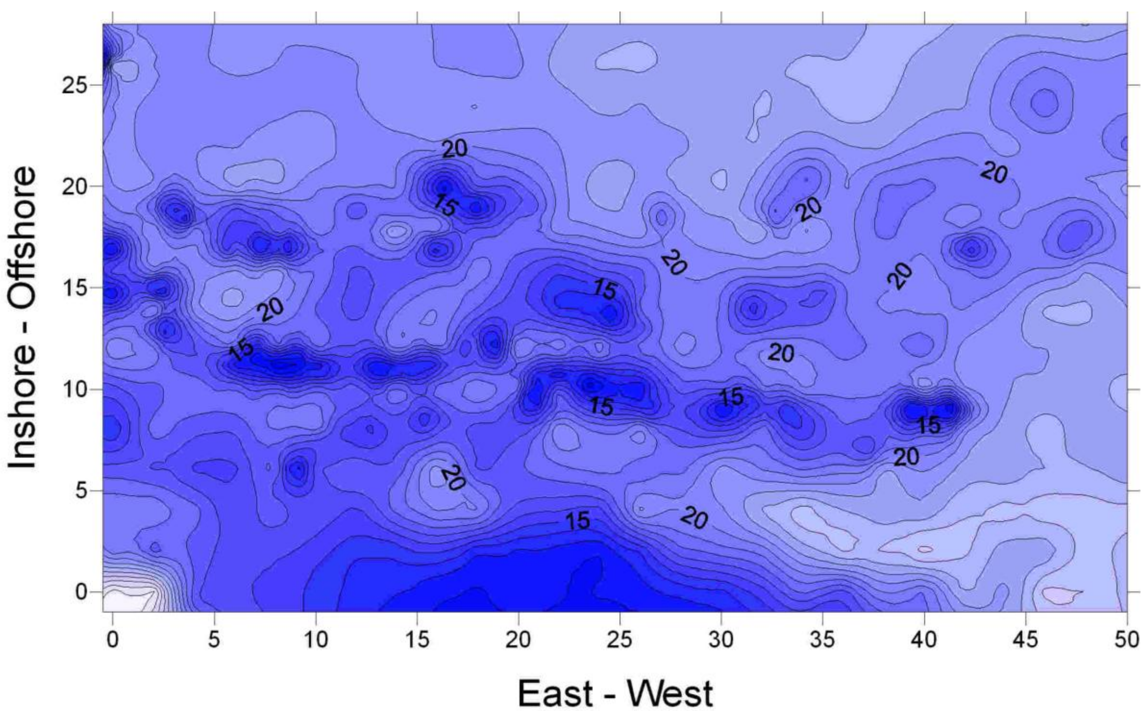


Figure 64: Temperature measurements taken in springs in Deer Lake on June 30, 2012.

Note bimodal distribution of temperatures. Lake temperature was approximately 25 ^{0}C.

Field Data

Minipiezometer and seepage meter measurements indicate that Deer Lake is a primarily a groundwater discharge lake with upward flow in all locations. Temperature measurements in the springs were generally less than lake temperature, thus corroborating flow of colder groundwater upward into the lake (Figure 64). The data were also bi-modally distributed, with a colder temperature group (mean of 12.85 °C) and a warmer temperature group (mean of 20.37 °C; Figure 65). Over 700 individual seepage flux measurements made by Tom Nelson in this area (Figure 66) show a multi-modal distribution with background seepage rates of around 10 ml/sampler/minute but some estimates an order of magnitude higher and more. The temperature groupings suggest variability in groundwater discharge (and flux) to the springs, probably indicative of sediment heterogeneity in the conduits that are feeding them.

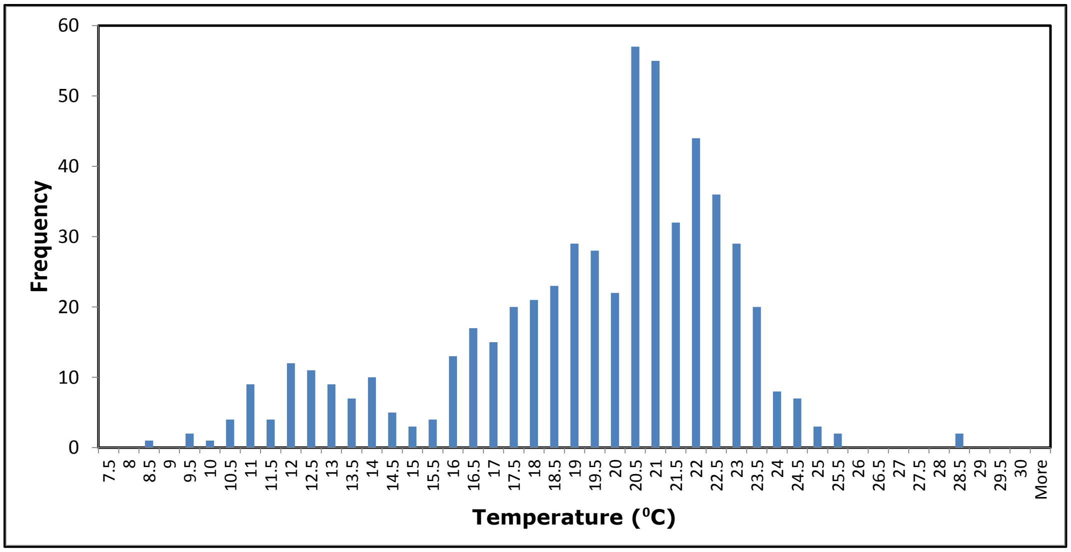


Figure 65: Temperature measurements taken in springs in Deer Lake on June 30, 2012.

Note bimodal distribution of temperatures. Lake temperature was approximately 25 °C.

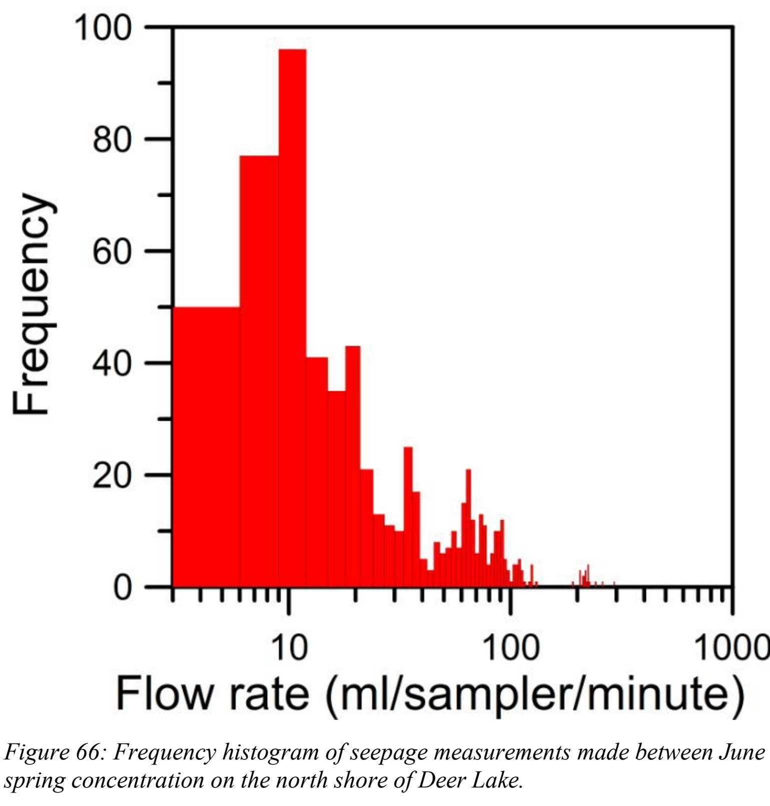


Figure 66: Frequency histogram of seepage measurements made between June 28, 2012, and April 2013 around a spring concentration on the north shore of Deer Lake.

Model Simulations

A simplified 1-D model consisting of a 10-cm zone with boundaries of the lake (top) and groundwater (bottom) was created to simulate the observed temperature measurements in VS2DHI (Figure 67).

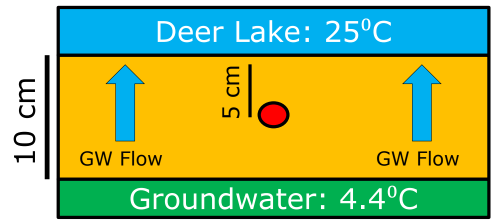


Figure 67: Conceptual model used in the coupled groundwater-heat transport model, VS2DHI.

The interface zone between groundwater and Deer Lake water is 10 cm and is kept under fully-saturated conditions. An upward hydraulic gradient of 0.01 was specified in all simulations.

An observation point was placed at 5 cm depth in the model where observed data would be compared with model results. Boundary conditions included a specified hydraulic gradient of 0.01 upward and inflow/outflow temperature boundaries reflecting the groundwater and lake temperatures, respectively. The entire 10-cm zone was specified at lake temperature as an initial condition. Heat transport across the 10-cm zone was simulated for 1 day with a time step of 100 seconds until temperature at the observation point equaled 4.4 °C, 12.85 °C, and 20.37 °C – the groundwater temperature and the mean temperatures of the bi-modal temperature distribution (Figure 64), respectively. The desired temperature at 5 cm was achieved by varying the hydraulic conductivity (K). The highest K value of 5 x 10^{-4} m/s produced 4.4 ^{0}C, a K value of 4.5 x 10^{-5} m/s produced 12.85 °C, and the lowest K value of 1 x 10^{-5} m/s produced 20.85 °C at the observation point. Groundwater discharge (Q) in m^3/sec was reported after each time step in the model and the value at the final time step was used to compare to the field discharge measurements. Because this is a one-dimensional problem with unit area, the model discharge is actually a seepage flux value (q), similar to the values of the seepage meters.

We constructed a relationship between temperature and seepage flux values from the model (Figure 68), the equation of which is: $\log_{10}q$= -0.094 * (Temp °C) - 0.092. It has an R^2=0.999 and is significant at $P<0.001$. The relationship provides direct estimation of flux from temperature measurements and also allows maps of temperature to be converted directly to maps of groundwater discharge or seepage flux. The results indicated that the values are generally one to two orders of magnitude greater than diffuse seepage flux measurements, which are generally less than 0.6 cm/day (Table 25).

Discharge values are of the same magnitude as values generated from seepage meters set in springs there and at other locations around the lake. Direct calculation of specific discharge (q=K*I) using the values of K and I in the model shows similar flux values at the modeled temperatures. By taking the mean value of the seepage fluxes (0.021 m/d; std dev=0.05) and multiplying it by the 1500 m^2 area in which the measurements were made, the estimated groundwater discharge in this small area is about 31.1 m^3/d. To put that in perspective, Zone A produced a Q of 80557.46 m^3/yr in 2012 based on seepage meter data, which when divided by 365 then reduces to 220.7 m^3/d. Hence, when extrapolated over a year's time, the springs could contribute about 14% of the groundwater discharge of Zone A. We thus added 14% to the shallow seepage flux of Deer Lake to account for the large number of springs observed there.

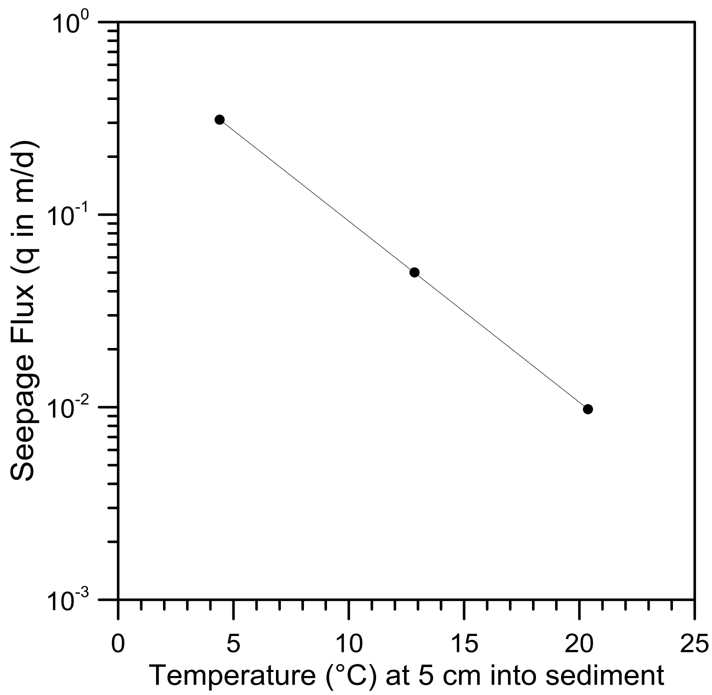


Figure 68: Relationship between groundwater temperature at 5 cm into lake sediment and log_{10} seepage flux (q), as produced by VS2DHI simulations.

R^2=0.999.

Example Temp. (⁰C)	Flux in seepage meter units (cm/d) from model	Groundwater discharge (m^3/d) in 1500 m^2 area	Hydraulic gradient	Estimated K (m/s) in spring sediment
12.0	6.03	90.45	0.01	~ 4.5×10^{-5}
17.6	1.79	26.85	0.01	1.0×10^{-5} to 4.5×10^{-5}
24.2	1.02	15.30	0.01	$<1 \times 10^{-5}$

Table 25: Example model calculations for groundwater flux (q).

Derived from temperature measurements, calculated discharge within the 1500 m^2 area, the specified hydraulic gradient, and estimated K values in the sediment.

The model value of 14% of the discharge in Zone A is not without uncertainty. Better results could be achieved with multiple observation points to match; hence, our answer is probably not unique (Stonestrom and Constantz, 2003). In addition, measurements were done one time and the discharge in springs is subject to variation in precipitation as are seepage meter measurements. Hence, the long-term contribution of the springs to discharge is not known. Better temperature measurements at more depths and over longer time periods would improve the q estimate and decrease the potential for non-uniqueness of the model result. Springs are significant contributors to groundwater flux in Deer Lake.

Figure 69: Andy Arens (ISWCD) measures shallow groundwater inflows to Pokegama Lake.

Conclusions

A coupled groundwater/heat transport model using lake temperature and a single temperature measurement in sediment was used to estimate groundwater flux from springs – with many implicit assumptions. Results suggest that fluxes in the springs are 10- to 100-times greater than those in areas of diffuse seepage in Deer Lake. Visual surveys of spring locations in Deer Lake suggest that that the higher flow areas are localized, perhaps where sand bodies connected to the shallow unconfined aquifer intersect the lake. Further work is needed to establish the hydrogeologic controls of the springs in Deer Lake. Model results could be improved by increased spatial and temporal temperature measurement. Nevertheless, “spring” inputs contribute substantially to the water and nutrient budget, potentially adding as much as 14% of the shallow water seepage.

Nutrient Transport and Nutrient Budgets

Consolidated Maps of Sampling Locations

Because our sampling program evolved over the sampling period, the original sampling plan and locations were modified. Figure 70 shows the consolidated map of sampling locations for Deer lake while Figure 71 shows the consolidated map of sampling locations for Pokegama Lake. Examining the correspondence of landscape and nutrient characteristics can give clues about sources of nutrient fluxes.

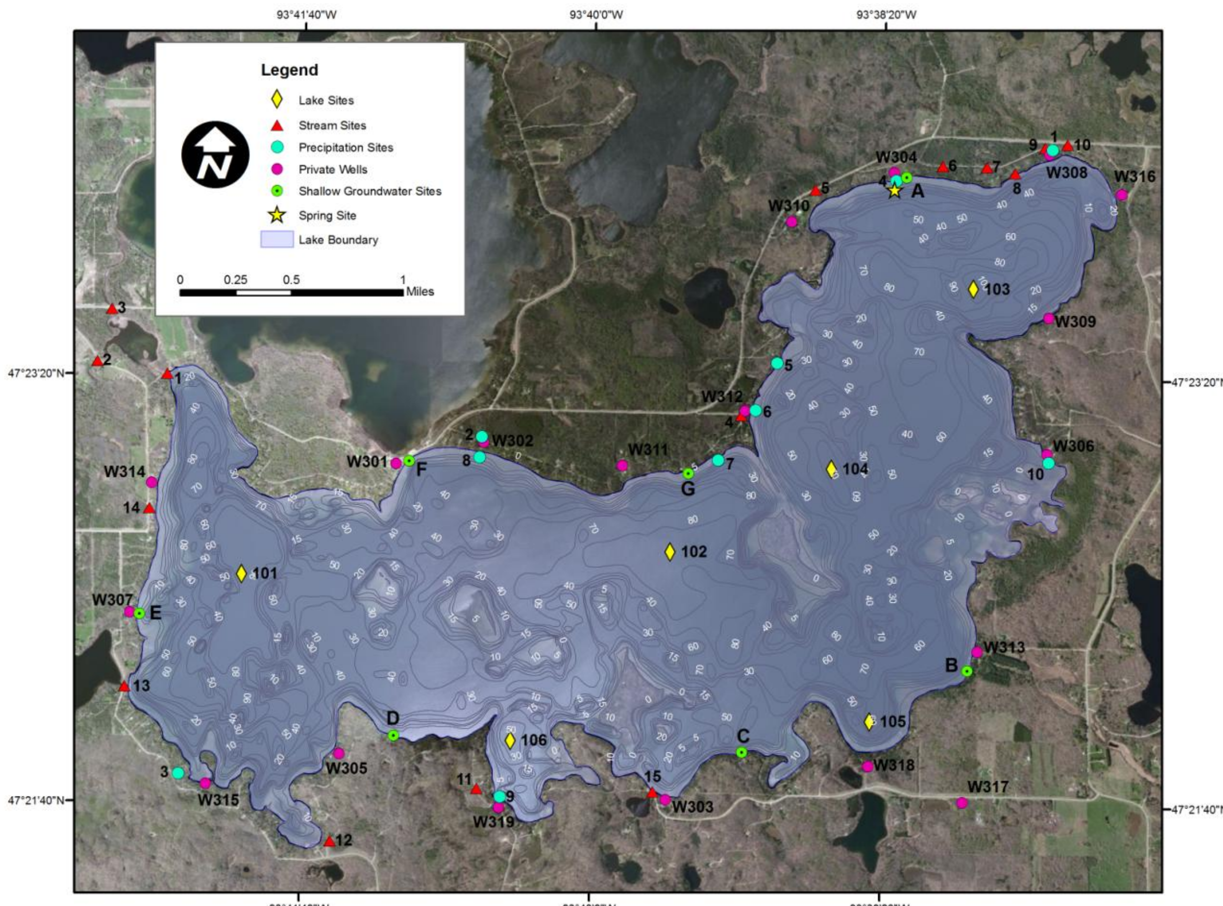


Figure 70: Consolidated map of sampling locations on Deer Lake.

Numbers refer to site number referred to in tables and text while symbols indicate the type of sampling site.

