

Prepared in cooperation with the
Grand Portage Band of Chippewa Indians

Ground-Water/Surface-Water Interaction in Nearshore Areas of Three Lakes on the Grand Portage Reservation, Northeastern Minnesota, 2003-04



Scientific Investigations Report 2006–5034

U.S. Department of the Interior
U.S. Geological Survey

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By Perry M. Jones

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**U.S. Department of the Interior
U.S. Geological Survey**

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Conversion Factors, Abbreviations, and Datums

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
micrometer (μm)	0.00003937	inch (in.)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
gallon (gal)	3.785	liter (L)
milliliter (mL)	0.0338	ounce, fluid (oz)
Flow rate		
gallon per minute (gal/min)	0.06309	liter per second (L/s)

Temperature in degrees Celsius ($^{\circ}\text{C}$) may be converted to degrees Fahrenheit ($^{\circ}\text{F}$) as follows:
 $^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$.

Temperature in degrees Fahrenheit ($^{\circ}\text{F}$) may be converted to degrees Celsius ($^{\circ}\text{C}$) as follows:
 $^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8$.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter ($\mu\text{g}/\text{L}$).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Ground-Water/Surface-Water Interaction in Nearshore Areas of Three Lakes on the Grand Portage Reservation, Northeastern Minnesota, 2003–04

By Perry M. Jones

Abstract

The U.S. Geological Survey (USGS), in cooperation with the Grand Portage Band of Chippewa Indians, applied three techniques to assess ground-water/surface-water interaction in nearshore areas of three lakes (North, Teal, and Taylor) on the Grand Portage Reservation in northeastern Minnesota. At each lake, analyses of existing aerial photographs, in-situ temperature measurements of shoreline lake sediment, and chemical analyses of surface water and pore water were conducted. Surface-water and pore-water samples were analyzed for major constituents, nutrients, and stable isotopes of oxygen and hydrogen. Bulk precipitation samples were collected and analyzed (1) for nutrient concentrations to determine nutrient input to the lakes through atmospheric deposition and (2) for stable isotope ratios of oxygen and hydrogen to determine a meteoric waterline that was needed for the stable isotope analyses of surface-water and pore-water samples.

Total nitrogen concentrations in the precipitation samples ranged from 0.51 to 8.4 mg/L (milligrams per liter) as nitrogen at the North Lake precipitation station and from 0.42 to 2.3 mg/L as nitrogen at the Grand Portage precipitation station. Oxygen-18/oxygen-16 and deuterium/protium isotope ratios for the bulk precipitation samples lie relatively close to a meteoric waterline for northern Wisconsin, except for the ratios for samples collected on May 20, 2004.

Analyses of existing aerial photographs, nearshore lake-sediment temperatures, and seasonal isotope ratios of surface-water and pore-water samples were the most valuable data for identifying locations of ground-water inflow and surface-water outseepage. Analyses of existing aerial photographs of the three lakes indicated the location of potential inflow channels and lineaments identifying potential ground-water inflow locations for pore-water sampling. Lake-sediment temperatures at potential ground-water inflow locations ranged from 4 to 16 °C, varying between lakes, seasons, and climatic conditions. Major constituent chemistry was valuable at Taylor Lake, and to a limited extent at North and Teal Lakes, in confirming results from the isotope and lake-sediment temperature data.

Ground-water inflow to North Lake likely occurs along the southwest and south shores, and along portions of the west, southeast, north, and northeast shores. Relatively cool lake-sediment temperatures along the southwest, south, west, and southeast shores, and in isolated beaver channels along the north and northeast shores of North Lake indicate potential ground-water inflow at these locations. Both localized ground-water inflow and surface-water outseepage occurs along portions of the north, northeast, southeast, and south shores, varying seasonally. Conflicting evidence for ground-water flow conditions exist for the northwest and north-northwest pore-water samples. Only minor differences in the major constituent concentrations were seen between the surface-water and pore-water samples from the North Lake area with the exception of iron and manganese concentrations.

Ground-water inflow likely takes place along the south-southwest and north shores of Teal Lake, with a mixture of ground-water inflow and surface-water outseepage occurring in other areas of the lake. Cooler lake-sediment temperatures occurred along the south-southwest, west, and northwest shores, portions of the north shore, and in channels identified in aerial photographs throughout the lake, indicating potential ground-water inflow at those locations. Warmer lake-sediment temperatures along the northeast and portions of the southwest and northwest shores of Teal Lake indicate potential locations where surface-water outseepage or little ground- and surface-water interaction occurs. The major constituent concentrations were higher in the pore-water samples collected from the south-southwest and northeast shores of Teal Lake, indicating ground-water inflow. Cation adsorption, cation exchanges with hydrogen ions, and chelation with organic materials occurring in the fen surrounding the lake likely resulted in the low dissolved calcium, magnesium, and sodium concentrations in north, northwest, and west pore-water samples from the Teal Lake area. Pore-water samples from the south-southwest, north, and southwest shores of Teal Lake had isotopic compositions that plotted closest to the meteoric waterline, indicating that little evaporation or transpiration occurred in these samples and that ground-water inflow may be occurring at these locations. Surface-water outseepage from Teal Lake likely occurs along the northeast shore even though major

constituent concentrations were high. Major constituent concentrations may be high because of a nearby beaver dam.

Ground-water inflow to Taylor Lake likely occurs at the north and south pore-water sampling sites. Higher major constituent concentrations and the least evaporative isotope ratios were found in pore-water samples along the south, north, and west shores of Taylor Lake, indicating potential locations of ground-water inflow. However, a combination of warmer and cooler lake-sediment temperatures along the west lowland indicated that ground-water inflow and surface-water outseepage may occur at that location. Surface-water outseepage likely occurs from Taylor Lake along the south shore through a surface-water drainage channel to a downgradient bog. Warmer lake-sediment temperatures along portions of the south and southeast shores indicate that surface-water outseepage may occur at those locations. Both ground-water inflow and surface-water outseepage may occur along the west, southeast, and east shores of Taylor Lake, varying seasonally and with local precipitation.

Knowledge of general water-flow directions in lake watersheds and how they may change seasonally can help water-quality specialists and lake managers address a variety of water-quality and aquatic habitat protection issues for lakes. Results from this study indicate that ground-water and surface-water interactions at the study lakes are complex, and the ability of the applied techniques to identify ground-water inflow and surface-water outseepage locations varied among the lakes. Measurement of lake-sediment temperatures proved to be a reliable and relatively inexpensive reconnaissance technique that lake managers may apply in complex settings to identify general areas of ground-water inflow and surface-water outseepage.

Introduction

Background

The availability of good quality water from lakes and wetlands on the Grand Portage Reservation in northeastern Minnesota is an important concern of the Grand Portage Band of Chippewa Indians. Development and changing land-use practices may affect the quality and quantity of water resources on the reservation. To effectively protect the water quality and quantity of the lakes and wetlands, an understanding of exchanges between ground water and surface water on local and regional scales is needed. Numerous hydrologic studies have been done on the reservation, but none of these studies has focused on determining ground-water/surface-water interactions of lakes and wetlands.

The Grand Portage Reservation is located along the northwest shore of Lake Superior in northeastern Cook County, Minnesota, at the boundary between Minnesota, USA, and Ontario, Canada (fig. 1). The resident population on the

Grand Portage Reservation is approximately 573 (U.S. Census Bureau, 2004), with a total reservation enrollment of approximately 1,089 (Bureau of Indian Affairs, 2001).

An important task in the protection of lakes is identifying and quantifying the components of a lake's water balance. Commonly, one of the most difficult components to assess in this balance is the amount and location of ground-water inflow to lakes. On the Grand Portage Reservation, most of the ground-water inflow to lakes occurs through fractures and bedding planes in igneous and sedimentary bedrock. In fractured-flow terrains, ground-water inflow to open-basin lakes often is not a substantial component to the overall water balance of the lake (Rosenberry and Winter, 1993). However, for most closed-basin lakes, ground-water inflow is a substantial component to the lake's water balance.

Mapping for source areas of ground-water discharge to lakes in terrains dominated by bedrock fractures and bedding planes is difficult because of the complex nature of ground-water flow. Detailed assessments of bedding plane and fracture orientations in bedrock around the lakes can help in identifying potential locations of ground-water inflow. Hydraulic-head data also are needed to determine flow directions in the fractures. Because of large changes in topography and associated hydraulic-head gradients on the reservation, ground-water inflow can be relatively rapid, with lake-water levels rising relatively quickly in response to ground-water discharge and overland flow following precipitation (Winterstein, 2002).