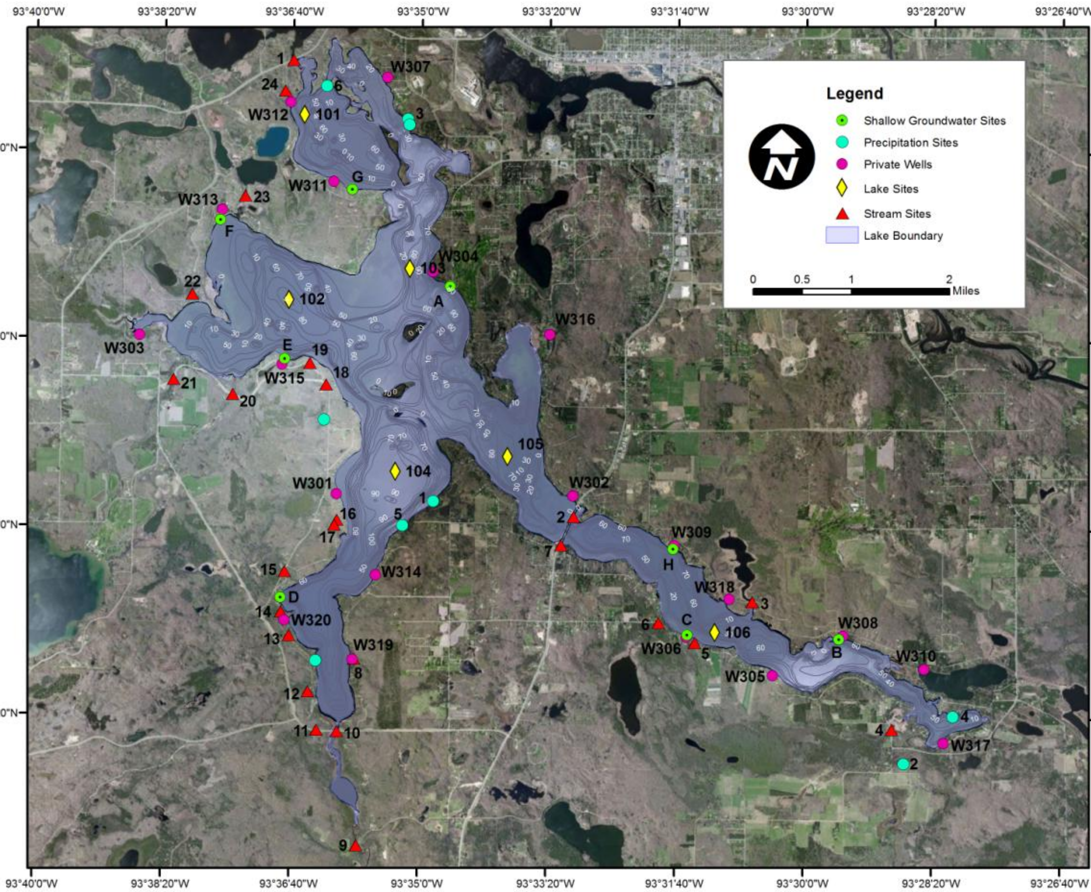


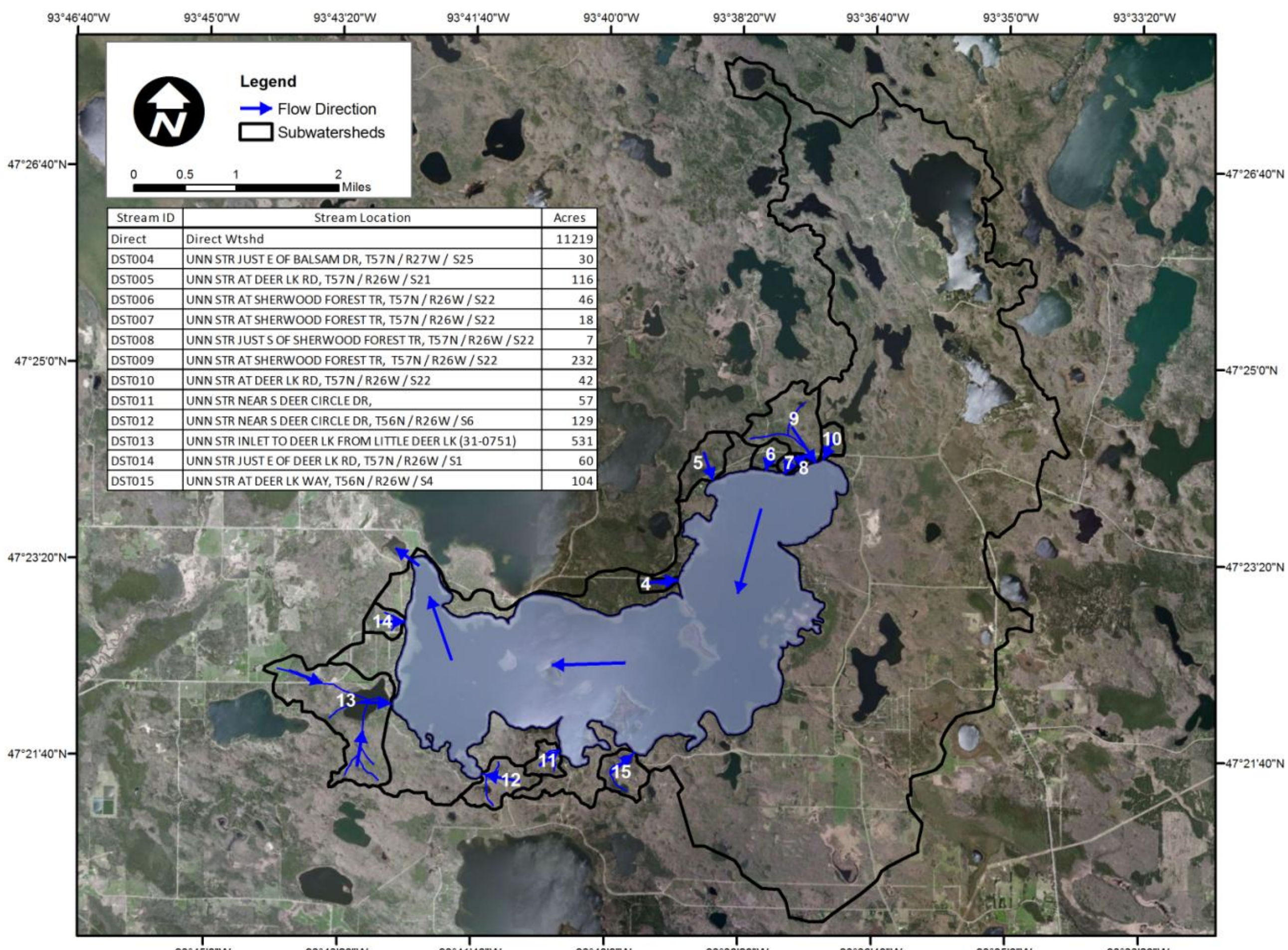
Figure 71: Consolidated map of sampling locations on Pokegama Lake.

Numbers refer to site number referred to in tables and text while symbols indicate the type of sampling site.

Surface Flux from Sub-Watersheds

Deer Lake

Much of the Deer Lake watershed has no consolidated surface stream tributary and therefore supplies water and nutrients via the groundwater system. For example, the very large portion of the watershed to the east of the lake and to the northeast (Figure 72) has no substantial flowing surface tributaries. Tributaries varied substantially, however, in their run-off coefficients and the amount of phosphorus supplied to the lake. Most notable are streams 4, 10, and 14 that seem to have substantially elevated phosphorus concentrations and export coefficients. Generally, export of phosphorus greater than 90 g/ha/y from forests would seem quite high and outside the range of unimpacted watersheds. A few tributaries are therefore carrying more phosphorus than might be expected in the absence of urbanization or other land use changes.



Stream ID	Stream Location	Acres
Direct	Direct Wtshd	11219
DST004	UNN STR JUST E OF BALSAM DR, T57N / R27W / S25	30
DST005	UNN STR AT DEER LK RD, T57N / R26W / S21	116
DST006	UNN STR AT SHERWOOD FOREST TR, T57N / R26W / S22	46
DST007	UNN STR AT SHERWOOD FOREST TR, T57N / R26W / S22	18
DST008	UNN STR JUST S OF SHERWOOD FOREST TR, T57N / R26W / S22	7
DST009	UNN STR AT SHERWOOD FOREST TR, T57N / R26W / S22	232
DST010	UNN STR AT DEER LK RD, T57N / R26W / S22	42
DST011	UNN STR NEAR S DEER CIRCLE DR,	57
DST012	UNN STR NEAR S DEER CIRCLE DR, T56N / R26W / S6	129
DST013	UNN STR INLET TO DEER LK FROM LITTLE DEER LK (31-0751)	531
DST014	UNN STR JUST E OF DEER LK RD, T57N / R26W / S1	60
DST015	UNN STR AT DEER LK WAY, T56N / R26W / S4	104

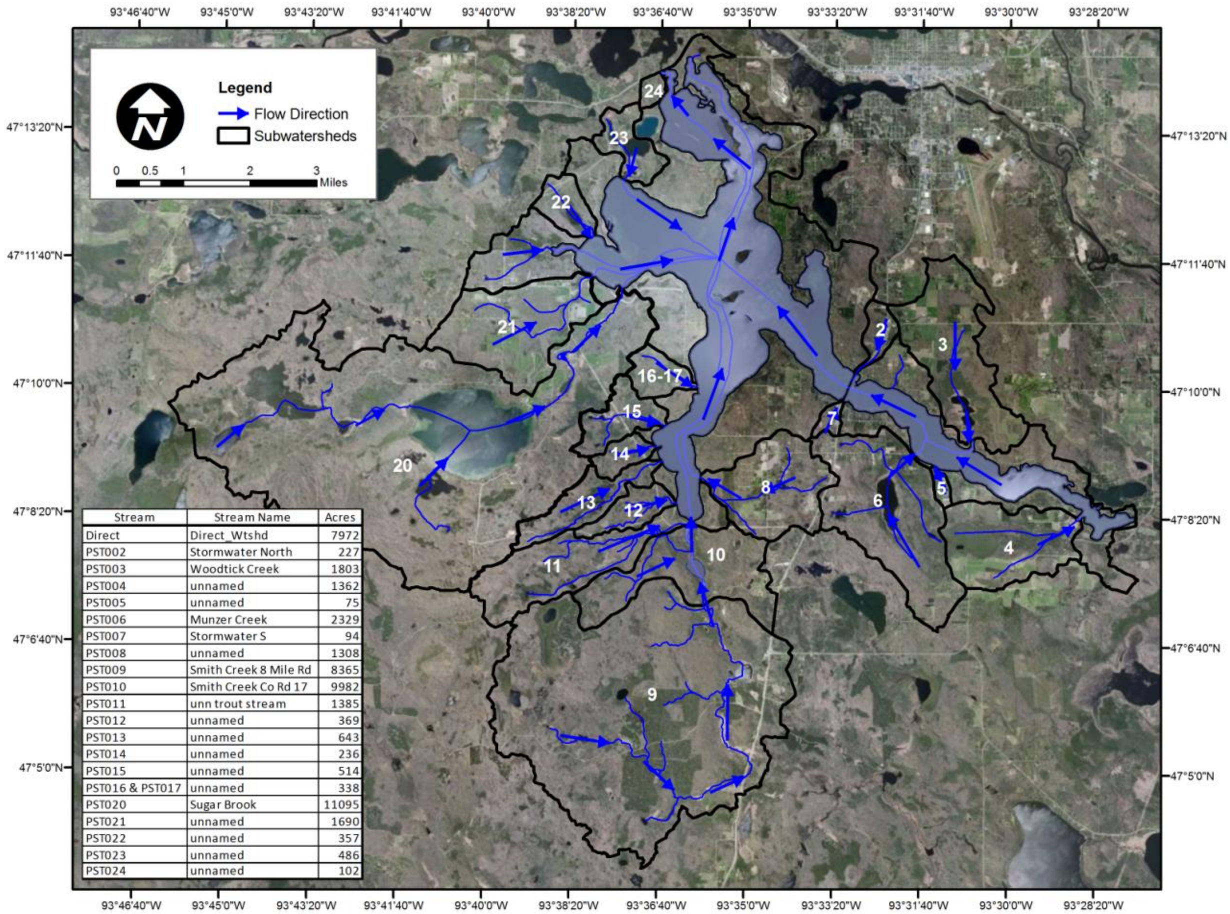
Figure 72: Sub-watersheds of Deer Lake showing flow-paths and consolidated tributaries.

Surface site	Area of watershed (ha)	Water load (m^3)	Run-off coefficient	Total TP flux (kg/y)	Phosphorus export (g/ha/y)	Average total P (ppb)
S001 (out)		8400971		98.1		12
S004	29.9	89535	41.5%	6.6	222	74
S005	115.8	41535	5.0%	3.0	26	72
S006	45.5	60557	18.5%	4.3	94	70
S007	18.2	40681	31.1%	1.1	63	28
S008	7.3	11892	22.7%	0.2	34	21
S009	231.6	298338	17.9%	16.4	71	55
S010	41.9	51805	17.2%	7.3	174	141
S011	57.4	19549	4.7%	1.0	18	52
S012	128.5	217935	23.6%	6.2	48	29
S013	531.0	945321	24.7%	24.5	46	26
S014	59.6	161336	37.6%	11.6	195	72
S015	104.4	30415	4.0%	1.2	11	38

Table 26: Annual water and nutrient fluxes supplied by various sub-watersheds of Deer Lake.

Pokegama Lake

Pokegama Lake clearly has a much more urbanized watershed than Deer, owing to its long history of development and proximity to the Grand Rapids metropolitan area (Figure 73). Most of the watershed is drained by consolidated streams although some were found to run very irregularly or not at all during the study period (Table 27). Run-off coefficients as high as 57% were found, indicating that impermeable surfaces may contribute to the water and nutrient load received by Pokegama. Most notable were tributaries 4, 5, 9, 11, and 24. These watersheds had elevated phosphorus export coefficients that are indicative of urbanization, drainage, agriculture, or other watershed modifications. Watershed 9 supplies a very large fraction of the nutrient input to the lake. This watershed contains farms, urban areas, managed forests, and other land-uses that may supply substantial nutrients to the lake.



Stream	Stream Name	Acres
Direct	Direct_Wtshd	7972
PST002	Stormwater North	227
PST003	Woodtick Creek	1803
PST004	unnamed	1362
PST005	unnamed	75
PST006	Munzer Creek	2329
PST007	Stormwater S	94
PST008	unnamed	1308
PST009	Smith Creek 8 Mile Rd	8365
PST010	Smith Creek Co Rd 17	9982
PST011	unn trout stream	1385
PST012	unnamed	369
PST013	unnamed	643
PST014	unnamed	236
PST015	unnamed	514
PST016 & PST017	unnamed	338
PST020	Sugar Brook	11095
PST021	unnamed	1690
PST022	unnamed	357
PST023	unnamed	486
PST024	unnamed	102

Figure 73: Sub-watersheds of Pokegama Lake showing flow-paths of consolidated tributaries.

Another large tributary is actually the outfall to the Mississippi River. When water levels in the Mississippi are very high and the Dam between Cohasset and Grand Rapids allows water to back up into Pokegama, this can represent a large fraction of the surface water and nutrient input to the lake. Nutrient concentrations in the River over the period of this study were only slightly higher than those of the lake. They were, however, quite variable. Additional sources of phosphorus added to the Mississippi above the Corps of Engineers dam could supply a lot of nutrients to Pokegama, and could contribute to its eutrophication.

Preservation of the current nutrient status of these lakes suggests that tributary nutrient export rates from sub-watersheds be managed to keep them low. Phosphorus export rates of >90 g/ha/y indicated the need for watershed and tributary remediation. Several of the streams had phosphorus concentrations that exceed Minnesota draft nutrient standards.

Site	Area of watershed (ha)	Water load (m3)	Run-off coefficient	Total P flux (kg/y)	Phosphorus export (g/ha/y)	Average total P (ug/L)
S001 (out)		112421101		1919.0		17
S001 (in)		41480437		761.3		18
S002	226.81	35621	2.2%	7.2	32	203
S003	1803.2	2136117	16.5%	44.2	25	21
S004	1361.7	2339055	23.9%	112.1	82	48
S005	75.34	311633	57.5%	61.0	810	196
S006	2328.98	2063465	12.3%	58.7	25	28
S007	94.13	0	0.0%	0.0	0	
S008	1308.46	33603	0.4%	3.9	3	117
S009	8364.86	15389628	25.6%	1070.9	128	70
S010	9981.82	0	0.0%	0.0		
S011	1384.85	1885887	18.9%	102.0	74	54
S012	369.51	80162	3.0%	3.2	9	40
S013	643.16	298840	6.5%	21.5	33	72
S014	236.42	118760	7.0%	2.3	10	19
S015	513.51	631875	17.1%	21.3	42	34
S016 &17	337.7	294101	12.1%	8.6	29	29
S020	11094.57	9740379	12.2%	212.9	19	22
S021	1689.81	595681	4.9%	29.1	17	49
S022	356.73	102136	4.0%	2.1	6	21
S023	486.27	195475	5.6%	0.0		
S024	101.73	62296	8.5%	7.4	73	119

Table 27: Annual water and nutrient fluxes supplied by various sub-watersheds of Pokegama Lake

Precipitation Deposition

Lakes with small watersheds relative to their areas are often dominated by atmospheric inputs of nutrients and water. The ratios of watershed:lake area are 3 and 18 for Deer and Pokegama Lakes, respectively. For this reason direct deposition to the lakes' surfaces, via wet deposition (rain, snow) and dry-fall (e.g., dust) are of particular interest.

Although efforts were made to avoid considering any samples of wet deposition that contained contaminants, total phosphorus analyses of clean, fresh samples revealed substantial total P in samples (Figure 74). Average total P was 24-26 µg/L. This is surprising, especially considering that we avoided contamination and dry deposition (dust).

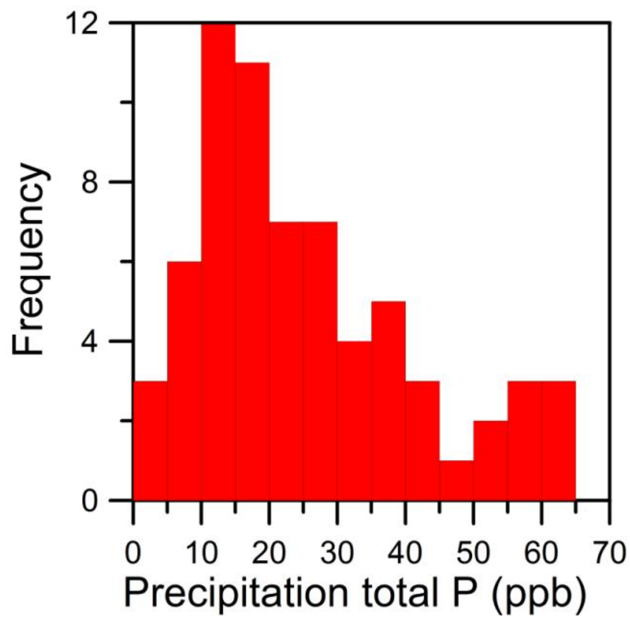


Figure 74: Pooled data on clean, fresh precipitation chemistry for data from both Deer and Pokegama Lakes.

Mass Balance Nutrient Budgets

Mass balance calculations were performed for both lakes for total phosphorus since phosphorus is the principal limiting nutrient in these ecosystems. Mass balances were calculated daily to account for lake-storage changes, daily precipitation, and daily changes in evaporative losses and then summed to calculate the average annual budget over the study period (Tables 28 and 29).

Source	Water flux (m3/y)	Total P flux (kg/y)	Percent of total P input	Average TP (ug/L)
Annual Average rainfall	11895055	312	73.4%	26
All Streams	1968900	83	19.6%	42
Deep Ground Water	1736500	21	5.0%	12
Shallow Ground Water	670032	8	2.0%	13
Outflow	8400971	98		12
Evaporation	1241959			

Table 28: Nutrient budget of Deer Lake from 2011-2013.

Source	Water flux (m3/y)	Total P flux (kg/y)	Percent of total P input	Average TP (ug/L)
Mississippi River backflow (S001-in)	41480437	761	23.7%	18
All Streams	36314713	1770	55.0%	49
Annual Average rainfall	19951630	472	14.7%	24
Deep Ground Water	15440000	50	1.6%	3
Shallow Ground Water	1766935	162	5.0%	92
S001 (outflow)	112421101	1919		17
Evaporation	1998817			

Table 29: Nutrient budget of Pokegama Lake from 2011-2013.

Deer Lake Phosphorus Budget

The average annual phosphorus budget is shown in Table 28. Owing to Deer Lake's very small watershed (Table 30), the phosphorus budget is very finely balanced with a small annual input of phosphorus (net 327 kg of total P). Considering that the annual P output of an individual human being is around 0.9 kg, the lake should be considered quite sensitive to additional P loading. 73% of the water and phosphorus input derives from direct precipitation (Figures 75 and 76). This is somewhat higher than would be expected based on total P measures in other regions. Phosphorus transported by rainfall appears to be about twice as concentrated in this watershed and the Pokegama watershed than seen in both developed and undeveloped areas. We feel that atmospheric transport and deposition of nutrients and other possible pollutants in this region bears further investigation so is included in the implementation section of this report. This study did not include enough funding to perform extensive analyses of precipitation chemistry and transport.