Physical, chemical, and biological techniques exist for determining the location of ground-water flow to lakes. Physical techniques include monitoring of hydraulic-head conditions in wells and piezometers around lakes, conducting lineament analyses, and mapping areas of iron, calcium, and other types of precipitates commonly present at seeps. Attempts were made in the early 1990s on the Grand Portage Reservation to install piezometers to measure head differences along the shore of lakes on the reservation (Tim Cowdery, U.S. Geological Survey, oral commun., January 25, 2003). Thin, unconsolidated, lakeshore sediments and the bedrock shores with complex fracture patterns found along many of the lakes on the reservation made installation of piezometers impractical. Lineament analyses tend to be successful in delineating ground-water flow patterns in areas where bedrock is at or close to the land surface (Dengnan and Clark, 2002), which is common throughout the reservation. Chemical techniques for determining ground-water inflow to lakes include monitoring pore-water quality in lakeshore sediment, assessing major ion chemistry (Robbins and others, 1997; Alexander and others, 2001), and isotopic compositions of water (Krabbenhoft and others, 1994; Kendall and others, 1997; Schuster and others, 2002). Schuster and others (2002) pointed to the importance of aquatic plants in the littoral zone affecting calcium concentrations in pore water, therefore limiting the use of major constituent chemistry for determining locations of ground-water inflow, and stressed the importance of stable isotope values for evaluation of ground-water/surface-water interactions. In-situ

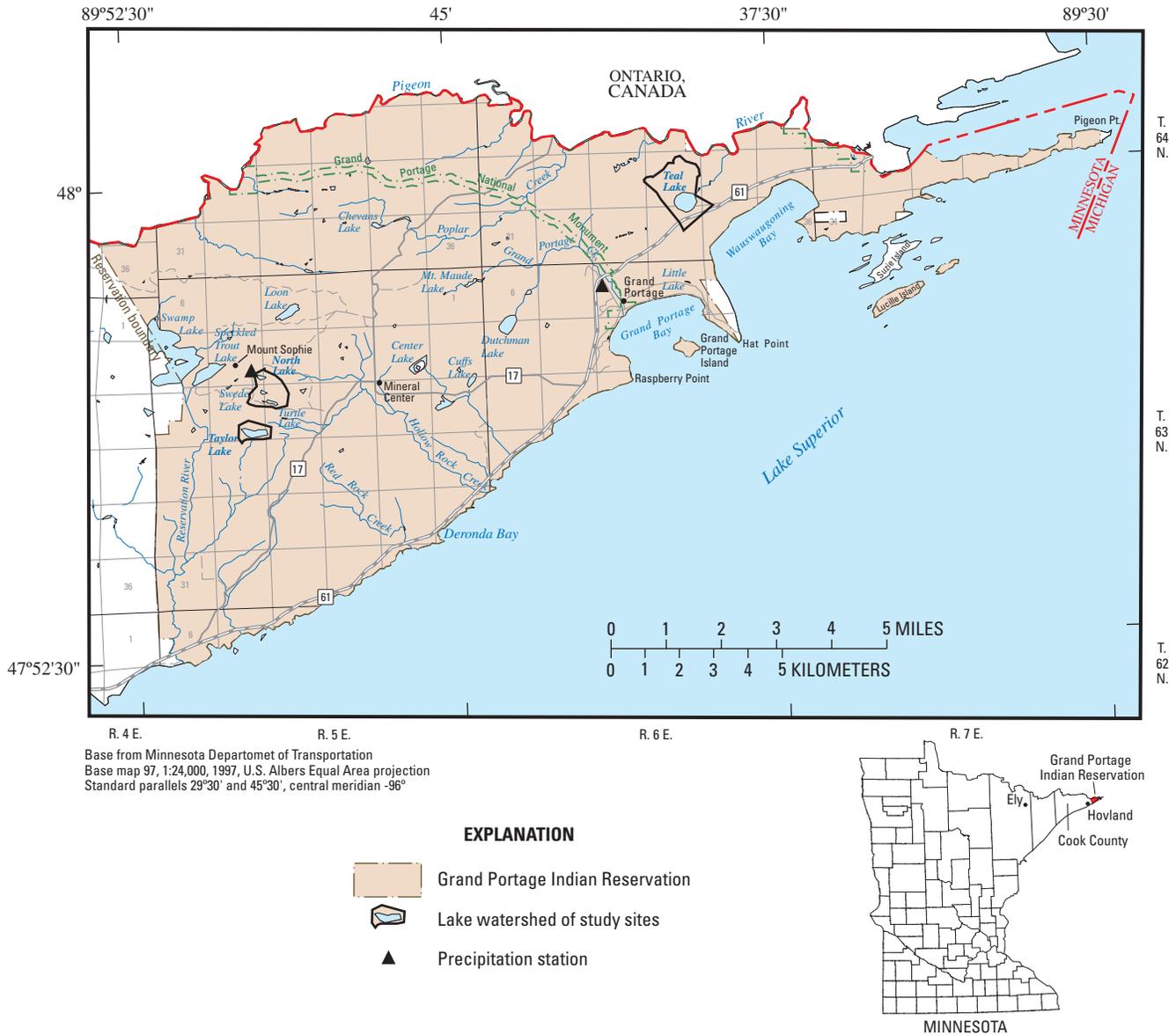


Figure 1. Location of study area and study sites, Grand Portage Reservation, northeastern Minnesota.

measurements of surface-water and lake-sediment temperatures have been used successfully to delineate ground-water and surface-water interactions in lakes (Schneider, 1962; Lee, 1985; Rosenberry and others, 2000; Alexander and others, 2001) and streams (Stonstrom and Constantz, 2003; Conant, 2004). Biological techniques include assessment of shoreline distribution and species assemblage of aquatic plants (Lodge and others, 1989; Rosenberry and others, 2000).

The U.S. Geological Survey (USGS), in cooperation with the Grand Portage Band of Chippewa Indians, conducted a study to assess ground-water/surface-water interactions in nearshore areas of three lakes, North, Teal, and Taylor Lakes (fig. 1), on the Grand Portage Reservation in 2003 and 2004.

These three lakes were selected on the basis of the relatively high specific conductance values of water from these lakes compared to other lakes on the reservation. The high specific conductance values of the lake water may indicate that ground-water inflow is an important component of the water balance of the lakes. The objective of the study was to identify areas of ground-water inflow to the three lakes and surface-water outseepage to local aquifers through the assessment of existing aerial photographs and water-quality data. No attempt was made to identify areas of ground-water inflow or surface-water outseepage in deeper water beyond the littoral zone of the lakes.

Purpose and Scope

This report presents the results from three techniques used to assess ground-water/surface-water interaction in near-shore areas of three lakes on the Grand Portage Reservation. Analyses of existing aerial photographs, in-situ temperature measurements of shoreline lake sediment, and water-quality data from surface- and pore-water samples collected in 2003 and 2004 were used. Rain-water-quality data also were collected. Available geologic and hydrologic data collected in previous USGS investigations were used in the analyses of the collected data. Information from scientific literature and other sources were used in data interpretation.

The terms ground-water inflow and surface-water outseepage are used throughout the report. In this report, ground-water inflow refers to ground-water flow into a lake, and surface-water outseepage refers to the flow of surface water from lakes through lake sediment into local aquifers. Surface-water discharge is used to describe surface-water flow from the lake through a surface channel or stream. Lineament is used to describe any linear feature where preferential ground-water flow may occur, such as along fractures in bedrock or glacial eskers and drumlins.

Acknowledgments

The author thanks the Grand Portage Reservation Environmental Department, in particular Margaret Watkins, Shannon Judd, and Kathryn King, for providing assistance in the collection of water samples, temperature data, and other activities needed to complete this study. The author also thanks Laurel Woodruff, Michael Menheer, Landon Gryczkowski, and Thomas Reppe, USGS, for their assistance in the collection and processing of water samples. The author thanks Robert Borgstede, USGS, for his work on the figures for this report.

Physical Setting and Hydrology

Grand Portage Reservation

The Grand Portage Reservation is about 88 mi² in area and contains numerous hills, small valleys, streams, lakes, and wetlands within boreal and mixed hardwood forest communities. The majority of the forest is second growth and undisturbed as the reservation was almost entirely logged during the late 1800s and early 1900s (Winterstein, 2002). Most of the residential areas and tourist and historical attractions are located in the community of Grand Portage, along State Highway 61, and along State Highway 17 east of Mineral Center (fig. 1). A thorough description of the physical setting and

hydrology for the Grand Portage Reservation is provided in Winterstein (2002).

Climate on the reservation is continental and locally affected by Lake Superior, with cold winters and warm summers. The annual normal temperature (1951–80) for the reservation is about 38 °F (Baker and others, 1985), with mean monthly normal temperatures ranging from about 8 °F in January to 62 °F in July and August. Mean annual precipitation is about 28 in. (Baker and Kuehnast, 1978), with about two-thirds of the precipitation occurring as rain between April and November.