Parameter	Deer Lake	Pokegama Lake
Lake volume (m^3)	147321752	146885990
Lake area (m^2)	16527590	27721802
Watershed area (m^2)	50900000	506130000
Watershed:lake area ratio	3.1	18.3
Mean depth (m)	8.9	5.3
Water Residence Time (y)	17.5	1.3
Phosphorus Retention (%)	76.9%	40.3%
Net annual P input (kg)	327	1296
Areal P loading (mg/m^2)	19.8	46.8
Volumetric P loading ($\mu g/m^3$)	2.2	8.8

Table 30: Basic nutrient and physical data on the two lakes and their watersheds.

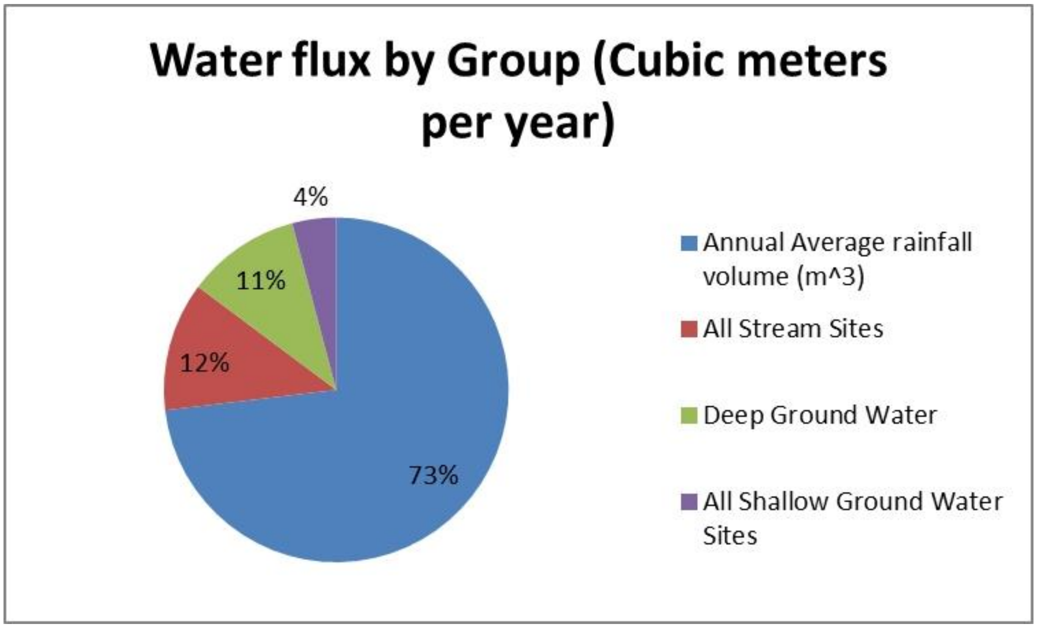


Figure 75: Annual average water flux from major sources to Deer Lake from 2011-2013.

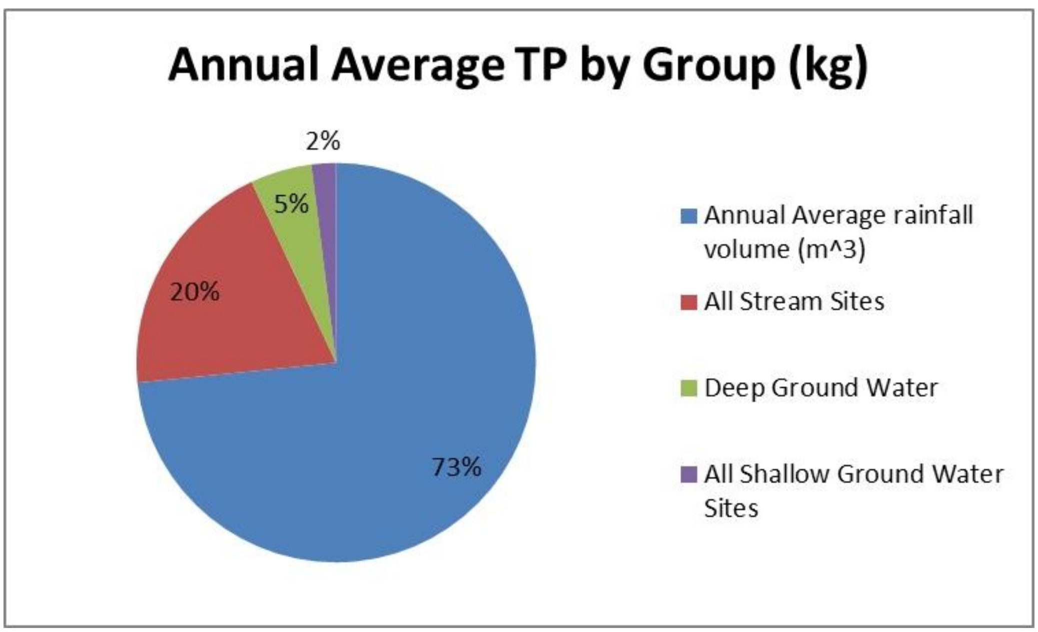


Figure 76: Annual average total phosphorus flux from major sources to Deer Lake from 2011-2013.

In spite of the dominance of precipitation as a source of nutrients to Deer Lake, substantial nutrient input also derives from surface streams (19.6% of inputs) and groundwater transport (7% of inputs). Stream chemistry is quite concentrated in a few of the tributaries to Deer Lake, especially 4, 6, 7, 9, 10, and 14 (Figure 77). In order to maintain the water quality of Deer Lake, it would be important to remediate these nutrient sources while protecting other tributaries from degradation. Some of the phosphorus concentrations were quite high in streams and this bears investigation and care.

Groundwater was also a substantial nutrient source in Deer Lake, especially the large deep groundwater flows. Generally, nutrient concentrations in groundwater were somewhat higher than those in lake water, perhaps indicating some level of contamination. A few areas (e.g., areas B, D, and F; Figure 78) showed P-contaminated groundwater, indicating some need for remediation of groundwater nutrient sources. Some of this could be due to septic tank effluent, although there is little correlation between the location of septic systems and extremely high P values (Table 31). Septic systems are most dense in sub-watersheds 7, 11, and the unconsolidated sub-watershed to the east and northeast (Table 31). The large, unconsolidated watershed to the east and northeast of Deer Lake contains many septic systems and so may play a role in adding this component of the nutrient budget. It would be useful to perform a more substantial study of groundwater flux and composition throughout this region to better understand this important component of Itasca County lake nutrient budgets. Moderate changes in groundwater P concentration could substantially change the water quality of Deer Lake due to the substantial water input from this source.

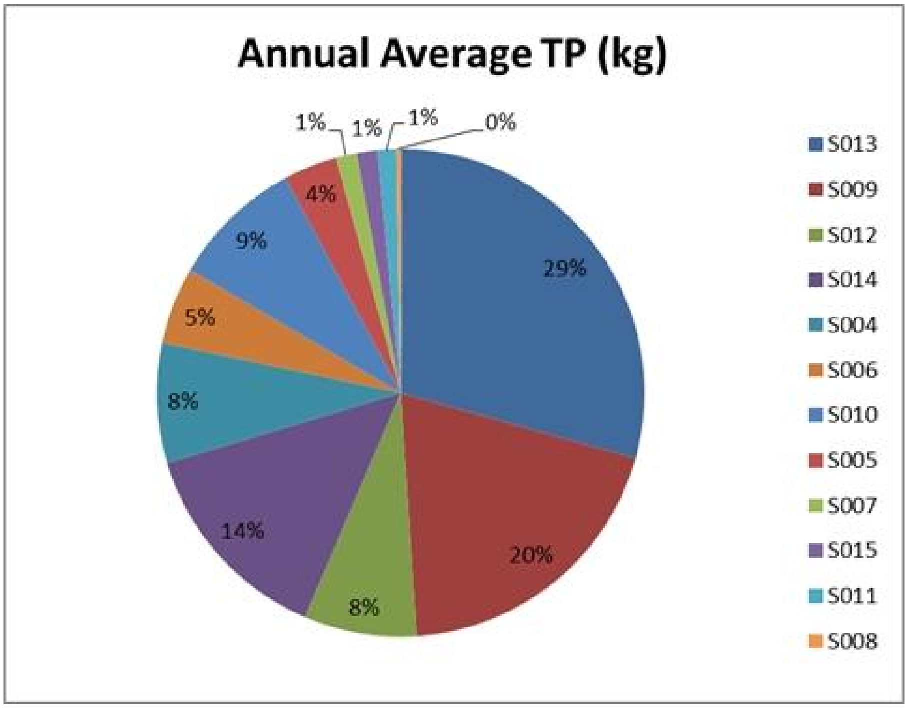


Figure 77: Annual average tributary P fluxes from stream sites around Deer Lake from 2011-2013.

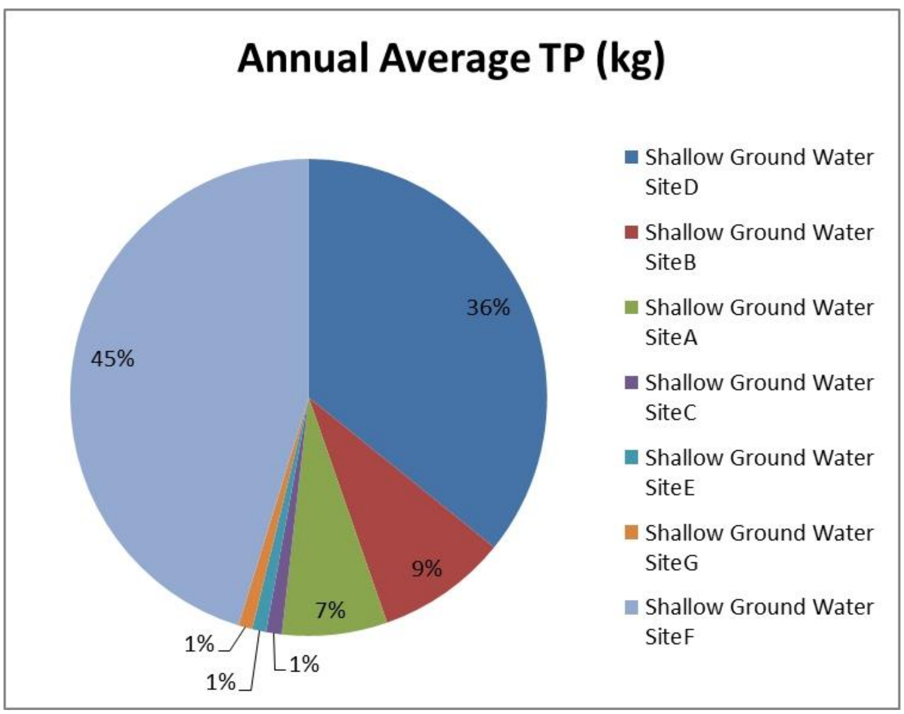


Figure 78: Annual average groundwater phosphorus fluxes from shallow groundwater regions around Deer Lake from 2011-2013.

Sub-watershed	Area (ha)	ha/septic system	% impervious
S001 (out)			
S004	29.9	29.9	8.98%
S005	115.8	38.6	6.78%
S006	45.5	22.8	9.18%
S007	18.2	6.1	1.32%
S008	7.3		10.99%
S009	231.6	57.9	1.97%
S010	41.9	41.9	5.06%
S011	57.4	19.1	1.71%
S012	128.5	128.5	2.92%
S013	531.0	40.8	1.46%
S014	59.6	59.6	4.26%
S015	104.4	34.8	0.75%
No-trib	4540.0	7.9	5.49%

Table 31: Density of septic systems and fraction of impervious surface in the watershed of Deer Lake.

Data are from Itasca County records.

Pokegama Lake Phosphorus Budget

The average annual phosphorus budget of Pokegama is shown in Table 29. The net P input to Pokegama is 4-times that of Deer. Because the ratio of watershed to lake area is larger for Pokegama Lake, precipitation is less dominant, although still surprisingly substantial, given the relatively pristine, non-industrial area in which the lake is located. Direct precipitation input is responsible for 15% of the P input and has an average P concentration of about 24 ppb. The reason for this elevation is unknown but should be analyzed.

Tributaries contribute the majority of the phosphorus input to Pokegama. For Pokegama, there are two types of tributaries – those that are natural and are part of the downhill, south to north flowage of the lake and its tributaries, and back-up of the Mississippi River, owing to a flood control dam on the Mississippi River above Grand Rapids and below Cohasset, Minnesota. Back-up from this structure has likely been common since the early 1900s when the dam created substantial storage behind it. Back-up from this dam at high water contributes 36% of the water flowing into Pokegama Lake and about 30% of the phosphorus input from surface fluxes (Tables 79 and 82). 79% of all phosphorus entering Pokegama derives from surface water inflows (Table 29).

Some of the inflows have very high fluxes of phosphorus, given the landscape. P concentraions at stream sites 3, 5, 8, 9, 13, and 24 are very high and P export rates from streams 4, 5, 9, 11, and 24 are higher than expected for similar types of landscapes.

Interestingly, water in the lake seems to be approaching the P concentration in the river (Table 29). This makes sense because the water resides in Pokegama only about 1.3 years, on average, much of the water comes from the river, and so the lake and river concentrations will tend to converge over time. Although there is a tight hydraulic connection between the lake and Mississippi, the lake continues to hold a phosphorus advantage over the river, likely due to upstream flushing. This implies that changes to water quality in the Mississippi River would be reflected in Pokegama in the future. The watershed of Pokegama thus periodically contains the watershed of the Mississippi River above Pokegama, an area (1976 square miles) about 100-times the size of the natural watershed. Because anything that discharges into the Mississippi River “Headwaters Watershed” would become part of the potential inflow to Pokegama at high water, management of the surface watershed is complex and vast in spatial and socio-economic scale.

The preponderance of surface water inputs should not imply that these are the only nutrient and water sources to Pokegama. Precipitation, for example, supplies 15% of the phosphorus input (Table 29) while groundwater (shallow and deep) supply about 6.6% of the total phosphorus supply. One of the regions of groundwater input dominates groundwater phosphorus supply, owing to very high concentrations (Figure 81). Site F supplies substantial P and the source of this excess P is not known. Potential sources could be natural or include septic or industrial effluent. Septic systems are densest in sub-watersheds 7, 24, and the part of the watershed with no consolidated tributaries (Table 32).

Internal Loading

Direct mass-balance calculation of potential internal loading was performed as part of the nutrient budget. Although there were periods during the study when internal loading occurred, both of these lakes showed net phosphorus retention rather than net internal loading.

Watershed Run-Off and Surface Water Nutrient Supply

Regardless of which lake is in question, the faster the water runs off the land surface the more nutrient supply there is to the water body downstream. Pooling all data on run-off coefficients (the fraction of rainfall that flows across the land to the lake) and phosphorus export coefficients (the amount of phosphorus given up from the land each year) from both lakes shows that the P export rises exponentially with land drainage (Figure 82). The fact that this graph is on a logarithmic scale means that the rate of P export from the land accelerates very rapidly with increased drainage and impermeable surfaces in this area. Indeed, a doubling in run-off from these watersheds more than doubles phosphorus supplies to the lakes.

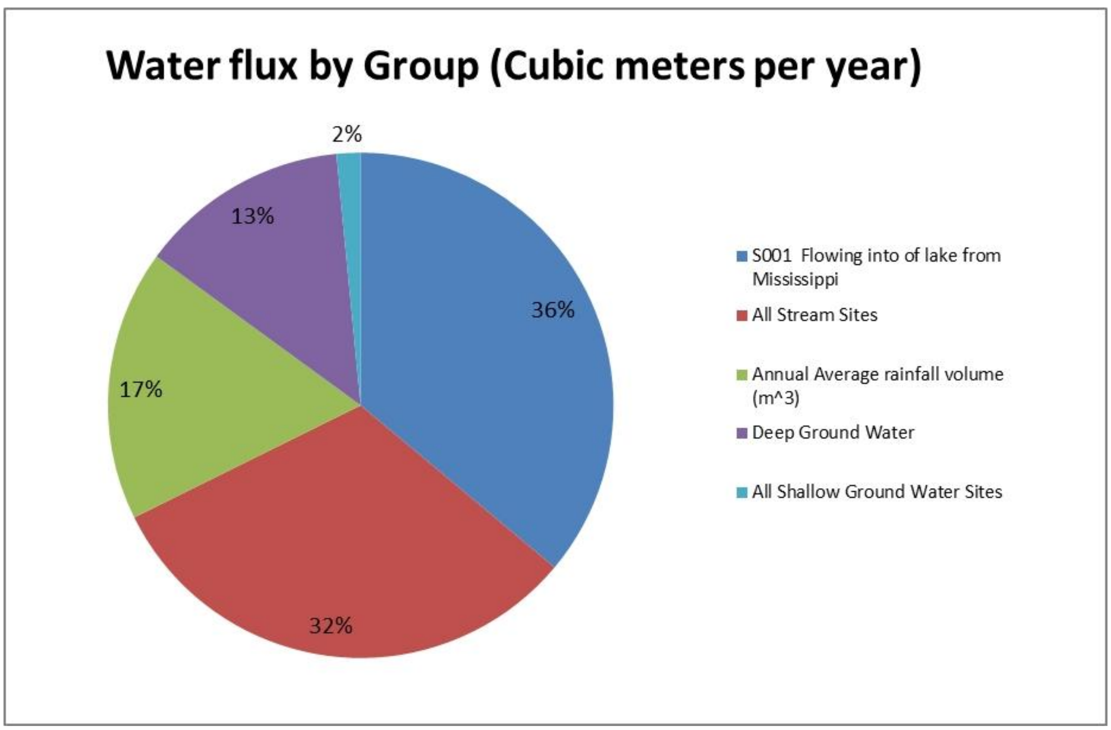


Figure 79: Annual average water inputs from major sources to Pokegama Lake from 2011-2013.

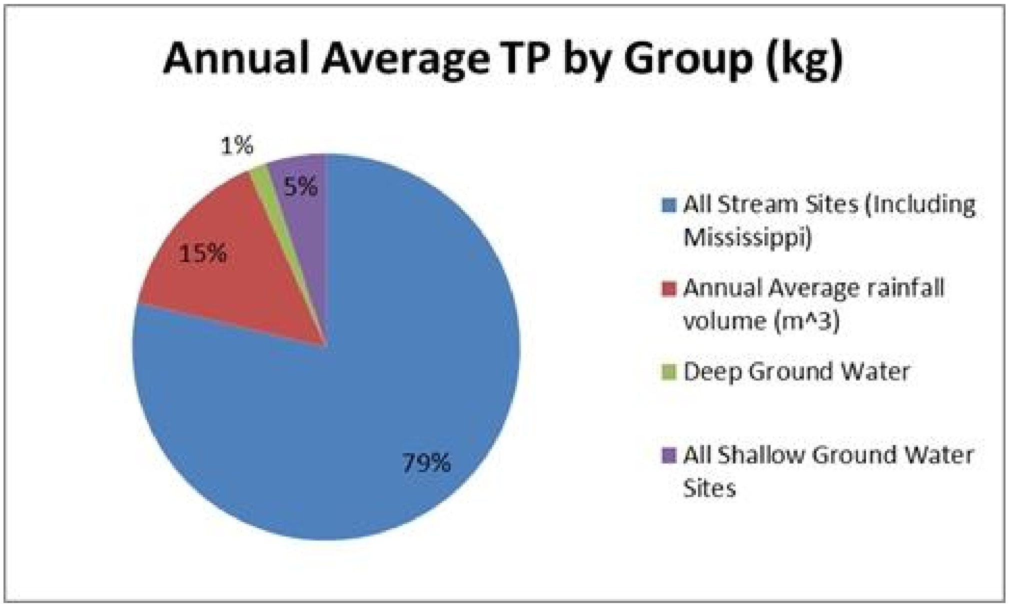


Figure 80: Annual average phosphorus fluxes to Pokegama Lake from major sources to Pokegama Lake from 2011-2013.

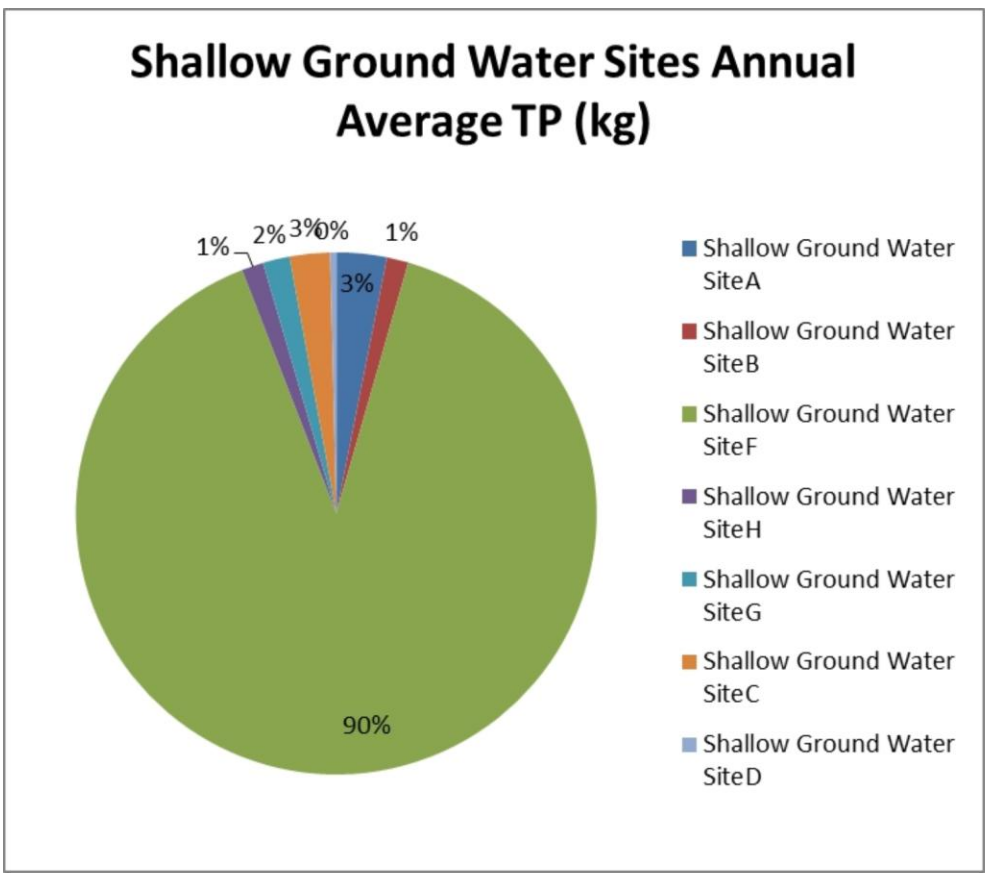


Figure 81: Shallow groundwater input from various regions around Pokegama Lake from 2011-2013.

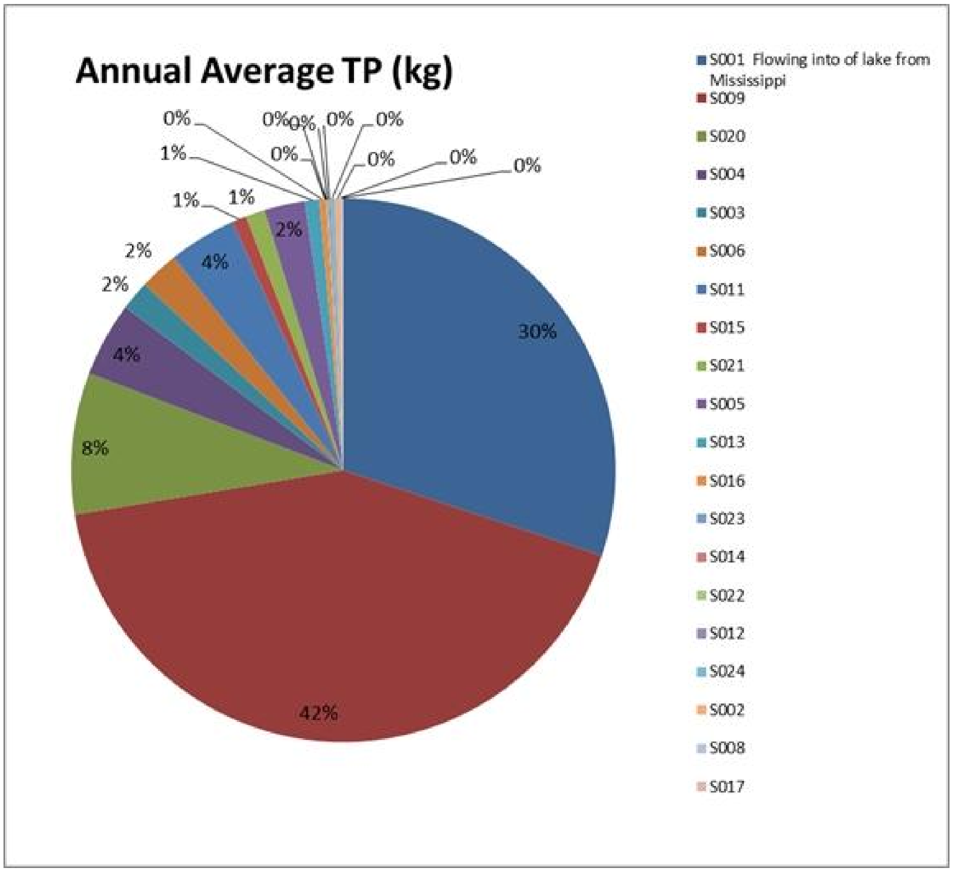


Figure 82: Tributary phosphorus inputs from various tributaries around Pokegama Lake from 2011-2013.

Site	Area (ha)	ha/septic	% impervious
S002	226.81	11.9	7.66%
S003	1803.2	36.8	2.00%
S004	1361.7	56.7	1.33%
S005	75.34	25.1	0.97%
S006	2328.98	26.2	1.36%
S007	94.13	2.6	10.02%
S008	1308.46	15.4	2.78%
S009	8364.86	253.5	0.83%
S010	9981.82	178.2	0.86%
S011	1384.85	1384.9	1.38%
S012	369.51	184.8	3.73%
S013	643.16	160.8	1.48%
S014	236.42	236.4	2.50%
S015	513.51	64.2	1.76%
S016 &17	337.7	33.8	1.71%
S020	11094.57	54.7	0.95%
S021	1689.81	41.2	3.05%
S022	356.73	71.3	1.71%
S023	486.27	54.0	1.81%
S024	101.73	4.8	3.62%
No-trib	3226	2.3	10.77%

Table 32: Density of septic systems and fraction of impervious surface in the watershed of Pokegama Lake.

Data are from Itasca County records.

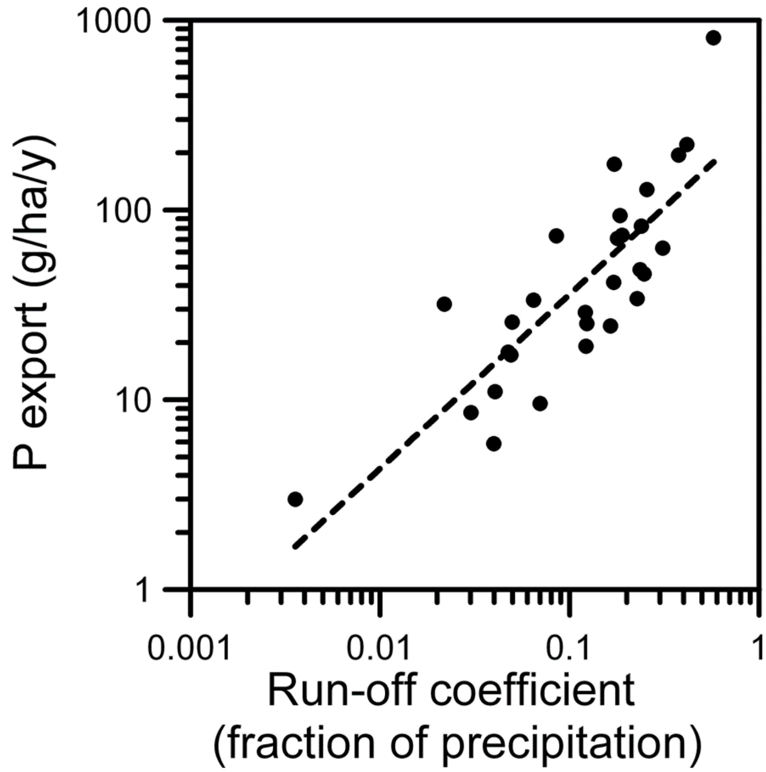


Figure 83: Relationship between P export coefficients and run-off coefficients for all subwatersheds in both lake catchments.

Septic Systems' Potential Contribution of Phosphorus

This study made no attempt to directly measure septic system input to Deer and Pokegama Lakes. These inputs were assumed to be subsumed under the groundwater flux estimates. Some calculations of the likely contribution of these sources (SP; kg/year) can be made from data on the number of septic systems in the watersheds and published methods. Dillon and Rigler (1975) indicate that the input of phosphorus to lakes and the soils of their watersheds from septic systems can be calculated as follows:

$$SP = 0.8 \times N \times T$$

where N is the number of cottages and T is the number of capita-years of habitation per cottage per year. They suggest, from habitation data, that year-round dwellings in Ontario's lake country have about 4.3 capita-years each (4.3 people present all year) while seasonal dwellings have about 0.7 (equivalent to a family of 4.3 being present for 8 weeks each year).

We can apply these analyses using data on the number of septic systems present for different types of dwellings in each watershed. Septic system data were obtained from Itasca County. This analysis assumes that each septic system serves only a single family home, that family size is roughly the same as in Ontario, that seasonal occupancy rates are as low as those found in remote areas of the Canadian Shield, and that diets of people living in Itasca County in 2011-2012 are the same as people in other parts of the world estimated in the past (thus, similar P excretion rates). The calculations made using this approach, therefore, probably underestimate the contribution of septic effluent to these two watersheds.

Septic effluent likely releases 1319 kg of P into the soils of the Deer Lake watershed annually with 89% originating from permanent dwellings and 11% from seasonal cottages. This is 4-times the overall P input to Deer Lake. Septic effluent likely releases 5611 kg of P into the soils of the Pokegama watershed annually with 96% originating from permanent dwellings and 4% from seasonal cottages. Again, this is 4-times the overall P input to Pokegama.

The sandy soils in this region probably have a very limited ability to retain phosphorus for long periods and extremely little under anaerobic conditions (Cheung and Venkitachalam, 2000). Coarse sands and gravels have very low P-retention capacity ranging from only 1% to as much as 48% (Brandes et al., 1974). These soils are prevalent across the region and septic drain-field installers often seek appropriate drain fields by percolation testing, selecting soils like sands that move effluent rapidly. Mixtures of sands and other soils can yield retention of 60-88% under some circumstances (Brandes et al., 1974). Assuming that septic systems are new, working well, that installers have sited them in soils where percolation is slow and soils are mixed, and soils do not clog (see Beal et al., 2005), we might optimistically suggest that P-retention could be as high as 60%. On the other hand, it is more likely that P-retention could be as low as 10%.

We know of no studies in this region of the migration of P through local soils under local hydrologic conditions. However, eventual annual P-transport to these lakes from septic systems will likely equal or exceed current annual loading of Deer and Pokegama lakes, potentially doubling the loading rates. The fact that groundwater loading to these lakes is as low as it was measured in this study may be due to long flow-paths of septic effluents. The average horizontal movement of shallow seepage in Deer Lake is around 2.8 feet and 4.4 feet in Pokegama. Septic effluent, on average, would take 34 to 53 years to reach the lake, assuming a 150-foot setback of the drain field. Avoiding contamination of groundwater is highly desirable because remediation of groundwater contaminants is extremely costly (e.g., Mackay and Cherry, 1989).

Summary of Nutrient Budgets

The nutrient budget of Deer Lake is based on long water retention and very low nutrient supplies. Indeed, much of the nutrients are supplied by rainfall. In spite of the lake having a tiny watershed relative to the lake, there are several hotspots of phosphorus in both groundwater and surface water supplies. These seem more enriched than normal for lakes of this trophic status. The nutrient budget of Pokegama Lake is based on short water retention times and is dominated by surface water flows, partly because the watershed is large compared to that of Deer Lake and partly because relatively nutrient enriched water backs up from the Mississippi River into it, comprising more than 20% of its nutrient supply. Some of the surface water inputs appear substantially richer in phosphorus than one might expect for this region and one are of groundwater flux in particular also seem quite enriched.

The net P input to Pokegama is four-times greater than that of Deer Lake. The net volumetric nutrient loading is also four-times greater than that of Deer Lake but the volumetric loading rate of Pokegama is only double that of Deer Lake.

Lake Water Quality Modeling and What-If Scenarios

Deer Lake

Deer Lake was fitted simultaneously perfectly by three different lake nutrient models, the Canfield-Bachmann (1981) natural lake model, Vollenweider's (1982) combined OECD model, and the Larsen-Mercier (1976) model. Therefore, solutions to all three of these models were considered under diverse scenarios of altered nutrient inputs. It should be noted that the Larsen-Mercier model estimates spring-overturn total P, the Vollenweider model predicts annual mean total P, while the Canfield-Bachmann approach estimates growing season mean total P. In Deer Lake, observed values of these quantities were within a few µg/L of each other. Solutions to all of these equations yield very small nutrient loads to Deer Lake that match the actual inputs under current conditions. These calculations depend upon inputs from the substantial part of the watershed that is not consolidated into surface stream flow (east and northeast of the lake) contributing only through groundwater flux. If that part of the watershed were to be brought into surface connection with the lake, all models predict a substantially increased total P level in Deer Lake, regardless of whether P export coefficients would be high or low in that sub-watershed area.

Calculations from all three models indicate that a 50 kg increase in total P loading to Deer Lake would result in an approximately 1 µg/L increase in lake water total phosphorus. A doubling of the input of P to Deer Lake would indicate predicted total P levels to around 14-18 µg/L at equilibrium (Figure 84). Propagating these changes through known relationships between total P, chlorophyll, and Secchi transparency indicate that addition of 400 kg of P annually to Deer Lake would raise chlorophyll to 3.5-5.5 µg/L, and would decrease Secchi transparency to around 2.5-3.3 meters (Figures 85 and 86).

Pokegama Lake

The Canfield-Bachmann (1981) natural lake model fit the observed data very well and showed now deviation between observed and predicted equilibrium phosphorus values. Walker's general model (1977) and Rechow's (1977) model for lakes with anoxic hypolimnia also fit with less than 13% deviation between observed and predicted total phosphorus. This is important because it indicates that these models will accurately predict changes in water quality that could result from hypothetical changes in nutrient loading. The fact that Rechow's (1977) model for anoxic lakes works well is important because changes in loading could yield changes in oxygen status that would make these predictions the most likely results.

The Canfield-Bachman model indicates that mid-range total P in Pokegama Lake would increase by 1 µg/L for every 10% increase in the overall level of total P input. A doubling of total P loading would likely see total P increase to a mean of 25 µg/L (range 15-41 µg/L) unless the lake follows the route indicated by Reckhow's anoxic hypolimnion model. In that case, common total P levels would be around 32 µg/L (Figure 87). Cholorophyll would likely increase about ½ µg/L for every 10% increase in the P load (Figure 88). Increasing P loading by 30% would have years of high P input show chlorophyll values exceeding 10 µg/L, the level at which visible algae blooms normally become common. If P concentrations follow the trajectory seen in lakes with anoxic hypolimnia, those threshholds would be attained more rapidly (Figure 88). The implications of increased total P loading for transparency would be similar (Figure 89). Transparencies in lake water would decline by about ½ foot for every increase of 10% in the P load to Pokegama Lake. Doubling the P loading to Pokegama would likely bring transparency into the range of 1.8-3.3 m, with most likely values around 2-2.4 m.

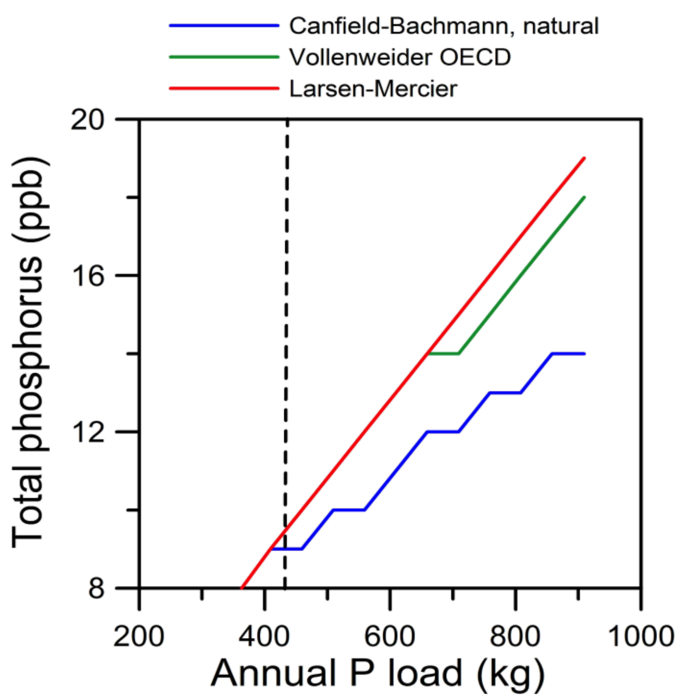


Figure 84: Predicted total P levels made for Deer Lake by three different lake models over diverse levels of change in total P input from the watershed and groundwater.

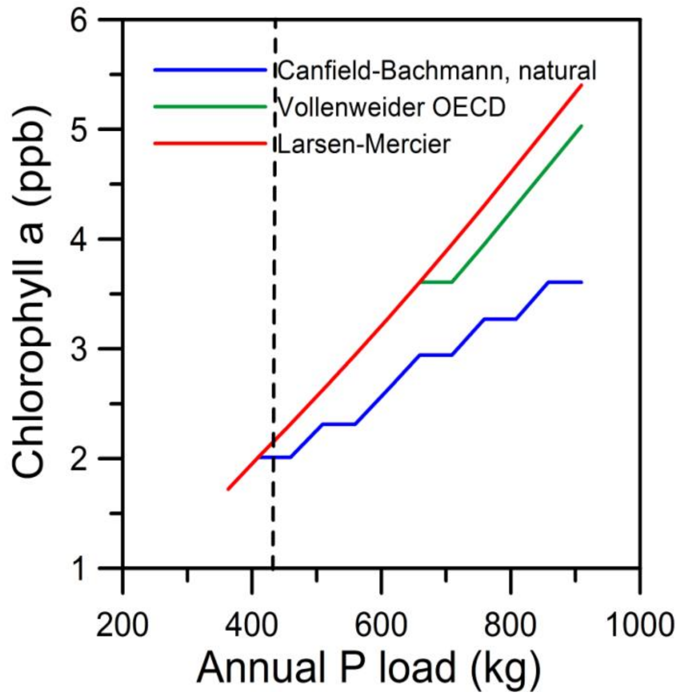


Figure 85: Predicted chlorophyll levels made for Deer Lake by three different lake models over diverse levels of change in total P input from the watershed and groundwater.

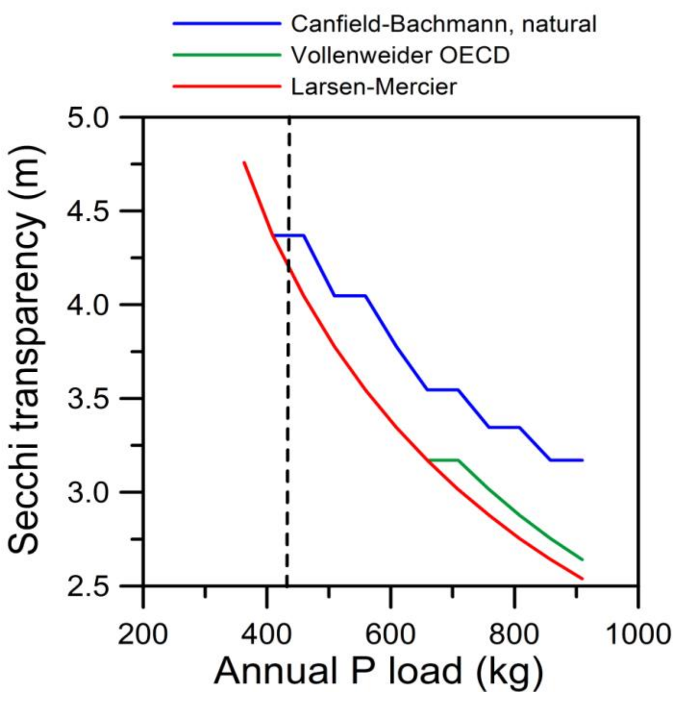


Figure 86: Predicted Secchi disk tansparency levels made for Deer Lake by three different lake models over diverse levels of change in total P input from the watershed and groundwater.