The topography and hydrology of the Grand Portage Reservation is affected by bedrock geology. Table 1 lists the geologic units on the reservation and their water-bearing characteristics. The Rove Formation of the Animikie Group is the oldest bedrock on the reservation and covers much of the northern part of the reservation (fig. 2) (Green, 1982; Miller and others, 2002). This formation is Paleoproterozoic in age and consists of nearly flat-lying argillaceous siltstone, carbonaceous shale, mudstone, and greywacke (Miller and others, 2001). Sandstone and conglomerate of the Puckwunge Formation of early Mesoproterozoic age overlay the Rove Formation as a narrow east-west strip through the center of the reservation and on parts of the chain of islands in Lake Superior between Hat Point and Pigeon Point (figs. 1 and 2) (Miller and others, 2001). Northeast- and northwest-trending Pigeon River diabase dikes of Mesoproterozoic age cut and cover the Rove Formation in parts of the northern half of the reservation (fig. 2) (Miller and others, 2001). The Rove Formation is partially metamorphosed near the dikes. Pigeon Point gabbro (sill) emplaces the Rove Formation between Wauswaugoning Bay and Pigeon Point (figs. 1 and 2).

In the southwestern half of the reservation and on Lucille and nearby islands, diabase dikes and the lower northeastern sequence of the North Shore Volcanics Group lava of Mesoproterozoic age, mostly consisting of the Grand Portage basalt and Hovland lavas, cover the Puckwunge Formation to the southwest (fig. 2) (Miller and others, 2001). The Pigeon River diabase dikes trend to the northeast and southeast, cutting through the North Shore Volcanics Group (fig. 2). Swarms of east-trending Grand Portage diabase dikes cut through the Grand Portage basalt along Lake Superior shore between Deronda Bay and Raspberry Point and cut through the Rove Formation northeast of Wauswaugoning Bay (fig. 2). Undifferentiated granophyric and quartzfelsic-monzodioritic rocks of unknown age cover a portion of the Pigeon River diabase dike at and near Red Rock Creek (figs. 1 and 2). Brule Lake-Hovland-Reservation River diabase was emplaced as a sheet-like intrusion on the Hovland lavas along the Lake Superior shore in the southwestern corner of the reservation (fig. 2) (Miller and others, 2001). At the location where Red Rock Creek discharges into Lake Superior and Deronda Bay, Red Rock porphyritic rhyolite and Deronda Bay andesite of the North Shore Volcanics Group are present (figs. 1 and 2), being emplaced at about the same time as the Hovland lavas (1,107 million years ago) (Davis and Green, 1997).

Table 1. Geologic units on the Grand Portage Reservation, northeastern Minnesota, and their water-bearing characteristics.

[Geologic nomenclature is that of the U.S. Geological Survey and differs somewhat from that of the Minnesota Geological Survey. gal/min, gallons per minute; K, potassium]

System	Series	Geologic unit	Lithology (Miller and others, 2002)	Water-bearing characteristics
Quaternary	Pleistocene	Glacial lake clay	Clay, silt, sand, and boulders.	Deposits too thin and impermeable to yield adequate domestic water supplies.
Quaternary	Pleistocene	Glacial till	Clay, sand, silt, pebbles, cobbles, and boulders.	Most deposits too thin and impermeable to yield adequate domestic water supplies. Ruhl (1995) reported a well yield of 2 gal/min. Only used for domestic or irrigation supplies.
Precambrian	Proterozoic Era/ Mesoproterozoic–lower northeast sequence of North Shore Volcanics Group	Hovland lavas	Mixed suite of intergranular basalt, basaltic andesite, icelandite, and rhyolite.	No available information, but likely similar to Grand Portage basalt.
Precambrian	Proterozoic Era/ Mesoproterozoic–lower northeast sequence of North Shore Volcanics Group	Red Rock porphyritic rhyolite	Reddish to tan, aphanitic rhyolite; contains quartz, K-feldspar, and oxidized mafic phenocrysts.	No available information.
Precambrian	Proterozoic Era/ Mesoproterozoic–lower northeast sequence of North Shore Volcanics Group	Deronda Bay andesite	Brown, aphanitic to fine-grained andesite, sparsely plagioclase-phyric flow.	No available information.
Precambrian	Proterozoic Era/ Mesoproterozoic–lower northeast sequence of North Shore Volcanics Group	Grand Portage basalt	Intergranular transitional basalt and basaltic andesite flows.	Highly variable yields, but generally low yields ranging from less than 1 to 100 gal/min (Ruhl, 1995), adequate for domestic water supplies.
Precambrian	Proterozoic Era/ Mesoproterozoic– Keweenawan volcanic rocks	Pigeon Point gabbro (sill)	Olivine gabbro, intermediate rocks, and granophyre.	No available information, but likely similar to Brule Lake-Hovland-Reservation River diabase/gabbro.
Precambrian	Proterozoic Era/ Mesoproterozoic– Keweenawan volcanic rocks	Pigeon River diabase (dikes)	Olivine diabase.	No available information, but likely similar to Brule Lake-Hovland-Reservation River diabase/gabbro.
Precambrian	Proterozoic Era/ Mesoproterozoic– Keweenawan volcanic rocks	Brule Lake-Hovland- Reservation River diabase/gabbro	Ophitic olivine gabbro, locally monzodioritic, fine- to coarse-grained.	Generally low yields ranging from less than 1 to 4 gal/min (Ruhl, 1995), sometimes adequate for domestic water supplies.
Precambrian	Proterozoic Era/ Mesoproterozoic– Keweenawan volcanic rocks	Grand Portage diabase (dikes)	Basalt to trachybasalt, unit forms east-trending swarm cutting Grand Portage basalt and the Rove Formation.	No available information.
Precambrian	Proterozoic Era/Mesoproterozoic	Logan diabase (intrusion)	Diabase to gabbro, locally granophytic, upper part commonly plagioclase-phyric, forms thick sill and northeast-trending dikes in Rove Formation.	No available information.
Precambrian	Proterozoic Era/Mesoproterozoic	Miscellaneous diabase (intrusion)	Isolated hypabyssal intrusions within Keweenawan volcanic or Paleoproterozoic rocks, poorly exposed.	No available information, but likely similar to Brule Lake-Hovland-Reservation River diabase/gabbro.
Precambrian	Proterozoic Era/Mesoproterozoic	Undifferentiated granophyric rocks	Isolated hypabyssal intrusions of granophyre rocks within Keweenawan volcanic or Paleoproterozoic rocks, age uncertain, poorly exposed.	No available information.
Precambrian	Proterozoic Era/Mesoproterozoic	Undifferentiated quartzfelsic- monzodioritic rocks	Isolated hypabyssal intrusions of intermediate rocks within Keweenawan volcanic or Paleoproterozoic rocks, age uncertain, poorly exposed.	No available information.
Precambrian	Proterozoic Era/Mesoproterozoic	Puckwunge Formation	Quartz arenite; gray, cross-bedded; some quartz-pebble conglomerate.	No available information.
Precambrian	Proterozoic Era/Paleoproterozoic	Rove Formation	Argillaceous siltstone, carbonaceous shale, mudstone, and greywacke.	Highly variable yields, but generally low yields ranging from less than 1 to 50 gal/min (Ruhl, 1995); adequate for domestic water supplies.

Surface-water discharge often is affected by beaver activity. Inactive and active dams and lodges were present on all three lakes assessed in this study; however, the activity seemed to be greater in North and Teal Lakes. A conservative estimate of beaver populations on the reservation in 2005 was 180 beavers with 45 active lodges (Margaret Watkins, Grand Portage Reservation Environmental Department, oral commun., March 15, 2005). Lodges often were located in areas where ground-water inflow was thought to occur.

Ground water in the reservation primarily moves through fractures in the Mesoproterozoic bedrock and in the Rove Formation. Little is known about the orientation and extent of fracturing on the reservation because little fracture mapping and hydrologic assessment of the fractures have been done. Paillet and Olson (1994) mapped fracture orientations and hydraulic properties in two boreholes drilled in the North Shore Volcanics Group within 2 mi of Lake Superior.

Surface water is used for most public water supplies, whereas ground water is used for domestic water supplies. The city of Grand Portage extracts water from Lake Superior. Most of the domestic wells are located within 2 mi of Lake Superior (Winterstein, 2002). Ground water on the reservation often is too saline to be used for water supplies, consisting of calcium-, sodium-, and chloride-rich water (Olcott and others, 1978; Winterstein, 2002). Throughout the reservation, springs also are used by individuals whose wells are completed in deep fractured bedrock aquifers supplying unusable saline and (or) iron-rich water.

North Lake

North Lake is a small, shallow lake, with a maximum depth of approximately 7 ft and an approximate surface area of 4.9 acres (fig. 3). The lake is relatively high at an elevation of 1,486 ft. In the spring, surface water flows into North Lake from the south through a small drainage originating from Swede and Turtle Lakes (figs. 1 and 3). In the summer and fall, surface-water flow in the drainage only occurs during major precipitation. Surface-water discharge from the lake occurs through an outflow channel to the northwest. Watershed area for North Lake, which includes Turtle and Swede Lakes, is about 0.4 mi².