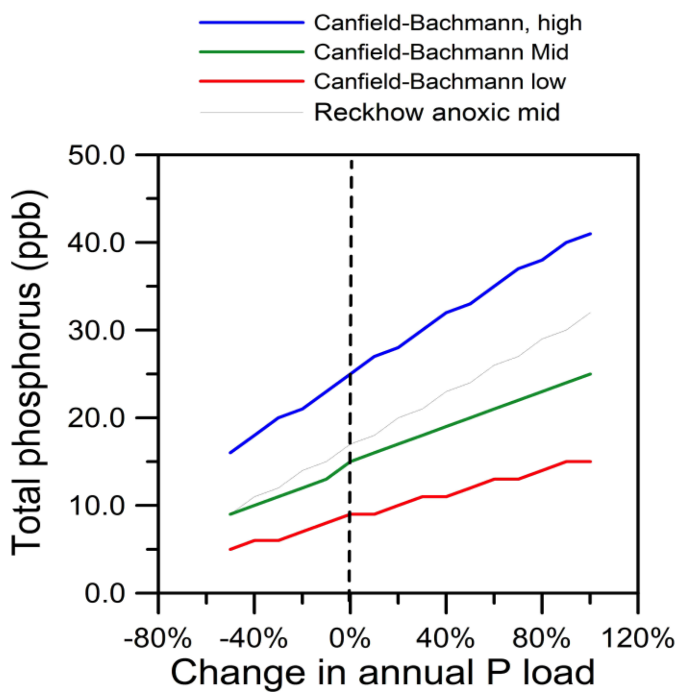


Figure 87: Predicted phosphorus levels made for Pokegama Lake at low, mid-range, and high calculations of the Canfield-Bachmann natural lake model and the Reckhow model for lakes with anoxic hypolimnia.

Calculations are shown over a range of percentage changes in total P input from the watershed, precipitation, and groundwater.

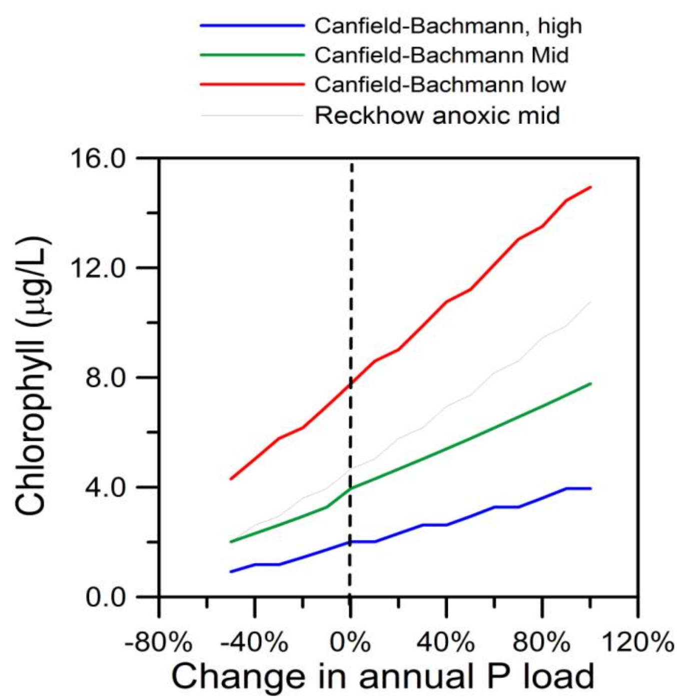


Figure 88: Predicted chlorophyll levels made for Pokegama Lake at low, mid-range, and high calculations of the Canfield-Bachmann natural lake model and the Reckhow model for lakes with anoxic hypolimnia.

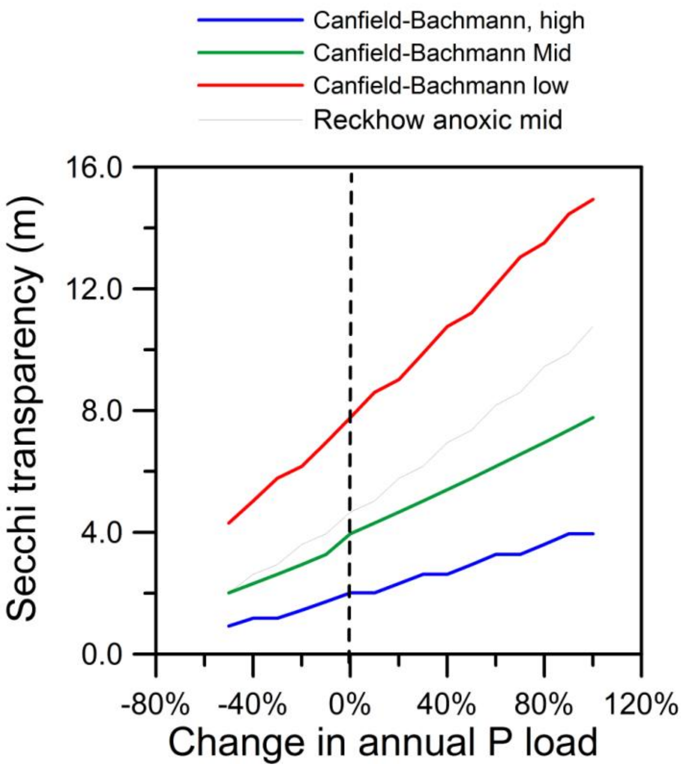


Figure 89: Predicted Secchi disk tansparency levels made for Pokegama Lake by three different lake models over diverse levels of change in total P input from the watershed and groundwater.

DISCUSSION

Assessment of the Project's Resource Water Quality

Morphology and Trophic State

Lakes in the Northern Lakes and Forest ecoregion of are among the highest quality in the state (Heiskary and Wilson, 2008) and nation. The two lakes studied in Itasca County – Deer and Pokegama – are examples of distinct lake-types within the region. Both were formed by glacial activity. Deer Lake was formed from the melting of a large ice block during deglaciation (kettle formation), and the basin is composed entirely of glacial materials. The watershed of Deer Lake is only about 3-times the lake surface area and a large area of the watershed is not drained by consolidated surface flow. Groundwater inputs and springs are an important feature of the water budget of Deer Lake. Pokegama Lake is located in a former meltwater channel that once drained lake basins to the north. It sits in bedrock and glacial sediment. It is surrounded by a watershed 18-times the lake surface area. It also has a connection to the Mississippi River regulated by a USCOE structure, making it a riverine influenced water body. Both lakes are deep (some 30 meters) but have complex morphology with numerous shallows. Both are dimictic and show distinct thermal stratification during summer. The upper 6-10 meters of the water column warms to >25 C and forms an epilimnion, which is mixed by wind and thermal convection. Because of density differences, epilimnion is physically isolated from water deeper in the respective basins and this limits the exchange of gasses and nutrients within the water column. The epilimnion of both lakes remain oxygen rich because of photosynthesis and atmospheric exchange.

The nutrient content, algal biomass, and transparency of Deer Lake are consistent with oligotrophic conditions. Total phosphorus averaged 9 ppb in this study; this value is modestly larger than past measurements and puts the lake near the breakpoint of mesotrophy based on standard criteria for this important element. The low algal biomass (about 1 ppb chlorophyll) and high transparency (5 m) are consistent with oligotrophic conditions and these features cause Deer Lake to be known locally as having desirable water quality.

Pokegama Lake is mesotrophic based on nutrients, algal biomass, and transparency. To some readers the small difference in phosphorus concentration between Deer and Pokagama lakes may seem modest (9 versus 15 ppb) but across this range the small increase in phosphorus results in a non-linear increase in algal biomass (3.6 versus 1 μg/L) and a decline in transparency (from 5 to 3.7 m). Pokegama Lake is classified as mesotrophic; lakes of this category are common in the Northern Lakes and Forest ecoregion, but are not of the most pristine within the region. Additional nutrient loading to Deer Lake would tip it toward mesotrophic conditions; modeling indicates a doubling of the phosphorus load to Deer Lake would make it similar to conditions measured in Pokegama Lake (Fig. 84). Added nutrients to Pokegama Lake would further increase algal biomass and reduce transparency; modeling indicates total P in Pokegama Lake would increase by 1 ppb for every 10% increase in the overall level of total P input. Chlorophyll would likely increase about ½ ppb for every 10% increase in the P load (Fig. 88), resulting in transparencies declining by about ½ foot in response to this incremental load. Doubling of total P loading to Pokegama Lake would likely see total P increase to a mean of 25 ppb, which would push the lake into the eutrophic category. The ratio of nitrogen-to-phosphorus in both lakes suggests phosphorus is the element limiting autotrophic production and, therefore, the element of concern.

Assessment of Pollutant Loads

Because the purpose of this diagnostic study was to analyze two systems for which no specific pollutant problem has been identified, the term "pollutant load" seems somewhat strong. This section is part of the suggested format for these types of reports, however. Because the most common threat to the health of recreational lakes such as these might be the potential to move toward eutrophic conditions due to mobilization of phosphorus, we interpret this section as an opportunity to discuss some of the phosphorus inputs that seem richer than might be expected in this region.

Precipitation

One surprise in this analysis was the concentration of phosphorus found in precipitation. Volunteers were given clear instructions on methods for collecting freshly fallen rainfall and delivering it promptly for analysis. We then rejected any samples that contained visible contaminant since these, especially insects, are known to add substantial phosphorus to samples (Anderson and Downing, 2006; Blake and Downing, 2009). Our assessment of atmospheric deposition to these lakes may even be underestimated because we did not have enough assistance or funding to estimate dry-fall deposition. Potential sources for atmospheric deposition of P include short- and long-range fine particulate transport (e.g., dust), ash, and domestic and industrial aerial effluents (e.g., fly-ash, etc.). Precipitation inputs would be most important for lakes with small catchment areas.

Surface tributaries

Specific land uses often have fairly stereotypical rates of export of various geochemical substances as they are washed down stream. Phosphorus export rates for forested landscapes such as these catchments are typically lower than 70-90 g/ha/y in this region and in others. Some of the streams draining Deer and Pokegama's watersheds have fairly high rates of P export as well as quite rich concentrations of phosphorus in the water leaving them. These tributaries are highlighted with arrows in Figures 90 and 91. Tables are supplied in the Results section showing concentrations of total phosphorus in stream tributaries. Concentrations greater than ambient lake water concentrations will, of course, contribute to enrichment of the lake, although the amount of water leaving the subwatershed may be so small that some high concentrations will have little observable impact on the lake water. It is clear from Figures 38 and 40 that landscape modification leading to increased run-off of precipitation leads to increased phosphorus export to the lake. This is logically necessary, of course, because run-off values are also used to calculate phosphorus fluxes. What is more important than the correlation is that the rate of export increases geometrically with the run-off coefficient. The data suggest that when export coefficients are highest, phosphorus export increases more rapidly than at lower rates of export.

Groundwater

Shallow groundwater flux is high in these lakes, as expected, since one can actually sense areas of intense shallow groundwater seepage as cooler areas in the sand and gravel of the lake bottoms. If nutrients are high in groundwater then groundwater can be an important source of nutrients to lakes. The funding for this study was not great enough to allow a study of shallow groundwater that was very specific but instead concentrated on estimating input of water and nutrients along several broad shore regions. Even though the study of groundwater was done on a fairly coarse scale, a few areas of the shores stood out as being particularly rich in phosphorus. The source of those nutrients is unknown. No detailed analysis of groundwater been done that would indicate what levels of phosphorus might be expected without human habitation of the area. Shallow groundwater was an important source of phosphorus, contributing 2% of the inputs in Deer Lake, with 14% of this likely contributed by conspicuous "springs". In Pokegama, shallow groundwater contributed 5% of the P input, which is surprising because the P input to Pokegama from streams and the river are quite large.

Deep ground water's contribution was unexpected. When we first planned the study, we expected it to be insignificant because groundwater seepage systems typically are thought to decline rapidly in flow with distance from shore. Because of dozens of willing volunteers and a well-developed private well inventory, we were able to determine the potential contribution of deeper flow systems. Concentrations of total phosphorus in the deep groundwater were typically moderate (although not insignificant) but flow rates can be large. Therefore, deep groundwater supplied 5% of the phosphorus input to Deer Lake and about 1.6% of the budget of Pokegama. The source of this groundwater is presently unknown, nor do we know the distance traversed by it before it is discharged into the lakes. Age estimates of the deep groundwater suggest that it is not ancient, however, and chloride values are quite high and variable, so it may come from nearby. High chloride values suggest influence from septic tanks, animals or road salt. The geology of these watersheds, especially Deer Lake, is very complex.

Groundwater, Nutrients, and Deep-Water Oxygen Depletion

Both lakes share one water quality "problem" that the volunteer professional limnologists and the groundwater hydrogeologist feel may be due to a natural phenomenon, but can be exacerbated by moderate levels of increased primary production. The unexpected observation is that oxygen depletion in deep water (HOD; hypolimnetic oxygen depletion) when the lakes are stratified is much more rapid than would normally be seen in lakes of good water quality. When lakes mix in spring, the oxygen in the deep waters is refreshed by atmospheric O_2. When stratification is attained, the oxygen locked in the deep waters by the thermocline needs to last until it can be refreshed again by autumn mixing. Oxygen can be used up by depletion from the decomposition of organic matter that grows in the upper waters, dies, and rains down into the deep waters (THOD; trophic hypolimnetic oxygen depletion). This is usually the dominant source of oxygen depletion in the hypolimnion (deep waters beneath the thermocline) so limnologists have created models based on eutrophication and primary production that normally allow prediction of oxygen depletion. There can be other sources of oxygen depletion in the hypolimnion and they consist of oxygen use by organisms (e.g., fish, plankton), decomposition of dissolved organic matter (like the tea-like stains in some small lakes and wetlands) by microorganisms, photo-oxidation of dissolved organic matter if light can penetrate to deep waters, and various chemical oxygen demands driven by the introduction of reduced chemicals that are either spontaneously oxidized or oxidized by biological processes (e.g., "nitrification" of ammonium) (NoTHOD; non-trophic hypolimnetic oxygen depletion). Normally, however, oligotrophic and mesotrophic lakes like these have sufficient oxygen and low enough hypolimnetic oxygen demand that they retain ample oxygen in deep waters throughout the growing season. This allows fish and other organisms an oxygenated refuge from high surface temperatures.

In Deer and Pokegama lakes, however, the deep waters are nearly devoid of oxygen for much of the summer season. Oxygen depletion is nearly complete by August and is not relieved again until the lakes circulate in late autumn. The monitoring work done by the Wabana Chain of Lakes Association shows very similar patterns in both Wabana and Trout Lakes (Downing, pers. comm.). As pointed out elsewhere in this report, rates of oxygen depletion are around twice as fast as would be expected based on the trophic status of the lakes alone (Figure 92). There is apparently a process acting in deep oligotrophic and mesotrophic lakes in this area to deplete hypolimnetic dissolved oxygen, even without the decomposition of dead organisms raining into deep water from the surface. That is, NoTHOD seems much higher than expected. Indeed, the rates of oxygen depletion in these lakes are on a par with those of some very eutrophic lakes in Europe (Müller et al., 2012). The importance of this finding to the ecology of these lakes is that they will be able to absorb a much lower degree of nutrient enrichment than other oligotrophic and mesotrophic lakes without creating hypoxic hypolimnia that are inhospitable to most organisms. In Pokegama, for example, we even see the metalimnion (the region around the thermocline) becoming hypoxic (too low in oxygen for most organisms to thrive).

Oxygen depletion in the water column below the epilimnion is common in mesotrophic lakes during summer stratification and occurs, but less extensively, in oligotrophic lakes. In Pokegama Lake, during 2012, there was low oxygen in the metalimnion, the layer immediately below the epilimnion, typically oxygenated and often a thermal refugia for fish. An empirical model developed for temperate lakes (Nurnberg, 1996) predicts summer oxygen depletion in Deer Lake would be 240 mg/m^2/day (hypolimnetic oxygen depletion) and depletion in Pokegama Lake would be 310 mg/m^2/day. Averaged across summer 2011 and 2012, the median AHOD value was over 500 mg/m^2/day in both lakes. The large difference between predicted and observed depletion suggests planktonic productivity in the epilimnion and subsequent decomposition of this organic matter in the hypolimnion cannot account for measured depletion.

Larger than expected AHOD values are a major finding of this study. Additional study is needed to quantify the factors that deplete deep-water oxygen in these lakes and others in the region. Oxygen in the metalimnion and hypolimnion is essential for a healthy fishery. Lake trout populations have declined over the past decade Itasca County lakes because of increased oxygen demand tied to increased productivity. Warm-water fish communities are also at risk of stress. Optimal conditions for warm-water fish species broadly include temperatures cooler than 24 C with dissolved oxygen > 5mg/L (Matthews et al.,1985). This situation is referred to as the temperature oxygen squeeze and in warm summers the metalimnion of these lakes may not provide an ideal refuge from epilimnetic temperatures. Conditions in Pokegama Lake during mid-summer 2012 approached these conditions. A warming climate and increasing nutrient inputs makes it increasingly important to identify the source of oxygen demand in the deep waters of these lakes and, if possible, remediate the cause or work toward avoiding its increase. The Minnesota DNR is concerned about this issue and has recognized that tullibee lakes (like Pokegama and Deer) are degrading in the region (http://www.dnr.state.mn.us/volunteer/julaug08/canaries_deepwater.html).

Because a major difference between these lakes and other oligotrophic lakes studied elsewhere may be the substantial input of groundwater (shallow and deep), there may be a natural background high level of NoTHOD driven by this source. Measurements of groundwater oxygen levels show that groundwater essentially is devoid of oxygen. Both shallow and deep groundwater would tend to flow toward the deep waters in both summer and winter. This is because regional groundwaters are about 4-5° C, which is the temperature at which water has its maximum specific gravity (density). Flushing of the deep water with groundwater may not be sufficient, however, to deplete deep-water oxygen concentrations. The flushing time or water residence time of the hypolimnia of these lakes, considering only flushing by low-oxygen groundwater is 40 and 6 years for Deer and Pokegama Lakes, respectively.

Other aspects of the groundwater input may deplete oxygen, however. Recent work has shown that oxygen depletion in hypolimnia is primarily the result of the supply of organic matter to the sediment surface and the upward diffusion of reduced substances into overlying water (Müller et al., 2012). Groundwater flow would enhance the supply of reduced substances because deep groundwater has a lot of these in this region (e.g., NH_4, CH_4, H_2S, reduced iron) and groundwater inflow would push these out of sediments into the water column. Groundwater is also very rich in dissolved organic matter that can fuel oxygen-scavenging microbial activity in the deep waters of these lakes. Because of the importance to fisheries and the biotic health of these ecosystems and because of the importance of this knowledge to management and policy decisions, it would seem somewhat urgent to understand the cause of these high oxygen consumption rates.

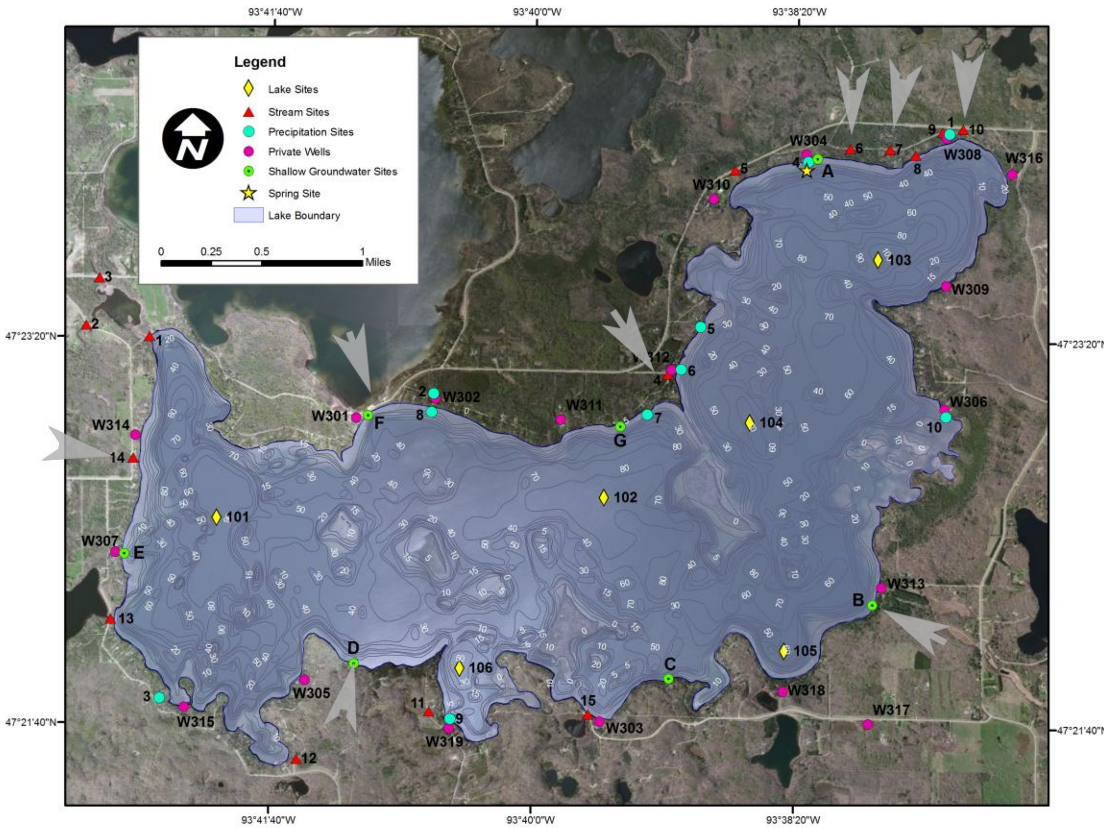


Figure 90: Map of Deer Lake highlighting the tributaries and shallow groundwater sites that had highest P export rates and/or high phosphorus concentrations.

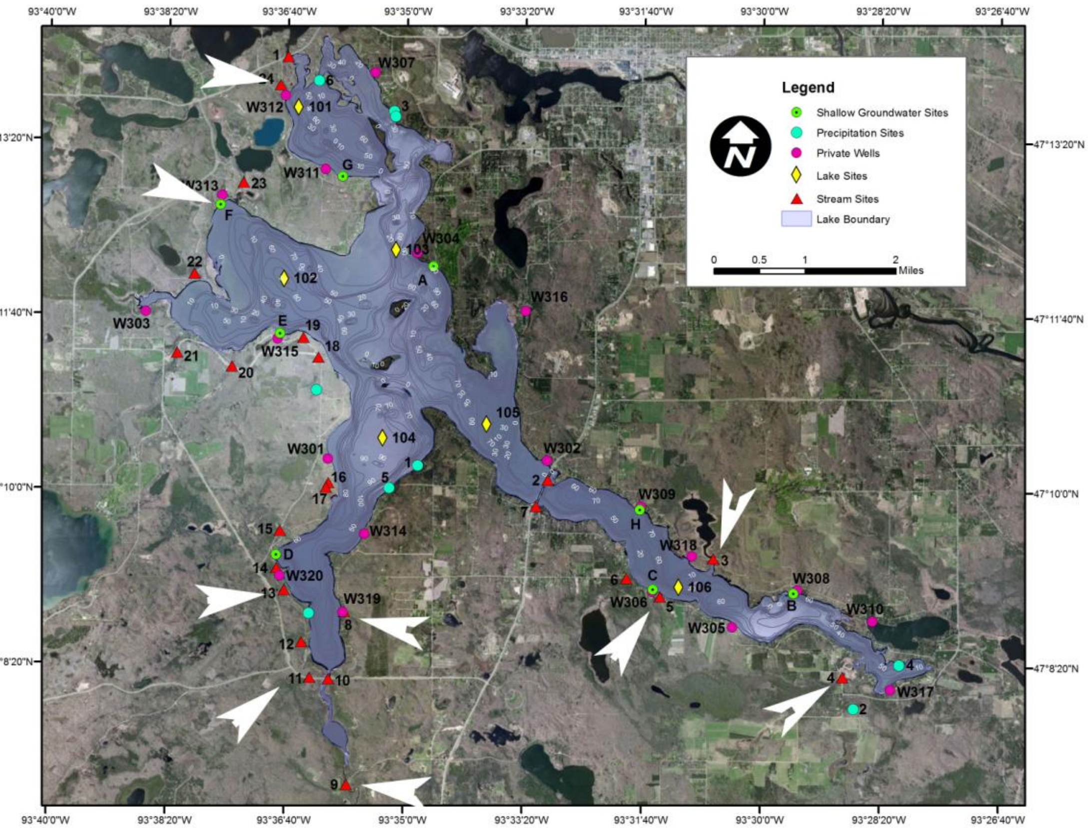


Figure 91: Map of Pokegama Lake highlighting the tributaries and shallow groundwater sites that had highest P export rates and/or high phosphorus concentrations.

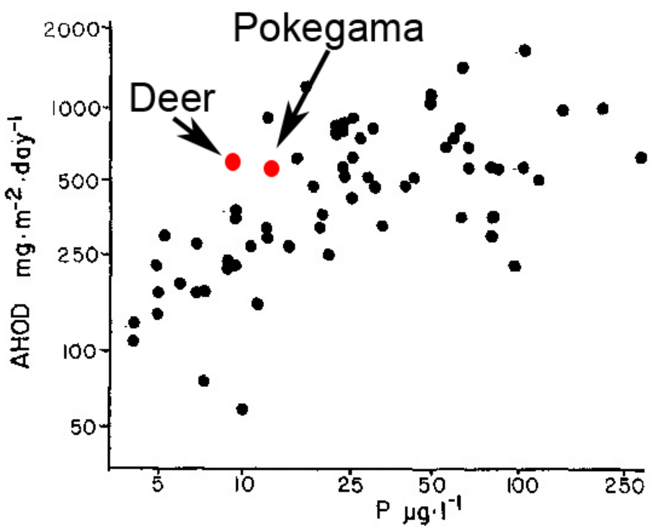


Figure 92: Relationship between P concentration in the upper mixed zone and areal hypolimnetic oxygen demand for several world lakes from Cornett and Rigler (1980).

Red dots show rates and concentrations for Deer and Pokegama lakes from this study.

Resource Water Quality Goals

The federal Clean Water Act requires states to adopt water quality standards to protect lakes, streams, and wetlands from pollution. The standards define how much of a pollutant (bacteria, nutrients, turbidity, mercury, etc.) can be in the water and still meet designated uses, such as drinking water, fishing, and swimming. A water body is "impaired" if it fails to meet one or more water quality standards. Deer and Pokegama Lakes currently meet State water quality standards that are in place to protect beneficial uses, such as healthy fish, invertebrates, and plant communities, as well as swimming and other water recreation. Both lakes are, however, on the State's 303d list of impaired waters for mercury impairment due to exceeding allowable fish tissue concentration. MPCA is addressing this issue on a statewide level through a mercury Total Maximum Daily Load study, which was approved by the EPA in March 2007.

Deer and Pokegama lakes are below the State's threshold for nutrient impairment and are high resource value lakes because of their excellent water quality and clarity. Dramatic impacts would be seen in these two systems if these two lakes were allowed to degrade to the State's impairment threshold for nutrients. In order to protect their quality and resource value, a goal of this project is to maintain or improve both lakes current water quality. The State is currently working on a non-degradation policy, with the goal of maintaining all waters in an unpolluted and natural state. A non-degradation water quality goal for Deer and Pokegama lakes not only means that future generations will have highly valued recreational and aesthetic resources to enjoy, but also preventing the degradation of these two highly valued waters is a lot less costly to society than trying to restore them once they have become degraded (Cole B., 2012).

CONCLUSIONS

Deer Lake is at the upper edge of nutrient concentrations for an oligotrophic lake while Pokegama is firmly within the range indicating mesotrophy. Deer Lake's phosphorus budget is very small inputs of phosphorus dominated by atmospheric input, although groundwater and streams are also important nutrient sources. Pokegama's phosphorus budget is dominated by surface water inflows from several tributaries and back-flow from the Mississippi. Numerous streams entering both lakes have concentrations exceeding Minnesota's draft nutrient standards and some groundwater flows have surprisingly high concentrations. Attention to groundwater and stream condition could assist in protecting water quality. Both lakes share a water quality problem in that oxygen demand in the deep waters is double what it should be for lakes of their trophic status. This leaves very little cushion against additional oxygen demand fueled by excess productivity driven by supplemental nutrient loading. Further, atmospheric loading (from rain and snow) is surprisingly high, begging the questions of why this occurs and what is the source. Although neither lake has demonstrated serious impairments at this time, this study indicates that implementation should initiate several actions that could protect these lakes in particular, as well as all lakes in the region.

IMPLEMENTATION PLAN

PLAN OBJECTIVES

This study was proposed in order to understand how to protect high quality lakes of this region, not to solve a degradation problem as in other studies. Therefore, implementation objectives were formulated: (1) to better understand how to protect similar waters and, (2) specifically for these lakes, move toward protection of declining aspects of these two ecosystems.

1. Implementation of the protection of similar waters in the Itasca County region

1a. Atmospheric deposition

Objective: Establish a network of citizen volunteers to monitor atmospheric deposition of phosphorus and other materials falling with precipitation.

1b. Hypolimnetic oxygen consumption

Objective: Involve students and volunteers in measuring background hypolimnetic oxygen demands across the county and the region.

1c. Public education on lake protection

Objective: Engage local volunteer organizations to teach the public about the special aspects of lakes in this region and what this means about the protection of this vital resource.

1d. Groundwater transport

Objective: Analyze regional groundwater transport using a network of private wells offered for analysis by volunteer households and permanent observation wells.

2. Implementation of specific programs on Deer and Pokegama Lakes

2a. Groundwater monitoring

Objective: Create and monitor a network of observation wells to examine trends in groundwater chemistry over time.

2b. Stream monitoring and remediation

Objective: Implement nutrient tracking nutrients in most nutrient-rich streams, especially those violating Minnesota draft standards. Work with communities to seek sources of nutrients and remediate high export values and concentrations.

2c. Hypolimnetic oxygen tracking and remediation

Objective: Understanding that oxygen depletion may exacerbate sensitivity to nutrient loading, install and operate hypolimnetic aeration devices and monitor their influence oxygen and nutrient concentrations. This should be a BACI (before-after control impact) analysis.

A hypolimnetic aeration project will likely require review and comment from several local and state agencies. Two permits are required from the Minnesota DNR for a hypolimnetic aeration project. The first is from the Division of Fisheries. The second is the General Work in Public Waters Permit due to work being conducted below the OHW elevation, such as the placement of the pipes, anchors and aeration units. The typical time frame to acquire a General Work in Public Waters permit is 60 days. However, depending on the complexity of the project and the potential for controversy with the lake shore residents and/or general public the permitting process could take considerably longer. DNR shoreline set-back requirements may apply to certain aspects of the project construction. The MPCA would also need to review the project in conjunction with the DNR permits.

2d. Bellwether lake water monitoring

Objective: Implement a regular monitoring program for lake water that seeks to analyze temporal trends in nutrients and water quality because both lakes have declined from historical quality.

2e. Road drainage modification at highway 169 Pokegama causeway

Objective: Implement discussions among community and government to modify or divert nutrient and water flux.

Figure 93: Highway 169 Pokegama causeway storm water retention pond after June 2012 storm event.

Figure 94: ICSWCD intern measuring discharge at highway 169 storm water retention pond.

2f. Mississippi River backflow to Pokegama

Objective: Implement discussions between community and Army Corps of Engineers about moderating or eliminating backflow from the Mississippi River. Implement policy or engineering solutions to decrease nutrient and water flux.

Figure 95: Pokegama high water due to June 2012 storm.

2g. Septic system improvement and education about septic systems

Objective: Eliminate failing and inefficient septic systems in both the Deer and Pokegama watersheds. Improve understanding of the importance of groundwater protection.

2h. Shore Stabilization: Riparian Buffer Plantings

Objective: Stabilize eroding shorelines and reduce nutrient loading from erosion through native buffer plantings.

2i. Shore Stabilization: Rock Rip Rap

Objective: Stabilize shorelines and reduce nutrient loading from erosion through hard armor (rock) engineering where buffer plantings will not be adequate to stabilize shoreline.

A General Work in Public Waters Permit will be required due to work being conducted below the OHW elevation. A shoreland alteration permit will also be required through Itasca County Environmental Services.

2j. Stormwater Runoff Management Projects

Objective: Develop and install stormwater management projects to reduce loading from runoff. Stormwater management projects also used as an educational tool for the public.

IMPLEMENTATION APPROACHES AND METHODS

We envision a 5-year program in order to accomplish the stated implementation goals.

Objective	**Methods**
1. Protection of Similar Waters in Itasca County	
1a. Atmospheric deposition	Establish a network of citizen volunteers to monitor atmospheric deposition of phosphorus and other materials falling with precipitation. • *Create a network of citizens in cooperation with a local radio station or social organization to monitor atmospheric deposition of phosphorus, acid, and Hg* • *Use standard clean techniques* • *Analyses done by Itasca Community College and the US Forestry laboratory at ICC* • *Look for patterns in and trace sources of atmospheric pollutants.*
1b. Hypolimnetic oxygen consumption	Involve students and volunteers in measuring background hypolimnetic oxygen demands across the county and the region. • *Establish a network of lakes across the region and estimate the summer and winter hypolimnetic oxygen demand* • *50 lakes will be monitored over two summer seasons, estimating phosphorus, clarity, chlorophyll, and profiles of common parameters every second week from May-August* • *Relate to lake and watershed characteristics* • *Compare with world rates based on trophic status* • *Perform spatial analysis of oxygen deficit anomalies*

Objective	**Methods**
1c. Public education on lake protection	Engage local volunteer organizations to teach the public about the special aspects of lakes in this region and what this means about the protection of this vital resource. • *Region's lakes are unusual in atmospheric deposition, groundwater transport (deep and shallow), and has frequent stream nutrient conditions that depart from state norms* • *Educate the public about the implications of these characteristics for the protection of regional water quality* • *Establish K-12 and adult education programs*
1d. Groundwater transport	Analyze regional groundwater transport using a network of private wells offered for analysis by volunteer households and permanent observation wells. • *Offer free well analysis for nitrates and coliforms to well owners across the region* • *Collect data on iron, DOC, phosphorus, DIC and other materials that may influence lake trophic status and oxygen demand* • *Use lake water levels and well water data across the region to estimate regional groundwater transport* • *Establish and monitor a network of regional observation wells to monitor background changes in groundwater chemistry*
2. Implementation of specific programs on Deer and Pokegama Lakes	
2a. Groundwater monitoring	Create and monitor a network of observation wells to examine trends in groundwater chemistry over time. • *Deep groundwater was analyzed using private wells but private wells are located near homes* • *Establish a network of observation wells placed randomly around the lakes to estimate regional temporal changes* • *Monitor groundwater for temporal trends*

Objective	**Methods**
2b. Stream monitoring and remediation	Implement nutrient tracking nutrients in most nutrient-rich streams, especially those violating Minnesota draft standards. Work with communities to seek sources of nutrients and remediate high export values and concentrations. • *Perform longitudinal analyses of stream long nutrient profiles to seek locations of primary phosphorus inputs* • *Once sources of nutrients in impaired streams are located, work with communities and SWCD to find means of reducing nutrient export* • *Monitor most nutrient-rich streams to track temporal changes in phosphorus export*
2c. Hypolimnetic oxygen tracking and remediation	Understanding that oxygen depletion may exacerbate sensitivity to nutrient loading, install and operate hypolimnetic aeration devices and monitor their influence oxygen and nutrient concentrations. This should be a BACI (before-after control impact) analysis. • *Choose control lakes to monitor while Deer and Pokegama are undergoing aeration* • *Use analyses of chemical components to determine source of oxygen depletion* • *Calculate theoretical oxygenation levels needed to sustain summer high oxygen levels* • *Build and install hypolimnetic aeration devices – Speece cones with surface vents* • *Operate tests of re-oxygenation using a BACI design* • *Determine effects of oxygenation on water quality in the hypolimnion* • *The summer O_2 consumption is 750 and 1300 tons (metric) for June-August. The economic feasibility of direct O_2 or air injection will be evaluated.*

Objective	**Methods**
2d. Bell-weather lake water monitoring	Implement a regular monitoring program for lake water that seeks to analyze temporal trends in nutrients and water quality because both lakes have declined from historical quality. • *Unexpected changes were found in ambient nutrient concentrations – these appear related to loading from landscape and atmospheric changes* • *Current widely-space monitoring events are not sufficient to note changes on short time-frames* • *We propose to establish regular, annual monitoring of these two lakes to track future changes in water quality* • *Monitoring would reflect MPCA monitoring norms and be of an annual frequency of 5-times, over the long term*
2e. Road drainage modification at highway 169 Pokegama causeway	Implement discussions among community and government to modify or divert nutrient and water flux. • *The causeway across Pokegama is supplying nutrients directly to the lake at concentrations that violate river tributary nutrient standards.* • *This constitutes an effective point-source that was created by a highway project* • *This is an avoidable nutrient input so could be mitigated* • *Data collected here suggest that community efforts and discussions with the Minnesota DOT could mitigate this ongoing nutrient flux* • *We would like the community to implement discussions toward a project directing highway effluent away from lakes*

Objective	**Methods**
2f. Mississippi River backflow to Pokegama	Implement discussions between community and Army Corps of Engineers about moderating or eliminating backflow from the Mississippi River. Implement policy or engineering solutions to decrease nutrient and water flux. • *A large portion of the phosphorus budget of Pokegama comes from backflow from the Mississippi, when it occurs.* • *Removal of this nutrient load would lead to improvements in water quality that would move the lake back to a more oligotrophic status (from mesotrophy)* • *We would like to implement discussions between the Army Corps of Engineers and the Pokegama Lake community about whether this nutrient load from the Mississippi River could be reduced.* • *If the existing dam cannot be operated in a way that minimizes this load, it is possible to evaluate means of installing a control structure between the Pokegama "outfall" and the Mississippi River* • *Such a structure might be similar to tide-control dams, designed to minimize marine backflow to rivers*

Objective	**Methods**
2g. Septic system improvement and education about septic systems	Eliminate failing and inefficient septic systems in both the Deer and Pokegama watersheds. Improve understanding of the importance of groundwater protection. • *This study indicated that some waters around these lakes have substantially elevated phosphorus, chloride, and dissolved organic carbon, all constituents that could originate in septic tank effluents.* • *Several watersheds have particularly high densities of septic systems.* • *Groundwater has a long water residence time so mitigation of this resource, once polluted, is a very long process* • *We suggest that the Itasca Water Legacy Partnership work with local officials and citizens to promote the inspection of septic systems and the replacement of those inadequate to keep phosphorus out of these lakes over the long term.* • *Itasca County Environmental Services is currently administering a low interest septic loan program for individuals with non compliant systems. This would seek to provide additional aid to expedite lakeshore septic upgrades.*
2h. Shore Stabilization: Riparian Buffer Plantings	4 buffer plantings/lake/year, where previously mowed lawn to the water's edge. •
2i. Shore Stabilization: Rock Rip Rap	15 rock rip-rap bank stabilization projects installed on Pokegama and 7 on Deer Lake.
2j. Stormwater Runoff Management Projects	8 stormwater runoff management projects installed on each lake

Table 33: Implementation objectives and methods.

IDENTIFICATION OF PRIORITY MANAGEMENT AREAS

Sub-Watersheds and Surface Input Management Priority Areas

Priority management areas for this project designed to protect these lakes from decline in water quality have been identified above. They are simply those that either do not meet Minnesota's draft stream and river standards (Table 34) (Heiskary et al, 2013) or have higher phosphorus export values than would be normal for watersheds in this region.

Deer Lake

Tributaries and sub-watersheds with annual P export >90 kg/ha/y were 4, 6, 10, and 14. Tributaries and sub-watersheds with annual, flow-weighted total phosphorus concentration >50 ppb were 4, 5, 6, 9, 10, 11, and 14.