The bedrock geology of the North Lake area consists of Grand Portage basalt of the North Shore Volcanic Group (fig. 2) (Green, 1982; Miller and others, 2002). In general, the basalt is overlain by less than 6 ft of glacial till, consisting of unstratified clay, silt, sand, gravel, and boulders, and isolated deposits of peat (Olcott and others, 1978).

Land cover in the North Lake watershed consists of northern white cedar, white spruce, balsam fir mix, black spruce, aspen, and white birch (U.S. Geological Survey, 2005d). A northern rich fen (shrub swamp) surrounds most of the lake with the exception of a 54-acre northern rich tamarack swamp (bog) that is attached to the northeast part of the lake (fig. 3) (U.S. Fish & Wildlife Service, 1994; Minnesota

Department of Natural Resources, 2003). No large game fish are present, but *Phoxinus eos* (northern redbelly dace) and *Culaea inconstans* (brook stickleback) minnows are found in the lake (Margaret Watkins, Grand Portage Reservation Environmental Department, oral commun., March 15, 2005).

Teal Lake

Teal Lake is shallow, with a maximum depth of approximately 5 ft and an approximate surface area of 72 acres (fig. 4). The lake is relatively low at an elevation of 948 ft. The perimeter of the lake is completely encompassed by a northern rich fen and northern cedar swamp (fig. 4) (U.S. Fish & Wildlife Service, 1994). Surface-water inflow occurs through several drainage channels around the lake cutting the fen and swamp. Surface-water discharge occurs through an outflow channel located to the northeast of the lake. The location and shape of the channels vary over time with changes in beaver activity. The watershed area for Teal Lake is about 0.8 mi².

The bedrock geology of the Teal Lake area consists of the Rove Formation of the Animikie Group (fig. 2) (Green, 1982; Miller and others, 2002). Keweenaw Pigeon River diabase dikes bound upstream parts of the watershed, cutting through the Rove Formation (fig. 2). Stratified glacial lake clay with some silt and sands overlie the bedrock (Olcott and others, 1978).

Land cover in the lowlands surrounding Teal Lake consists of a mixture of black spruce, northern white cedar, deciduous shrub, and tamarack (U.S. Geological Survey, 2005d). The uplands of the Teal Lake watershed consist of aspen, white birch, balsam fir mix, black spruce, white spruce, and northern white cedar. No large game fish are present, but *Culaea inconstans* (brook stickleback) and *Pimephales promelas* (fathead) minnows are found in the lake (Margaret Watkins, Grand Portage Reservation Environmental Department, oral commun., March 15, 2005).

Taylor Lake

Taylor Lake is much deeper than Teal and North Lakes, having a maximum depth of about 26 ft (fig. 5). The lake is approximately 32 acres in area and sits at an elevation of about 1,543 ft. No apparent surface-water inflow occurs to the lake, but surface-water inflow may occur in the spring from a bog north of the lake through a lowland (fig. 5). Surface water flows out of the lake to the south over a beaver dam to a downgradient bog (fig. 5). The watershed area for Taylor Lake is relatively small compared to the size of the lake, being about 0.2 mi².

The bedrock geology of the Taylor Lake area consists of Grand Portage basalt. Younger Pigeon River diabase dikes cut

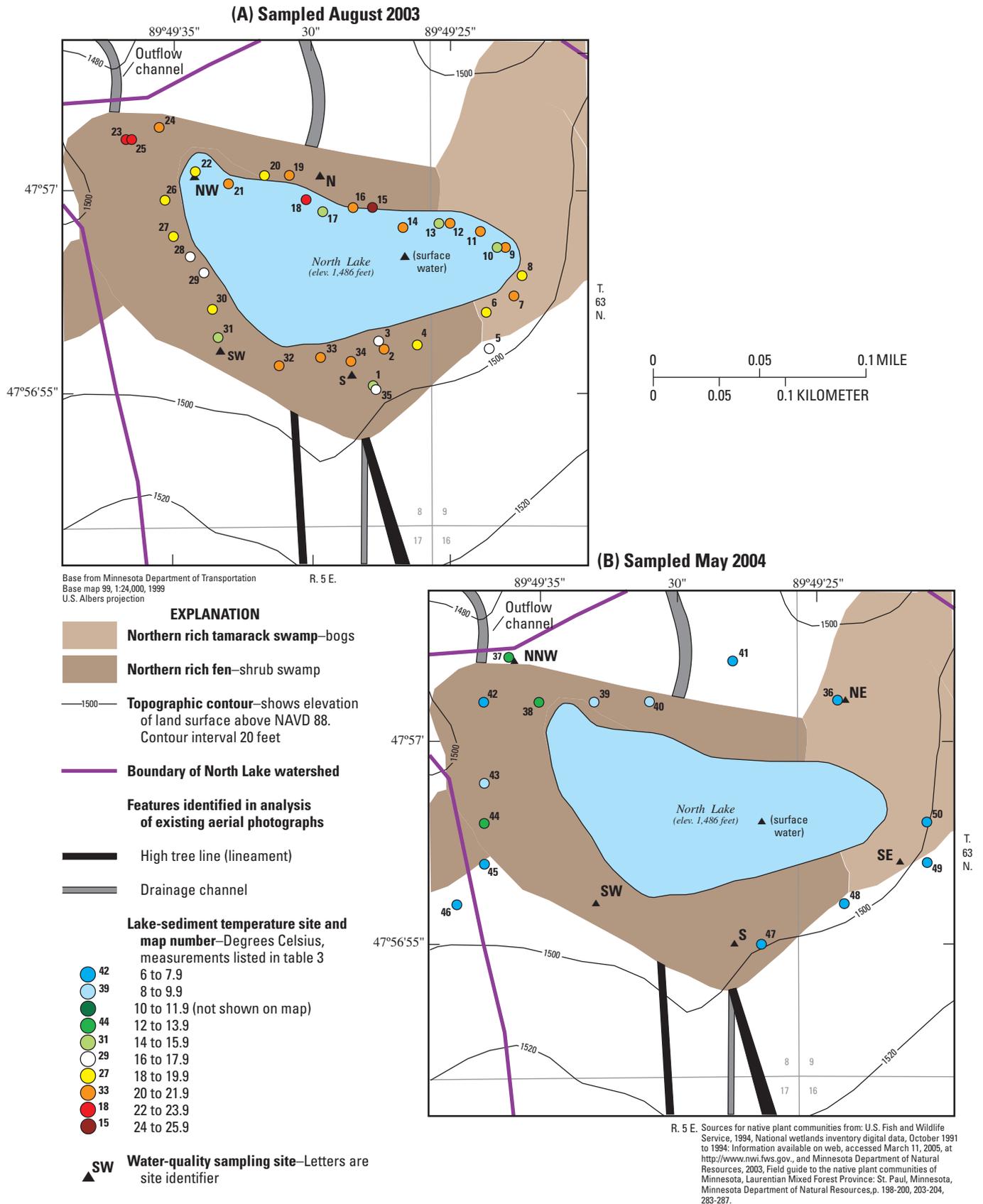


Figure 3. North Lake area, Grand Portage Reservation, northeastern Minnesota, land-surface elevations, bogs, swamps, high tree line, drainage channels, watershed boundary, lake-sediment temperatures, and water-quality-sampling sites sampled in (A) August 2003 and (B) May 2004.