Pokegama Lake

Tributaries and sub-watersheds with annual P export >90 kg/ha/y were 4(?), 5, and 9. Tributaries and sub-watersheds with annual, flow-weighted total phosphorus concentration >50 ppb were 2, 4(?), 5, 8, 9, 11, 13, 21(?), and 24.

Groundwater Management Priority Areas

As pointed out above, groundwater in this region has been little studied and may be quite heterogeneous. Groundwater is, however, generally naturally quite dilute in phosphorus. Priority groundwater management areas were indicated based on high concentrations of phosphorus in seepage samples and the potential for groundwater contamination was indicated based on high spatial densities of septic systems.

Deer Lake

Groundwater priority management areas for Deer Lake indicated by concentrations in piezometer analyses were seepage areas B, D, and F. Densest aggregations of septic systems were found in sub-watersheds 7, 11, and the large unconsolidated basin to the east and northeast of Deer Lake.

Pokegama Lake

Groundwater priority management areas for Pokegama Lake indicated by concentrations in piezometer analyses included primarily seepage area F. Densest aggregations of septic systems were found in sub-watersheds 7, 24, and the unconsolidated basin with no consolidated tributaries.

Table 1. Draft river eutrophication criteria by River Nutrient Region for Minnesota.

	Nutrient	Stressor		
Region	TP µg/L	Chl-a µg/L	DO flux mg/L	BOD_5 mg/L
North	≤50	≤7	≤3.0	≤1.5
Central	≤100	≤18	≤3.5	≤2.0
South	≤150	≤35	≤4.5	≤3.0

Table 34:Draft river eutrophication criteria for Minnesota (Heiskary et al 2013).

BEST MANAGEMENT PRACTICES

Lakeshore Buffers

The importance of shoreline buffers is a continued educational endeavor of both lake associations and the Itasca Coalition of Lake Associations. Individual lakeshore buffers typically range from $30 to $50 per foot. For a typical lakeshore property owner with 100 feet of shoreline, the cost would be approximately $3,000 to $5,000. This would include some in-kind labor from property owners and possibly assistance from the Itasca SWCD or Watershed Association. The SWCD has staff that can provide consultations on plant selection and buffer design. Cost-sharing programs are available to provide approximately 25% to 75% of the total cost for the project.

Lakeshore Stabilization

Combinations of wave action and mowed shorelines are creating erosion problems and increased eutrophication on both Deer and Pokegama lakes. Pokegama is particularly susceptible to shoreline erosion during periods of high water when the lake is being used as a reservoir as was the case during the June 2012 storm which raised the lake level 1 meter (3 feet) from its normal summer level. Itasca SWCD currently has a cost-share program available to assist landowners and works with the Joint Powers Board engineer to provide a design specific to the site. Other opportunities for cost share assistance may be available through the Board of Water and Soil Resources (BWSR).

Figure 96: Pokegama high water due to June 2012 storm.

Septic System Improvements

Replacing all failing septic systems is a high priority. Mandatory compliance inspections of existing septic systems are currently triggered upon transfer of property and through variance requests. Landowners are required by law to upgrade their system within 2 years of being issued a certificate of non-compliance. Project partners will continue to work with the County on finding solutions to expedite upgrade of all failing systems around both lakes.

Septic BMP Education

Educational BMPs encouraging lakeshore property owners to use low phosphorus products will help to address phosphorus discharge from septic systems of owners who aren't required to upgrade their system or who expand their water use through activities that do not trigger septic upgrade requirements (an increase in family size, installation of dishwashers or washing machines). Phosphorus fact sheets and proper septic maintenance can be distributed through the lake associations and at public meetings. It should also be noted that as of July 1, 2010, stores in Minnesota are no longer allowed to sell household dishwashing detergent with a phosphorus content of more than 0.5% by weight.

Riparian stream restorations

Riparian stream restorations can range from $50 to $200 per lineal foot. Grants are typically available for such work but often require staff time for grant preparation and sometimes matching funds. It is advisable to perform baseline evaluation and periodic monitoring to assess stream stability to prioritize areas for restoration and avoid downstream impacts. The Wisconsin Method is a basic low-cost but highly-effective method for evaluating recision rates, and provide load reduction scenarios. Anthropogenic vs. natural stream rescission should be determined as well. Riparian stream restorations are typically tied more to turbidity and biotic impairments. To better quantify the impact of stream bank failures and anthropogenic erosion, biologically available soil P content and rescission rates should be evaluated to quantify the actual annual load to the lakes. It is also important, then, to add a parameter such as TSS and/or turbidity to the stream monitoring. A small portion of the stream load from occasional stream bank failures that occur between the monitoring station and the lake (several hundred feet) may not be represented in the overall load from these lakes. An added benefit of conducting riparian or channel restorations is the creation of additional fisheries habitat that can be utilized by fish populations from the main lake.

MONITORING AND EVALUATION

GPLA and DLA have long-term Secchi programs in place to keep track of lake trends, and Deer Lake Association already has a long-term water quality monitoring program in place. Itasca SWCD and ICC will work closely with GPLA to develop a plan for Pokegama Lake and provide technical assistance where needed to carry out the plan. This monitoring will continue, along with some recommended additions, and will be sufficient to track significant water quality trends, assess progress towards goals and make adjustments towards adaptive management. Recommended monitoring plan and adaptive management framework is listed below:

Data Gaps

Collection of additional data will assist in targeting the implementation and tracking effectiveness. Data gaps are listed below:

1. Due to high nutrient levels recorded in precipitation samples during the CWP, further atmospheric data collection is important to understand its affect on lakes. A network of citizen volunteers will be established to monitor atmospheric deposition of phosphorus and other materials falling with precipitation.
2. Groundwater transport and its interaction with lakes proved to be important piece of this study but information for this region is lacking. Further research consisting of a monitoring network of new and existing wells will provide needed insight into local and regional groundwater transport and chemistry and its role in lake management.
3. Streams were not anticipated to have had as high of nutrient levels as were measured in the CWP. Performing a longitudinal analysis of streams high in nutrients is necessary to locate primary phosphorus inputs further up in the watershed. Once sources of nutrients in impaired streams are located, efforts will be focused on remediation. Monitoring will continue in those streams to evaluate effectiveness of remediation.

Recommended Monitoring

1. Continue to monitor lake water quality annually or 2 years on 2 years off depending on budgets, staff, and volunteers. Sampling will be scaled back in order to make long term monitoring feasible. Reduction in the number of long term monitoring sites could also be considered to keep costs to a minimum. Surface samples will be collected monthly for TP and Chlorophyll-a at a minimum. Field monitoring parameters (Secchi depth, temperature, dissolved oxygen, and conductivity profiles) will also be collected monthly to characterize the depth and period of anoxia to quantify annual internal loads and bracket the variability.
2. Assess monitoring data annually and report findings in Annual Monitoring Report. The report should list implementation activities, evaluate progress towards goals, and make recommendations towards course corrections in terms of monitoring and implementation annually. This is the framework for adaptive management.
3. In addition to baseline lake water quality data, add special monitoring to track progress of implementation strategies. Assess special monitoring needs annually based on implementation projects underway, report findings the Annual Monitoring Report. For example, if watershed loading is targeted, watershed loads should be measured.

ROLES AND RESPONSIBILITES

Itasca SWCD
The mission of the Itasca SWCD is to provide a local organization through which landowners and operators, local units of government, and state and federal agencies can cooperate to improve, develop, and conserve soil, water, wildlife, and recreational resources. The SWCD will seek grants to fund implementation objectives and will work cooperatively with project partners to carry out the implementation plan. SWCD staff will provide technical assistance with shoreland stabilization practices and BMPs. Itasca SWCD will also provide technical assistance as needed with continued lake monitoring and annual data review.

Itasca Water Legacy Partnership
IWLP's mission is to work collaboratively on water issues and mobilize on-the-ground actions that encourage diverse sustainable use, protection, recovery, and enjoyment of Itasca County's world-class water and shoreland resources that are critical to a strong economy. IWLP will continue to focus their efforts on public awareness and education to protect the future quality of Deer and Pokegama lakes along with all lakes in Itasca County. IWLP will also provide assistance with grant research and writing to help fund implementation objectives.

Deer Lake Association (DLA) and Greater Pokegama Lake Association (GPLA)
DLA and GPLA both have mission statements to protect and maintain the quality of their lakes and will continue to be active in educational components of the implementation plan. Both associations already have long-term Secchi programs in place to keep track of lake trends, and Deer Lake Association already has a long-term water quality monitoring program in place. Itasca SWCD and ICC will work closely with GPLA to develop a plan for Pokegama Lake and provide technical assistance where needed to carry out the plan. These programs will also be used to do effectiveness monitoring for implementation activities. Lake associations will also provide assistance with volunteer recruitment for developing a network of citizen volunteers to monitor atmospheric deposition.

Itasca County
Itasca County is the local regulative authority which oversees the implementation of the Itasca County Land Use Ordinance, which has been established to guide growth and development in the County and around its lakes. Itasca County is prepared to assist with any necessary actions based on project findings. Itasca County will continue to provide support in upgrading septic systems on Deer and Pokegama lakes through compliance inspections and its low interest septic loan program, which is currently in place.

Itasca Community College (ICC)
ICC is the certified laboratory (Minnesota Department of Health) that was responsible for analyzing project samples. ICC will continue collaborating with project partners on the implementation phase and be utilized in analyzing any further lake, stream, atmospheric, or groundwater samples. ICC is focused on developing an educational program around its lab and will provide trained students to assist with carrying out implementation activities.

Dr. John Downing and Dr. Jack Jones:
Dr. John Downing and Dr. Jack Jones were the volunteer scientists for the study and provided technical oversight of the project and were responsible for running selected models and completing necessary reporting of project findings. They have volunteered to continue to provide technical assistance with developing and implementing objectives focused on atmospheric deposition, hypolimnetic oxygen tracking and remediation, stream monitoring and remediation, and groundwater monitoring.

Dr. Bill Simpkins and Grad Student
Dr. Simpkins and a grad student researched the groundwater flow and nutrient flux for Deer and Pokegama lakes and utilized a 2-D groundwater flow model to estimate the role of groundwater in the two lakes. Dr. Simpkins will continue to assist with groundwater implementation objectives as a volunteer to further understanding groundwater transport in this region, which is currently lacking.

Minnesota Pollution Control Agency (MPCA)
The Minnesota Pollution Control Agency is charged with executing the Clean Water Act, which is our nation's law for protecting our most irreplaceable resource. Because of its role, MPCA will continue to be involved in working with local partners and provide funding where available to implement objectives on Deer and Pokegama lakes that will protect their future quality for generations to come.

BMP OPERATION AND MAINTENANCE PLAN

Itasca SWCD is active in the design and oversight of shoreland BMPs in Itasca County to ensure they are properly installed. Annual follow up inspections are scheduled to make a determination on their function and effectiveness. Itasca SWCD works closely with landowners at the time of installation to help them understand how to properly maintain the BMPs installed along their shorelines.

INFORMATION AND EDUCATION PROGRAM

The Itasca Water Legacy Partnership (IWLP) has been a strong force for education on water-related issues in the county over the past decade. This organization will be instrumental in creating and operating the education and information elements of the implementation plan outlined above. This organization has performed at least six similar functions in the county that are outlined below.

In 2010, IWLP did the library program where they invited Pokegama and Deer Lake interested individuals to a public meeting to initiate this present study. Around 65 interested people attended, learned about the study, and registered to volunteer to assist with it. IWLP secured the materials to make the seepage meters and peizemeters, and with the help of the Deer River and Grand Rapids vo-tech students, built 90 seepage meters. The employees of Minnesota Power later assisted IWLP in this function. An education program explained to vo-tech students what they were building and what we were trying to measure.

The IWLP Adult Water Summit at ICC in May of 2011 focused on about a dozen aspects of water stewardship including basic water science principals. Over 100 people took part along with 25 volunteers.

In 2012 and 2013, IWLP put on a youth water summit for 5th graders from Grand Rapids ISD# 318. Students from Deer River ISD #317 were also included in 2013. The first year, 260 students attended and were educated on many different water science principals. The topics included lake turnover, raingardens, density, pH, the hydrologic cycle, aquatic invertebrate identification, and aquatic plant ecology, to name a few. IWLP has also been instrumental in incorporating the Native American aspects of water into the curriculum. In 2013, 340 students participated with 90 volunteers from the community.

IWLP has also sponsored and held a series of mini water Summits. Topics have included invasive aquatic species, pharmaceuticals in water, the lake shoreland management challenge, and rain gardens. 40-50 adults attended these educational briefings.

PROGRAM ELEMENTS AND MILESTONE SCHEDULE

The table below identifies the specific elements of the implementation program and shows the proposed milestone schedule.

Objective	**Methods**	**2014**	**2015**	**2016**	**2017**	**2018**
1. Protection of Similar Waters in Itasca County						
1a. Atmospheric deposition	Create a network across county to collect fresh rain					
	Analyze rainfall					
	Analyze spatial patterns and seasonality of atmospheric deposition					
1b. Hypolimnetic oxygen consumption	Choose lakes for study – determine 50 lakes covering range of sizes, depths, trophic status					
	Monitor 25 lakes each year					
	Analyze AHOD data					
1c. Public education on lake protection	Create education program for adults					
	Create education program and materials for K-12					
	Administer outreach program					
1d. Groundwater transport	Recruit private well owners to submit water samples for analysis – maximize coverage			Fill in gaps		
	Analyze well samples					
	Install random well grid					
	Monitor well grid					

Objective	**Methods**	**2014**	**2015**	**2016**	**2017**	**2018**
	Use regional lake water elevation and soil maps to estimate transport rates	■	■			
2. Implementation of specific programs on Deer and Pokegama Lakes						
2a. Groundwater monitoring	Install groundwater monitoring wells with some as clear control points	■				
	Monitor groundwater for temporal trends		■	■	■	■
2b. Stream monitoring and remediation	Perform longitudinal stream analyses along long profiles of priority management subwatersheds	■	■	■		
	Create management plans including BMPS for nutrient and erosion control		■	■	■	
	Seek funding for BMP installation		■	■	■	
	Install BMPs			■	■	■
	Monitor BMP effectiveness using BACI and paired streams				■	■
2c. Hypolimnetic oxygen tracking and remediation	Create hypolimnetic aeration devices with community assistance	■	■			
	Install devices and test		■	■		
	Establish BACI design and monitor lakes 2 years		■	■		
	Activate aerators and monitor two years				■	■
	Determine effects and evaluate economic feasibility of operation					■
2d. Bell-weather lake water monitoring	Monitor one site in each lake every year to track temporal changes in water quality	■	■	■	■	■

Objective	**Methods**	**2014**	**2015**	**2016**	**2017**	**2018**
2e. Road drainage modification at highway 169 Pokegama causeway	Create discussions about options for causeway drainage	■	■			
	Hold community roundtable on choosing options		■	■		
	Seek funding and support for modified drainage			■	■	■
2f. Mississippi River backflow to Pokegama	Implement discussions between community and Army Corps of Engineers about moderating or eliminating backflow from the Mississippi River	■	■			
	Seek support for policy or engineering solutions		■	■	■	
	Implement policy or engineering solutions to decrease nutrient and water flux.				■	■
2g. Septic system improvement and education about septic systems	Itasca Water Legacy Partnership (IWLP) works with local officials and citizens to promote the inspection of septic systems.	■	■			
	IWLP works with lake associations, government agencies and private citizens to find support for septic system upgrading and replacement		■	■	■	■
2h. Shore Stabilization: Riparian Buffer Plantings	4 buffer plantings/lake/year, where previously mowed lawn to the water's edge.	■	■	■	■	■

Objective	**Methods**	**2014**	**2015**	**2016**	**2017**	**2018**
2i. Shore Stabilization: Rock Rip Rap	15 projects installed on Pokegama and 7 on Deer.					
2j. Stormwater Runoff Management Projects	8 stormwater runoff management projects installed on each lake.					
Write final report on implementation projects						

Table 35: Specific elements of the implementation program and shows the proposed milestone schedule.

IMPLEMENTATION PROJECT BUDGET

We propose a five-year program of implementation of measures to protect these and other waters in Itasca County. The total requested budget is $1,072,000.

Objective	**Methods**	**Justification**	**Estimated cost**
1. Protection of Similar Waters in Itasca County			
1a. Atmospheric deposition	Establish a network of citizen volunteers to monitor atmospheric deposition of phosphorus and other materials falling with precipitation. • *Create a network of citizens in cooperation with a local radio station or social organization to monitor atmospheric deposition of phosphorus, acid, and Hg* • *Use standard clean techniques* • *Analyses done by Itasca Community College and the US Forestry laboratory at ICC* • *Look for patterns in and trace sources of atmospheric pollutants.*	$5000 to organize 300 rain samples at $100 Analyze and present data	$40,000

Objective	Methods	Justification	Estimated cost
1b. Hypolimnetic oxygen consumption	Involve students and volunteers in measuring background hypolimnetic oxygen demands across the county and the region. • *Establish a network of lakes across the region and estimate the summer and winter hypolimnetic oxygen demand* • *50 lakes will be monitored over two summer seasons, estimating phosphorus, clarity, chlorophyll, and profiles of common parameters every second week from May-August* • *Relate to lake and watershed characteristics* • *Compare with world rates based on trophic status* • *Perform spatial analysis of oxygen deficit anomalies*	50 lakes 8 samples each	$145,000

Objective	**Methods**	**Justification**	**Estimated cost**
1c. Public education on lake protection	Engage local volunteer organizations to teach the public about the special aspects of lakes in this region and what this means about the protection of this vital resource. • *Region's lakes are unusual in atmospheric deposition, groundwater transport (deep and shallow), and has frequent stream nutrient conditions that depart from state norms* • *Educate the public about the implications of these characteristics for the protection of regional water quality* • *Establish K-12 and adult education programs*		$35,000

Objective	**Methods**	**Justification**	**Estimated cost**
1d. Groundwater transport	Analyze regional groundwater transport using a network of private wells offered for analysis by volunteer households and permanent observation wells. • *Offer free well analysis for nitrates and coliforms to well owners across the region* • *Collect data on iron, DOC, phosphorus, DIC and other materials that may influence lake trophic status and oxygen demand* • *Use lake water levels and well water data across the region to estimate regional groundwater transport* • *Establish and monitor a network of regional observation wells to monitor background changes in groundwater chemistry*		$125,000
2. Implementation of specific programs on Deer and Pokegama Lakes			
2a. Groundwater monitoring	Create and monitor a network of observation wells to examine trends in groundwater chemistry over time. • *Deep groundwater was analyzed using private wells but private wells are located near homes* • *Establish a network of observation wells placed randomly around the lakes to estimate regional temporal changes* • *Monitor groundwater for temporal trends*	40 wells @$3k	$200,000

Objective	**Methods**	**Justification**	**Estimated cost**
2b. Stream monitoring and remediation	Implement nutrient tracking nutrients in most nutrient-rich streams, especially those violating Minnesota draft standards. Work with communities to seek sources of nutrients and remediate high export values and concentrations. • *Perform longitudinal analyses of stream long nutrient profiles to seek locations of primary phosphorus inputs* • *Once sources of nutrients in impaired streams are located, work with communities and SWCD to find means of reducing nutrient export* • *Monitor most nutrient-rich streams to track temporal changes in phosphorus export*	16 streams at $7k +35k +20k116	$167,000

Objective	**Methods**	**Justification**	**Estimated cost**
2c. Hypolimnetic oxygen tracking and remediation	Understanding that oxygen depletion may exacerbate sensitivity to nutrient loading, install and operate hypolimnetic aeration devices and monitor their influence oxygen and nutrient concentrations. This should be a BACI (before-after control impact) analysis. • *Choose control lakes to monitor while Deer and Pokegama are undergoing aeration* • *Use analyses of chemical components to determine source of oxygen depletion* • *Calculate theoretical oxygenation levels needed to sustain summer high oxygen levels* • *Build and install hypolimnetic aeration devices – Speece cones with surface vents* • *Operate tests of re-oxygenation using a BACI design* • *Determine effects of oxygenation on water quality in the hypolimnion* • *The summer O_2 consumption is 750 and 1300 tons (metric) for June-August. The economic feasibility of direct O_2 or air injection will be evaluated.*		$180,000