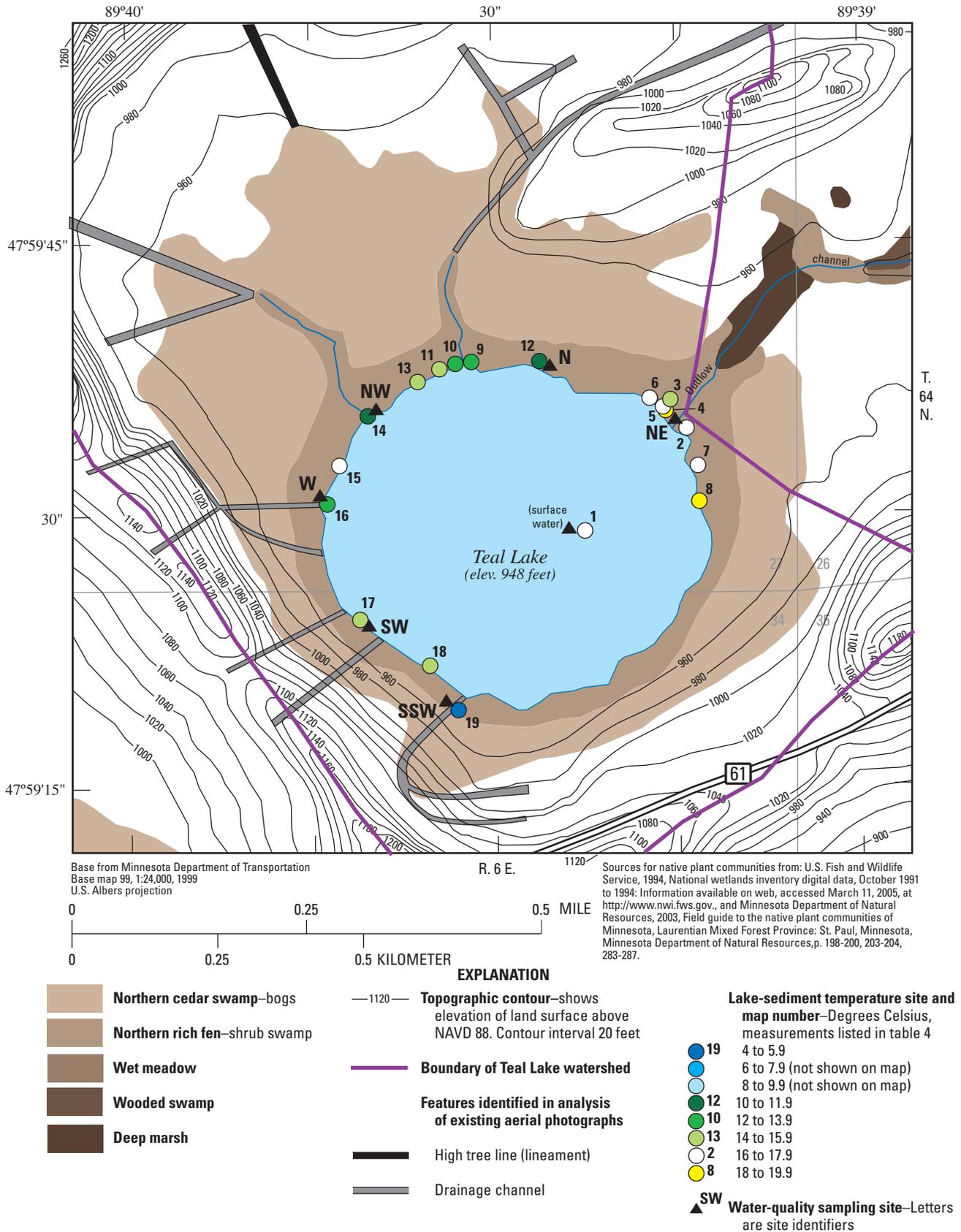


Figure 4. Teal Lake area, Grand Portage Reservation, northeastern Minnesota, lake-surface elevations, bogs, swamps, meadows, marshes, high tree line, drainage channels, watershed boundary, lake-sediment temperatures, and water-quality-sampling sites sampled in September 2003.

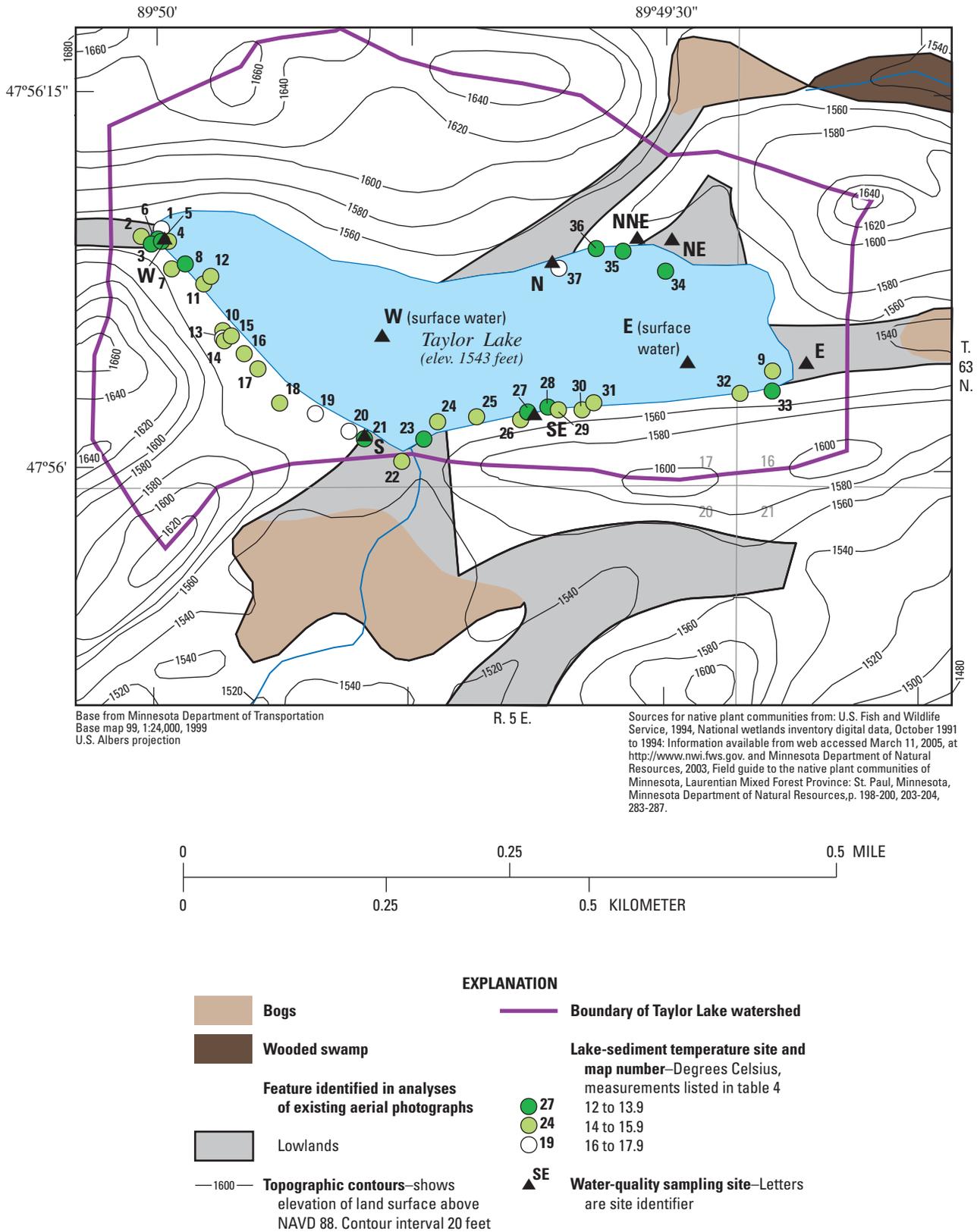


Figure 5. Taylor Lake area, Grand Portage Reservation, northeastern Minnesota, land-surface elevations, bogs, swamps, lowlands, watershed boundary, lake-sediment temperatures, and water-quality-sampling sites sampled in August–September 2004.

the Grand Portage basalt from the northeast to the southwest (Green, 1982; Miller and others, 2002). In general, the basalt and dikes are overlain by less than 6 ft of glacial till, consisting of unstratified clay, silt, sand, gravel, and boulders, and isolated deposits of peat (Olcott and others, 1978).

Land cover in the Taylor Lake watershed consists mainly of aspen and white birch in the uplands, with black spruce and balsam fir mix in lowland areas around the lake (U.S. Geological Survey, 2005d). Upgradient bogs and wooded swamps are present east and northeast of Taylor Lake (fig. 5). The lake is stocked with *Oncorhynchus mykiss* (rainbow trout), *Salvelinus fontinalis* (brook (speckled) trout), and *Lepomis gibbosus* (pumpkinseed sunfish) (Margaret Watkins, Grand Portage Reservation Environmental Department, oral commun., March 15, 2005).

Previous Hydrologic Studies

From 1991 to the present, the USGS has cooperated with the Grand Portage Band of Chippewa Indians on five previous studies characterizing surface-water and ground-water resources on the reservation. However, none of these hydrologic studies focused on ground-water/surface-water interactions or on determining locations of ground-water inflow to lakes.

Ruhl (1995) estimated transmissivity values and storage coefficients for the three principal fractured bedrock aquifers on the reservation—North Shore Volcanic Group basalt, Keweenawan volcanic rocks, and intrusive diabase and gabbro dikes, and Rove argillite, slate, and greywacke. As part of this 3-year study, the effects of hydrofracturing were tested on two low-producing boreholes on the reservation. The hydrofracturing slightly improved flow rates from 0.05 and 0.25 gal/min to 1.5 and 1.2 gal/min, respectively (Paillet and Olson, 1994).

Ruhl (1997) determined the physical and chemical properties of water, suspended sediment, and bottom sediment of the Grand Portage and Wausaugoning Bays of Lake Superior. Winterstein (2000) reported surface-water-quality data collected by the USGS during 1997 and 1998 from four lakes, two wetlands, and two streams on the reservation. A guidance document and monitoring program were developed by Goldstein (2000) to identify factors affecting the quality of aquatic resources on the reservation. Hydrologic and water-quality data collected by the USGS and the Grand Portage Reservation Environmental Department, between 1991 and 2000 on the reservation were assessed by Winterstein (2002).

Methods of Study

Analyses of existing aerial photographs, in-situ temperature measurements in lakeshore sediment, and water-quality analyses of collected surface-water and pore-water samples were done for the three study lakes on the reservation. Analy-

ses of existing aerial photographs were done to identify drainages and potential fracture zones in the watershed for each lake in hopes of delineating preferential ground-water inflow to the lakes. These analyses were done prior to onsite surveys and sampling to identify locations in the lake where in-situ temperature measurements and pore-water sampling would be done. Bulk precipitation samples were collected to determine a meteoric waterline for stable isotope analyses of surface-water and pore-water samples and to assess total nitrogen concentrations in precipitation falling on the reservation. In-situ pore-water temperatures in lakeshore sediment, hereafter referred to as lake-sediment temperatures, were measured at locations of potential ground-water inflow and surface-water outseepage to local ground-water systems to confirm these hydrologic conditions. Once lake-sediment temperatures indicated potential ground-water inflow, onsite water-quality measurements of the pore water were made, and pore-water samples were collected for major constituent, nutrient, and oxygen and hydrogen isotope analyses. The assessments were done at North Lake in August 2003 and May 2004, at Teal Lake in September 2003, and Taylor Lake in August–September 2004.

Analyses of Existing Aerial Photography

Analyses of aerial photographs were done on the watersheds for the three study lakes using National Aerial Photography Program (NAPP) photographs from 1991, 1992, 1999, and 2000 (U.S. Geological Survey, 2005e), and Digital Orthophoto Quadrangles (DOQ) from 1991 (Minnesota Department of Natural Resources, 2005). The photographs were viewed with a four-power stereoscope to identify surface-water drainages and any linear features where preferential ground-water flow may occur. Drainages and lineaments obtained from these analyses were used only to provide insight into possible ground-water inflow locations to focus in-situ lake-sediment temperature surveys and pore-water sampling along the shores of the lakes. Onsite confirmations of the identified drainage and lineament features were limited to views from the lakes and short onsite excursions along the lakeshore. More detailed analyses and onsite confirmation surveys would need to be done to determine the fracture patterns for source-water delineation throughout the lake watersheds. Morey (1981) conducted a much larger scale lineament assessment for northeastern Minnesota, which was used in this study as an initial guide in the analyses of aerial photographs.

Water Quality

Bulk precipitation samples were collected for total nitrogen and stable isotope analyses. Surface-water and lake-sediment temperatures were measured along the lakeshores to determine where small and large differences between the two temperature measurements occurred, indicating potential locations for surface-water outseepage to local ground-water

systems and ground-water inflow to lakes. Surface-water and pore-water samples were collected at both potential surface-water outseepage and ground-water inflow locations.

Precipitation

Bulk precipitation samples were collected in 2004 from two stations located on the reservation—Grand Portage and North Lake precipitation stations (fig. 1). Samples were collected in openings of the forest canopies for total nitrogen, oxygen-18/oxygen-16 ratio, and deuterium/protium ratio analyses. Bulk precipitation was collected from five rain storms in 4-L baked amber glass bottles with plastic collection funnels. Samples were collected by the water-quality specialist of the Grand Portage Reservation from the Grand Portage and the North Lake precipitation stations following rainfall on May 20, May 31, July 5, and July 29, 2004, and a sample was collected at the Grand Portage precipitation station following rainfall on August 24–25, 2004. Total precipitation at the Grand Portage precipitation station for the May 20, May 31, July 5, July 29, and August 24–25 rainfall was 0.09, 2.18, 0.85, 0.06, and 0.09 in., respectively (Larry Dahl, Grand Portage Reservation Environmental Department—Forestry, written commun., March 18, 2005) (Minnesota Climatology Working Group, 2005). The amber glass bottles used to collect the precipitation samples were deployed by the water-quality specialist of the Grand Portage Reservation within 24 hours of the start of anticipated precipitation and collected within 24 hours following the end of rainfall. Between rainfall, the bottles and funnels were rinsed with deionized water and dried.

Once collected, the sample water was poured into separate bottles for chemical analyses. The sampled water for total nitrogen analyses was poured into a 125-mL translucent polyethylene bottle with a plastic cap, acidified with 1 mL of 4.5-normal sulfuric acid, placed in a chilled cooler, and shipped within 24 hours after rainfall to the USGS National Water-Quality Laboratory, Lakewood, Colorado. Sample water for oxygen-18/oxygen-16 ratio and deuterium/protium ratio analyses was poured into a 60-mL clear glass bottle with a polyseal cap, placed in a chilled cooler, and shipped within 24 hours after rainfall to the USGS Reston Stable Isotope Laboratory, Reston, Virginia. Total nutrient analyses were done between 6 and 18 days after sampling by alkaline persulfate digestion (Patton and Kryskalla, 2003), whereas the oxygen-18/oxygen-16 ratio and deuterium/protium ratio analyses were done between 30 to 108 days after sampling using a carbon-dioxide-water equilibrium technique (Epstein and Mayeda, 1953) and a gaseous hydrogen equilibrium procedure (Coplen and others, 1991), respectively.

Lake-Sediment Temperatures

In-situ temperature measurements were made in lake sediment along the shores of North, Teal, and Taylor Lakes.

These lake-sediment measurements were made along the lakeshores from a canoe, in beaver-made channels flowing to the lakes, and on the fens and swamps surrounding the lakes. In-situ temperature measurements of lake sediment are indicative of pore-water and sediment temperatures. These measurements were made along the shorelines because it was impractical to collect temperature data for the entire lakes, and ground-water inflow to shallow lakes of Minnesota is less likely to occur with depth and distance from the shore as thicker accumulations of low-permeable organic sediment are present (Rosenberry and others, 2000). These temperature measurements provided a basis to identify the major ground-water inflow locations where water-quality samples could be collected to further confirm the inflow of ground water. For the most part, the lake sediment along the shorelines of the three lakes consisted of loose, organic materials, silt, and sand. Logs, boulders, and other low-permeable materials also were present on the lake bottoms.

A thermocouple probe was used to make the temperature measurements. The probe consisted of a thermocouple placed at the end of a 6-ft stainless steel hollow tube with a stainless steel screen secured at the end of the tube to prevent sediment from entering the tube. The thermocouple was connected to a handheld display, which showed the temperature reading. The thermocouple probe was calibrated using a thermally regulated water bath and a registered thermometer before and after the collection of temperature data. The use of a towed temperature probe, such as used by Lee (1985), was not attempted at the lakes because of the dense aquatic vegetation and the presence of abundant rotting logs in the littoral zones of the lakes.

Temperature measurements were made during the early spring and late summer months when the difference between lake-water and ground-water temperatures was thought to be the largest. At each measurement location, surface-water temperature was taken with the thermocouple probe, and then the probe was imbedded by hand into the sediment as deep as possible. The water column depth to the sediment interface and depth of probe insertion into the sediment were recorded at each location. Water depths ranged from 0.1 to 4.9 ft at each measurement location, and insertion depths into the sediment ranged from 0.2 to 5.0 ft, with most depths greater than 0.5 ft. Rosenberry and others (2000) found at Shingobee Lake in northern Minnesota that areas of ground-water discharge could be mapped effectively by measuring temperature only a few centimeters beneath the lakebed along a lake shoreline. Temperature stabilization in the surface water and lake sediment took approximately 3 to 10 minutes at each location, depending upon the temperature difference between the air, surface water, and pore water.

Surface- and Pore-Water Quality

Surface-water and pore-water samples were collected at locations where in-situ temperature measurements and onsite water-quality measurements of pore water in the lake sedi-

ment indicated potential ground-water inflow to the lakes or surface-water outseepage to local ground-water systems. Surface-water samples were collected following USGS protocols outlined in the USGS National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated). Surface-water and pore-water samples were collected at the three lakes for major constituents, nutrients, and oxygen and hydrogen isotope analyses. Major constituent and nutrient analyses were done by the USGS National Water-Quality Laboratory, Lakewood, Colorado, whereas the oxygen and hydrogen isotope analyses were done by the USGS Reston Stable Isotope Laboratory, Reston, Virginia. Alkalinity and bicarbonate concentrations were determined by USGS hydrologic technicians through inflection point titrations of the alkalinity samples performed within 24 hours after sampling. Replicate samples also were collected at each of the three lakes (see section on “Quality Assurance”).

Onsite water-quality measurements were made using a water-quality multiprobe meter prior to the collection of surface-water and pore-water samples. These measurements were specific conductance, pH, air temperature, water temperature, dissolved oxygen concentration, and barometric pressure. The specific conductance, pH, and dissolved oxygen probes on the multiprobe meter were calibrated on each of the sampling dates prior to sampling. Onsite water-quality measurements of surface water were made by lowering the multiprobe meter into the lake 2 to 3 ft below the water surface. Onsite water-quality measurements of pore water were made by pumping pore water into the multiprobe cup through a 0.25-in. outside-diameter, stainless-steel tube inserted into the lake sediment and connected to 0.19-in. inside-diameter, C-Flex tubing. The stainless-steel tube was slotted at one end with four 1-in. slots to allow pore water to enter the tube. The stainless-steel tubing was inserted between 0.5 and 3.0 ft into the lake sediment. The C-Flex tubing was run through a peristaltic pump to extract pore water from the sediment.