Objective	**Methods**	**Justification**	**Estimated cost**
2d. Bell-weather lake water monitoring	Implement a regular monitoring program for lake water that seeks to analyze temporal trends in nutrients and water quality because both lakes have declined from historical quality. • *Unexpected changes were found in ambient nutrient concentrations – these appear related to loading from landscape and atmospheric changes* • *Current widely-space monitoring events are not sufficient to note changes on short time-frames* • *We propose to establish regular, annual monitoring of these two lakes to track future changes in water quality* • *Monitoring would reflect MPCA monitoring norms and be of an annual frequency of 5-times, over the long term*		$50,000

Objective	**Methods**	**Justification**	**Estimated cost**
2e. Road drainage modification at highway 169 Pokegama causeway	Implement discussions among community and government to modify or divert nutrient and water flux. • *The causeway across Pokegama is supplying nutrients directly to the lake at concentrations that violate river tributary nutrient standards.* • *This constitutes an effective point-source that was created by a highway project* • *This is an avoidable nutrient input so could be mitigated* • *Data collected here suggest that community efforts and discussions with the Minnesota DOT could mitigate this ongoing nutrient flux* • *We would like the community to implement discussions toward a project directing highway effluent away from lakes*		$10,000

Objective	Methods	Justification	Estimated cost
2f. Mississippi River backflow to Pokegama	Implement discussions between community and Army Corps of Engineers about moderating or eliminating backflow from the Mississippi River. Implement policy or engineering solutions to decrease nutrient and water flux. • *A large portion of the phosphorus budget of Pokegama comes from backflow from the Mississippi, when it occurs.* • *Removal of this nutrient load would lead to improvements in water quality that would move the lake back to a more oligotrophic status (from mesotrophy)* • *We would like to implement discussions between the Army Corps of Engineers and the Pokegama Lake community about whether this nutrient load from the Mississippi River could be reduced.* • *If the existing dam cannot be operated in a way that minimizes this load, it is possible to evaluate means of installing a control structure between the Pokegama "outfall" and the Mississippi River* • *Such a structure might be similar to tide-control dams, designed to minimize marine backflow to rivers*		$10,000

Objective	**Methods**	**Justification**	**Estimated cost**
2g. Septic system improvement and education about septic systems	Eliminate failing and inefficient septic systems in both the Deer and Pokegama watersheds. Improve understanding of the importance of groundwater protection. • *This study indicated that some waters around these lakes have substantially elevated phosphorus, chloride, and dissolved organic carbon, all constituents that could originate in septic tank effluents.* • *Several watersheds have particularly high densities of septic systems.* • *Groundwater has a long water residence time so mitigation of this resource, once polluted, is a very long process* • *We suggest that the Itasca Water Legacy Partnership work with local officials and citizens to promote the inspection of septic systems and the replacement of those inadequate to keep phosphorus out of these lakes over the long term.* • *Itasca County Environmental Services is currently administering a low interest septic loan program for individuals with non compliant systems. This would seek to provide additional aid to expedite lakeshore septic upgrades.*		$120,000.00 (including $100,000 in septic system grants and low-cost loans)

Objective	**Methods**	**Justification**	**Estimated cost**
2h. Shore Stabilization: Riparian Buffer Plantings	4 buffer plantings/lake/year, where previously mowed lawn to the water's edge. • Landowner installed/planted	*Avg Project: 50ft long , 10 ft deep = 500 sqft* Avg cost/proj = $2,000 2 year project	$32,000.00
2i. Shore Stabilization: Rock Rip Rap	15 rock rip-rap bank stabilization projects installed on Pokegama and 7 on Deer Lake. • 75 *lineal* ft/project= • 1125 ft on Pokegama, • 525 ft on Deer • Contractor installed	1650 total ft protected. Avg cost $50/lineal foot	$82,500.00
2j. Stormwater Runoff Management Projects	8 stormwater runoff management projects installed on each lake • rain gardens, water bars/open top box *culverts*, gutter downspout catch barrels, thicker/taller mowed lawn, side slope stabilization native plantings, etc	16 Projects @ $1000 avg cost/project	$16,000.00

Table 36: Implementation of measures.

CONCLUSIONS

This study proposes implementing several actions to protect these and other lakes of this region. Four major issues surfaced during this study of these unimpaired systems. They are that precipitation and atmospheric loading is an unexpectedly large source of nutrients, that hypolimnetic oxygen demands are double what they should be for lakes of this trophic status, that several streams had unexpectedly high nutrient concentrations, and that deep and shallow ground water are substantial sources of water and nutrients (as well as, perhaps substances fueling hypolimnetic oxygen demands). It is the conclusion of those of us working on this study that protecting these and other similar waters in the region require implementing ten specific actions. For Deer and Pokegama lakes, therefore, we propose: 1) that a detailed and controlled groundwater monitoring network be established and tracked, 2) that streams identified as contributing excess phosphorus (e.g., out of compliance with Minnesota draft standards) be carefully examined and remediated, (3) that the causes of extreme deep-water oxygen consumption be analyzed and experimentally managed, (4) that the two lakes be monitored continuously to act as bellwethers of regional change, (5) that road drainage modification be sought to alleviate high nutrient inputs, (6) that the Mississippi River backflow be decreased if possible, and (7) that a septic system improvement and education program be implemented. For regional lakes in general, we propose (8) the implementation of a county-wide atmospheric deposition monitoring network, (9) the implementation of an analysis of deep groundwater chemical transport and quality, and (10) the establishment of a program of public education and lake protection.

REFERENCES

American Public Health Association (APHA), American Waterworks Association, and Water Environment Federation. 2005. *Standard methods for the examination of water and wastewater, 21st edition.* Washington, D.C.: American Public Health Association.

American Public Health Association. 1998. Standard methods for the examination of water and wastewater, 20th ed. APHA.

Anderson, K.A. and J.A. Downing 2006. Dry and wet atmospheric deposition of nitrogen, phosphorus, and silicon in an agricultural region. Water, Air, and Soil Pollution 176 (1-4): 351-374.

Anderson, M.P. 2005. Heat as a ground water tracer. Ground Water 43(6): 951-968.

Beal, C.D., E.A. Gardner and N.W. Menzies. 2005. Process, performance, and pollution potential: a review of septic tank – soil absorption systems. Australian Journal of Soil Research 43: 781-802.

Blake, T.W. and J.A. Downing. 2009. Measuring atmospheric nutrient deposition to inland waters: evaluation of direct methods. *Limnology and Oceanography: Methods* 7: 638–647

Bradbury. K.R. and Rothschild, E.R. 1985. A computerized technique for estimating hydraulic conductivity of aquifers form specific capacity data. Ground Water 23(2):240-245.

Brandes, M., N.A. Chowdry and W.W. Cheng. 1974. Experimental study on removal of pollutants from domestic sewage by underdrained soil filters. National Home Sewage Disposal Symposium, Am. Soc. Agric. Eng. Chicago, Ill.

Cable, J.E., J. B. Martin, and J. Jaeger. 2006. Exonerating Bernoulli? On evaluating the physical and biological processes affecting marine seepage meter measurements. *Limnol. Oceanogr.: Methods* 4 : 172–183.

Canfield, D. E., and R. W Bachmann, 1981. Prediction of total phosphorus concentrations, chlorophyll-a, and Secchi depths in natural and artificial lakes. Can. J. Fish. Aquat. Sci. 38: 414-423.

Carpenter SR, Kitchell JF, Hodgson JR. 1985. Cascading trophic interactions and lake productivity. BioScience 13:675–678.

Cheung, K.C. and T.H. Venkitachalam. 2000. Improving phosphate removal of sand infiltration system using alkaline fly ash. Chemosphere 41: 243-249.

Clark, I.D. and P. Fritz. 1997. Environmental Isotopes in Hydrogeology. Florida: CRC Press.

Clark, I.D. and P. Fritz. 1997. Environmental Isotopes in Hydrogeology. New York. Lewis Publishers. 328 p.

Cole, B. 2012. Guide to the Proposed Permanent Rules Relating to Antidegradation of State Waters, MPCA.

Conant, Jr. B.P. 2004. Delineating and quantifying ground water discharge zones using streambed temperatures. Ground Water 42(2): 243-257.

Craig, H.I. 1961. Isotopic variations in meteoric waters. *Science* 133: 1702-1703.

Crumpton, W.G., Isenhart, T.M. and Mitchell, P.D. 1992. Nitrate and Organic N Analysis Using Second-Derivative Spectroscopy. *Limnology and Oceanography*, 37: 907-913.

Dillon, P. J., and F. H. Rigler, 1974. A test of a simple nutrient budget model predicting the phosphorus concentration in lake water. J. Fish. Res. Board Can. 31: 1771-1778.

Dillon, P.J. and F.H. Rigler. 1975. A simple method for predicting the capacity of a lake for development based on lake trophic status. J. Fish. Res. Board Canada 32(9): 1519-1531.

Dutton, A. B.H. Wilkinson,J.M. Welker, G.J. Bowen, K.C. Lohmann, 2005. Spatial distribution and seasonal variation in $^{18}O/^{16}O$ of modern precipitation and river water across the conterminous USA. *Hydrol. Process.* 19: 4121–4146

Eutrophication of waters: monitoring, assessment and control, Paris. 154p.

Freeze, R.A. and J.A. Cherry, 1979. Groundwater . New York, Prentice Hall, 604 p.

Geological Society of America Field Guides 2011, 24:545-585.

Groundwater-surface-water exchange and the geologic setting of northern Minnesota's lakes, wetlands, and streams: the modern-day relevance of Tom Winter's legacy. doi: 10.1130/2011.0024(27e)

Groundwater-surface-water exchange and the geologic setting of northern Minnesota's lakes, wetlands, and streams: the modern-day relevance of Tom Winter's legacy. doi: 10.1130/2011.0024(27e)

Harwell, G.R., 2012, Estimation of evaporation from open water—A review of selected studies, summary of U.S. Army Corps of Engineers data collection and methods, and evaluation of two methods for estimation of evaporation from five reservoirs in Texas: U.S. Geological Survey Scientific Investigations Report 2012–5202, 96 p.

Healy, R.W. and A.D. Ronan. 1996. Documentation of computer program VS2DH for simulation of energy transport in variably saturated porous media – modification of the U.S. Geological Survey's computer program VS2DT. U.S. Geological Survey WRI 96-4230, 36 pp.

Heiskary S, Wilson b. 2008. Minnesota's approach to lake nutrient criteria development. Lake and Reserv. Manage. 24:282–297.

Heiskary, S., R.W. Bouchard, Jr., H. Markus. 2013. Minnesota nutrient criteria development for rivers. Minnesota Pollution Control Agency, St. Paul, MN. WQ-S6-08.

Hobbs, H.C., 1983. Drainage relationships of Glacial Lake Aitkin and Upham and early Lake Agassiz in northeastern Minnesota, in Teller, J.T., and Clayton, L. eds. Glacial Lake Agassiz: Geological Society of Canada Special Paper 26, p. 245-259.

Hsieh, P.A., W. W. Wingle, and R.W. Healy. 2000. VS2DI – a graphical software package for simulating fluid flow and solute or energy transport in variably saturated media. U.S. Geological Survey WRI 9-4130, 16pp.

Itasca Economic Development Corporation (IEDC) http://www.itascadv.org/lifestyle.html

Jones JR, Bachmann RW. 1976. Prediction of phosphorus and chlorophyll levels in lakes.

J Water Poll Cont Fed. 48:2176–2182.

Jones JR, Bachmann RW. 1978. Trophic status of Iowa lakes in relation to origin and glacial geology. Hydrobiologia 57:276–273.

Jones, P.E., 2005. Simulated effects of water-level changes in the Mississippi River and Pokegama Reservoir on ground-water levels, Grand Rapids area, Minnesota. U.S.

Geological Survey, Scientific Investigations Report 2005-5139, 13 p.

Jones, P.E., 2005. Simulated effects of water-level changes in the Mississippi River and Pokegama Reservoir on ground-water levels, Grand Rapids area, Minnesota. U.S. Geological Survey, Scientific Investigations Report 2005-5139, 13 p.

Jones, P.E., J. J. Trost, D. O. Rosenberry, P. R. Jackson, J. A. Bode, and R.M. O'Grady. 2013. Groundwater and surface-water interactions near White Bear Lake, Minnesota, through 2011. U.S. Geological Survey, Scientific Investigations Report 2013–5044, 73pp.

Jones, P.E.. 2004. Simulation of ground-water flow in glaciofluvial aquifers in the Grand Rapids Area, Minnesota. U.S. Geological Survey, Scientific Investigation Report 2004-5159, 23 p.

Kirchner, W B. and P J. Dillon, 1975. An empirical method of estimating the retention of phosphorus in lakes. Water Resources Research. 11: 182-183.

Kishel, H.F., and Gerla, P.J., 2002, Characteristics of preferential flow and groundwater discharge to Shingobee Lake, Minnesota, USA: Hydrological Processes, v. 16, p. 1921–1934, doi:10.1002/hyp.363.

Knowlton MF, Jones JR. 2006. Temporal variation and assessment of trophic state indicators in Missouri reservoirs: implication for lake monitoring and management. Lake and Reserv Manage. 22:261–271.

Krabbenhoft, D.P., C.J. Bowser, M.P. Anderson, and J.W. Valley. 1990. Estimating groundwater exchange with lakes: 1. The stable isotope mass balance method. Water Resources Research 26(10):2445-2453.

Kreider, J. 2001. Wisconsin Lake Modeling Suite (WiLMS) version 3.3.18.1. Wisconsin Department of Natural Resources, Madision, Wisconsin, USA. http://www.dnr.state.wi.us/org/water/fhp/lakes/laketool.htm

Labaugh, J.W. and D.O. Rosenberry, eds. 2008. Field techniques for estimating water fluxes between surface water and ground water. U.S. Geological Survey Techniques and Methods 4-D2. Washington D.C. 128 pp.

Lapham, W.W. 1989. Use of temperature profiles beneath streams to determine rates of vertical flow and vertical hydraulic conductivity. U.S. Geological Survey Water-Supply Paper 2337, 35 pp.

Larsen D. P. and H. T. Mercier. 1976. Phosphorus retention capacity of lakes. J. Fish.Res. Board Can. 33: 1742-1750.

Lusardi, B.A. 1997. Minnesota at a Glance: Quaternary Glacial Geology. Univ. of Minnesota, Minnesota Geological Survey. 4p.

Mackay, D.M. and J.A. Cherry. 1989. Groundwater contamination: pump-and-treat remediation. Environmental Science and Technology 23(6): 630-636.

Marlow, L., P. Larson, and H. Mooers. 2004. Glacial and postglacial landscape evolution in the Glacial Lake Aitkin and Upham basin, northern Minnesota. Field Trip 6 of Severson, M.J. and Heinz, J. eds. Institute On Lake Superior Geology. 50th Annual Meeting, Duluth MN, Proceedings, v. 50. Field Trip Guidebook pt. 2, 170-199.

Matthews WJ, Hill LG, Schellhaass SM. 1985. Depth distribution of striped bass and other fish in Lake Texoma (Oklahoma-Texas) during summer stratification. Trans Am Fish Soc. 114:84–91.

Meyer, G.N. and M. A. Mirsa. 2005. Aggregate endowment of southeast Itasca County. Plate 6-Aggregate Endowment, Southeast. Miscellaneous Map Series, Map M-131. Minnesota Geological Survey.

Müller, B., L.D. Bryant, A. Matzinger, and A. Wüest. 2012. Hypolimnetic oxygen depletion in eutrophic lakes. Environmental Science and Technology 46: 9964-9971.

NCASI Technical Bulletin No. 253. 1971. An Investigation of Improved Procedures for Measurement of Mill Effluent and Receiving Water Color.

Nürnberg GK. 1996. Trophic state of clear and colored, soft- and hardwater lakes with special consideration of nutrients, anoxia, phytoplankton and fish. Lake and Reserv Manage. 12:432–447.

Nurnberg, Gertrud K. 1984. The prediction of internal phosphorus load in lakes with anoxic hypolimnia. Limnol. Oceanogr., 29 (1) 111-124.

Oakes, E.L. 1970. Geology and ground-water resources of the Grand Rapids area, north-central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-322, scale 1:48,000.

Organisation for economic cooperation and development (OECD), 1982. Eutrophication of waters: monitoring, assessment and control. OECD, Paris. 154pp.

Ostrofsky, M.L., 1978. Modification of phosphorus retention models for use with low areal water loading. J. Fish Res. Board Can 35: 532-536.

Panuska, J.C. and J.C. Kreider. 2003. Wisconsin Lake Modeling Suite, Program Documentation and User's Manual. Wisconsin Department of Natural Resources. PUBL-WR-363-94.

Reckhow, K. H., 1977. Phosphorus models for lake management. Ph.D. dissertation, Harvard University, Cambridge, Massachusetts. Catalog No. 7731778, University Microfilms International, Ann Arbor, Michigan.

Reckhow, K. H., 1979. Uncertainty applied to Vollenweider's phosphorus criterion. J. Water Poll. Cont. Fed. 51: 2123-2128.
Rodvang, S.J. and W.W. Simpkins, 2001. Agricultural contaminants in Quaternary aquitards: a review of occurrence and fate in North America. *Hydrogeology Journal* 9(1):44-59.

Rosenberry, D.O. 2011. The need to consider temporal variability when modelling exchange at the sediment–water interface in Conceptual and Modelling Studies of Integrated Groundwater, Surface Water, and Ecological Systems. Proceedings of Symposium H01 held during IUGG2011 in Melbourne, Australia, July 2011. IAHS Publ. 345: 3-9.

Rosenberry, D.O., R.C. Melchior, P.M. Jones, A. Streitz, K.D. Barr, David R. Lee, and J.J. Piegat. 2011.

Rosenberry, D.O., Striegl, R.G., and Hudson, D.C., 2000, Plants as indicators of focused ground water discharge to a northern Minnesota lake: Ground Water, v. 38, no. 2, p. 296–303, doi:10.1111/j.1745-6584.2000.tb00340.x.

Simpkins, W.W. 2006. A multi-scale investigation of ground water flow at Clear Lake, Iowa. *Ground Water* 44(1):35-46.

Simpkins, W.W. and T.B. Parkin, 1993, Hydrogeology and redox geochemistry of methane in a late Wisconsinan till and loess sequence in central Iowa. Water Resources Research 29(11): 3643-3657.

Simpkins, W.W., 1995. Isotopic composition of precipitation in central Iowa. *Journal of Hydrology* 172: 185-207.

Stonestrom, D.A. and J. Constantz, eds. 2003. Heat as a tool for studying movement of groundwater near streams. U.S. Geological Survey Circular 1260, 96pp.

Stumm, W. and J.J. Morgan. 1981. Aquatic Chemistry: An Introduction Emphasizing Chemical Equlibria in Natural Waters, 2nd ed. New York, John Wiley and Sons. 780 p.

Walker, W W, Jr., 1977. Some analytical methods applied to lake water quality problems. Ph.D. dissertation, Harvard University.

Walker, W.W. 1984. Statistical bases for mean chlorophyll a criteria. Lake Reserv. Manage. 2:57-62.

Walker, W.W. Jr., 1985. Empirical methods for predicting eutrophication in impoundments. Report No. 3. Phase II: Model refinements. USCOE waterways experiment station technical report No. E-81-9. Vicksburg, Mississippi. 300p.

Winter, T.C. 1973. Hydrogeology of glacial drift, Mesabi Iron Range, northeastern Minnesota: U.S. Geological Survey Water-Supply Paper 2029-A, 23 p.

Winter, T.C. 1999. Relation of streams, lakes, and wetlands to groundwater flow systems. Hydrogeology Journal. 7:28-45.

Winter, T.C., D.O. Rosenberry and A.M. Sturrock. 1995. Evaluation of 11 equations for determining evaporation for a small lake in the north central United States. Water Res. Res. 31(4): 983-993.

Winter, T.C., J.W. Harvey, O. Lehn Franke, W.M. Alley. 1999. Ground water and surface water: a single resource. U.S. Geological Survey Circular 1139. 79 p.

Woessner, William W. 2007. Building a compact, low-cost, and portable peristaltic sampling pump. Ground Water 34(6):795-797

Wright, H.E. Jr. 1972. Quaternary History of Minnesota, in Sims, P.K. and Morey, G.B. eds. Geology of Minnesota: A Centennial Volume: Minnesota Geological Survey, p. 515-547.