Surface-water samples were collected at approximately the centers of North and Teal Lakes (figs. 3 and 4). Two surface-water sites on Taylor Lake (fig. 5) were sampled to assess any variability in major constituent, nutrient, and stable isotope chemistry at shallow depths across the lake. Historically, onsite water-quality measurements at the two sites have varied with depth and spatially (Margaret Watkins, Grand Portage Reservation Environmental Department, oral commun., August 31, 2004), which could be the result of offshore ground-water discharge. The surface-water samples were collected 2 to 3 ft below the water surface using a peristaltic pump and 0.19-in. inside-diameter, C-Flex tubing.

Pore-water samples were collected at lakeshore locations of potential ground-water inflow and surface-water outseepage in the three lakes. The pore-water samples were collected using the same stainless-steel tube/C-Flex tubing/peristaltic pump sampling set-up used to collect the onsite water-quality measurement data. The samples were collected immediately following the collection of onsite water-quality measurement data. Like the onsite water-quality measurement data, pore-

water samples were collected at lake-sediment depths between 0.5 and 3.0 ft.

For each of the analyzed constituents, the sample filtration, preservation, and shipping methods were the same for the surface-water and pore-water samples, except for the nutrient samples. The water samples collected for anion, dissolved solids, and alkalinity analyses were filtered during sampling using a 0.45- μm pore-sized filter and stored in 250-mL polyethylene bottles. Water collected for cation analyses was filtered during sampling using a 0.45- μm pore-sized filter, preserved with sufficient nitric acid to maintain the water's pH at less than 2.0 standard units, and stored in a 250-mL acid-rinsed, polyethylene bottle. Unfiltered, unpreserved water samples were collected in 250-mL polyethylene bottles for determining specific conductance and pH values made at the USGS National Water-Quality Laboratory (NWQL). Unfiltered surface-water samples for nutrient analysis were collected in 125-mL translucent polyethylene bottles and preserved with 1 mL of 4.5-normal sulfuric acid to determine total ammonia plus organic nitrogen concentrations and total phosphorus concentrations. Surface-water samples for the other nitrogen and phosphorus constituent analyses were filtered using a 0.45- μm pore-sized filter and collected in 125-mL brown polyethylene bottles. Methods used for sample analysis are available at the USGS National Water-Quality Laboratory Web site (U.S. Geological Survey, 2005f).

Pore-water samples for all of the nitrogen and phosphorus constituent analyses were filtered using a 0.45- μm pore-sized filter and collected in 125-mL brown polyethylene bottles. The total ammonia plus organic nitrogen analyses and total phosphorus concentrations were determined for the pore-water samples using alkaline persulfate digestion and semiautomated colorimetric analyses (U.S. Geological Survey, 2005f). All of the major constituent and nutrient samples were shipped within 24 hours in chilled coolers to the USGS National Water-Quality Laboratory for analyses. Like bulk precipitation samples, unfiltered, unpreserved surface-water and pore-water samples were collected for oxygen-18/oxygen-16 ratio and deuterium/protium ratio analyses in 60-mL clear glass bottles with polyseal caps and shipped in chilled coolers within 24 hours after sampling to the USGS Reston Stable Isotope Laboratory.

Quality Assurance

Quality assurance and quality control are high priorities for USGS laboratories. The USGS National Water-Quality Laboratory, Lakewood, Colorado, has a rigorous set of procedures for assuring and controlling the quality of received water samples and analytical results determined by the laboratory (Ludtke and others, 2000; U.S. Geological Survey, 2005c). The USGS Reston Stable Isotope Laboratory, Reston, Virginia, has an internal quality-assurance policy and works directly with the USGS National Water-Quality Laboratory to assure the quality of their analytical results (U.S. Geological Survey, 2005b). All of the water-quality data and pore-water

sampling site information, including quality-assurance and control-sample information, are stored in the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2005g). Field log books and sample field forms were used to record onsite water-quality measurements, lake-sediment temperature data, and water-quality instrument calibration data.

One sequential replicate water sample was collected at each of the three lakes. A sequential replicate sample is a water sample collected consecutively following the collection of the regular sample to assess variability among samples resulting from sample collection, processing, shipping, and laboratory procedures performed at different sampling times (U.S. Geological Survey, 2005a). The replicate samples were collected following protocols outlined in the USGS National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, 2005a).

Results of Analyses

The oxygen and hydrogen isotope chemistry coupled with the lake-sediment temperatures proved to be the best tools for determining ground-water inflow to the three lakes. Drainages and lineaments identified in the analyses of existing aerial photographs were valuable in selecting the location of temperature measurements and pore-water sampling. In some cases, large differences in the major constituent chemistry between the surface water and pore water provided evidence of ground-water inflow. However, cation exchange in hydrogen ions, cation adsorption, and chelation occurring in the surrounding fens and swamps affected the major constituent concentrations of inflowing ground water, especially in pore-water samples collected at Teal Lake.

Existing Aerial Photography

Three potential drainage channels and two lineaments were identified in the analyses of existing aerial photographs of North Lake. The drainage channels are located to the south, northwest, and north of North Lake (fig. 3), and all trend generally to the north. There are two north-northwest-trending lineaments located south of North Lake near the southern drainage channels (fig. 3). Lineaments identified on the aerial photographs are likely lines of taller trees, which may represent a fracture zone where ground water is prevalent.

Multiple drainage channels and a lineament were identified in the analyses of existing aerial photographs of Teal Lake. These drainages are located north, northwest, west, and southwest of the lake (fig. 4). These drainage channels often correlate with locally lower land-surface elevations and are likely all flowing to the lake because they are all higher in elevation than Teal Lake. A north-northwest-trending lineament was identified on the aerial photographs northwest of

the lake (fig. 4) and is likely a line of taller trees, which may represent a fracture zone where ground water is prevalent.

No distinct lineaments or drainage channels were identified in the vicinity of Taylor Lake through the analyses of existing aerial photographs. Only apparent lowlands in the north, northeast, east, south, and west where ground-water inflow and surface-water outseepage may occur were identified (fig. 5). The lowland identified in the west (fig. 5) may provide only a relatively small amount of ground-water inflow to or surface-water outseepage from the lake because the watershed boundary of the lake is relatively close to the lake shore in that lowland.

Water Quality

Nine bulk-precipitation samples were collected between May and August 2004 at the two precipitation stations on the reservation. A total of 106 surface-water and 106 lake-sediment temperature measurements were made along the shores of the three lakes. Six surface-water and 24 pore-water samples, including replicate samples, were collected at the three lakes for water-quality analyses between August 2003 and August 2004.

Precipitation

Total nitrogen concentrations ranged from 0.51 to 8.4 mg/L as nitrogen in precipitation samples from the North Lake precipitation station and from 0.42 to 2.3 mg/L as nitrogen in the precipitation samples from the Grand Portage precipitation station (table 2). These concentrations are similar to the total nitrogen concentrations measured for bulk precipitation at the National Atmospheric Deposition Program/National Trends Network precipitation monitoring site at Hovland, Minnesota (National Atmospheric Deposition Program/National Trends Network, 2005) (fig. 1). The three largest concentrations were found in rain-water samples collected from the North Lake precipitation station (table 2). The North Lake precipitation station was located in a denser forested area than the Grand Portage precipitation station, and therefore, the forest canopy may catch and retain more of the atmospheric nitrogen from dry deposition that could wash off into the collected rain samples.

Oxygen-18/oxygen-16 ratios ranged from -5.0 to -8.1 per mil (table 2), whereas deuterium/protium ratios ranged from -28.8 to -56.4 per mil for bulk precipitation samples collected from the North Lake and Grand Portage precipitation stations. All of these ratios except for the ratios for samples collected on May 20, 2004, lie relatively close to a meteoric waterline determined by Krabbenhoft and others (1994) for precipitation in northern Wisconsin (fig. 6A). Oxygen-18 and deuterium values for river water in northern Wisconsin are similar to values in northeastern Minnesota (Kendall and Coplen, 2001), and therefore, the meteoric waterline for northern Wisconsin

Table 2. Water-quality data for bulk precipitation samples collected at North Lake and Grand Portage precipitation stations, Grand Portage Reservation, northeastern Minnesota, 2004.

[mg/L, milligrams per liter; per mil, parts per thousand]

Station name (fig. 1)	Station number	Date of collection (month/day/year)	Total nitrogen (mg/L as N)	Oxygen-18/ oxygen-16 ratio, unfiltered water, per mil	Deuterium/ protium ratio, unfiltered water, per mil
North Lake precipitation station	475702089493601	5/20/2004	3.15	-6.07	-56.40
		5/31/2004	.51	-7.93	-48.50
		7/5/2004	2.77	-7.80	-53.50
		7/29/2004	8.36	-5.62	-31.50
Grand Portage precipitation station	475814089412801	5/20/2004	.67	-5.39	-54.60
		5/31/2004	.59	-6.91	-44.80
		7/5/2004	.42	-8.10	-56.10
		7/29/2004	2.29	-5.02	-28.80
		8/24/2004	1.53	-7.39	-44.40

was used to evaluate the bulk precipitation isotopic ratios for the North Lake and Grand Portage precipitation stations.

Bulk precipitation samples collected on May 20, 2004, at both the North Lake and Grand Portage precipitation stations lie far to the right of the northern Wisconsin meteoric waterline (fig. 6A), indicating that the oxygen-18/oxygen-16 ratios for these samples are larger than the meteoric waterline. Potential explanations for these larger oxygen-18/oxygen-16 ratios for the May 20 samples are evaporation of the samples, which occurs when sample bottle caps are loose or made with foam inner liners (Tyler Coplen, U.S. Geological Survey, written commun., September 16, 2004), or a different source of water for the May 20 precipitation than for the other precipitation samples. Because most of the ratios are relatively close to the northern Wisconsin meteoric waterline, this meteoric waterline was used to assess the oxygen and hydrogen isotopes for the collected surface-water and pore-water samples.

Lake-Sediment Temperatures

Lake-sediment temperatures at the three lakes ranged from 4 to 25 °C. Lake-sediment temperatures at identified ground-water inflow locations were generally between 4 and 16 °C, varying greatly between the lakes, seasons, and the climatic conditions prior to and during the temperature measurements. Differences between the surface-water and lake-sediment temperatures at the temperature measurement locations ranged from -1 to 10 °C.

North Lake

Surface-water temperatures ranged from 16 to 25 °C in August 2003, with all but one value between 20 to 25 °C

(table 3). In May 2004, surface-water temperatures ranged from 9 to 17 °C. A total of 50 lake-sediment temperature measurements were made in the North Lake area, with 35 measurements in August 2003 and 15 measurements in May 2004 (table 3). Lake-sediment temperatures along the shore of North Lake varied from 15 to 25 °C in August 2003, and from 6 to 12 °C in May 2004. Multiple regression analysis of the lake-sediment temperature, probe depth into lake sediment, and water-depth data indicated that no relations (all p-values >0.43) existed between the variables, implying that the depth into lake sediment and water depth of the lake were unlikely factors affecting the lake-sediment temperature measurements at North Lake.

In August 2003, lake-sediment temperatures between 14 and 18 °C occurred along the southwest, south, west, and southeast shores (fig. 3A), and in isolated beaver channels in the north and northeast. The cooler temperatures in the south were measured near a north-south trending drainage and a lineament found between North and Swede Lakes (figs. 1 and 3A). Beaver dens commonly were present in the cool-temperature beaver channels in the north and northeast. The lower temperatures to the west and southwest are associated with a western extension of the northern rich fen surrounding the lake (fig. 3A). Beaver activity is common throughout this western extension of the fen. Lake-sediment temperatures above 18 °C were found throughout North Lake but were focused along the northwestern, northern, and southern lakeshores.

In May 2004, lake-sediment temperatures between 6 and 8 °C occurred along the southeast, west, southwest, north, northeast, and east shores of North Lake (fig. 3B). In an onsite survey of the south shore, surface-water discharge from Swede Lake to North Lake was noted near site 47 where lake-sediment temperature was 7 °C. Warmer lake-sediment

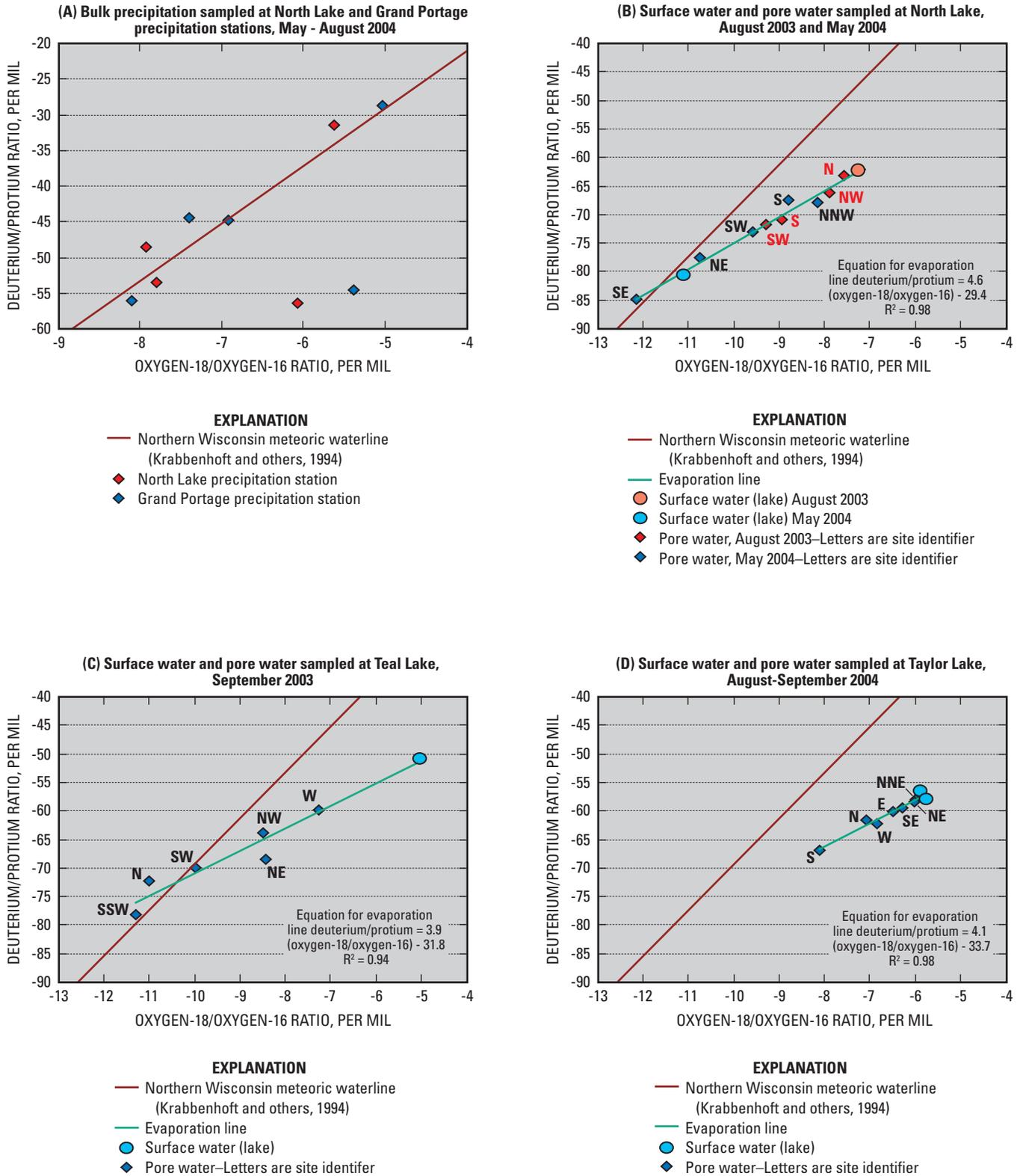


Figure 6. Comparison of oxygen-18/oxygen-16 ratios and deuterium/protium ratios with northern Wisconsin meteoric waterline for (A) bulk precipitation sampled at North Lake and Grand Portage precipitation stations, and for surface water and pore water sampled from (B) North Lake, August 2003 and May 2004, (C) Teal Lake, September 2003, and (D) Taylor Lake, August-September 2004, Grand Portage Reservation, northeastern Minnesota.

Table 3. Temperature measurements made in surface water and lake sediment of North Lake, Grand Portage Reservation, north-eastern Minnesota, August 2003 and May 2004.

[ft, feet; °C, degrees Celsius; --, no data]

Map number (fig. 3)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Date (month/day/year)	Time (24-hour)	Surface-water temperature in North Lake (°C)	Lake-sediment temperature (°C)	Probe depth into lake sediment (ft)	Water depth (ft)
1	N 47° 56' 55"	W 89° 49' 28"	8/27/2003	9:50	16	15	1.0	--
2	N 47° 56' 56"	W 89° 49' 27.5"	8/27/2003	10:06	23	22	1.0	1.7
3	N 47° 56' 56.5"	W 89° 49' 27.5"	8/27/2003	10:15	21	18	2.0	4.5
4	N 47° 56' 56"	W 89° 49' 26"	8/27/2003	10:25	21	19	4.0	2.5
5	N 47° 56' 56"	W 89° 49' 23.5"	8/27/2003	10:36	20	17	2.2	1.4
6	N 47° 56' 57"	W 89° 49' 23.5"	8/27/2003	10:47	21	19	2.0	4.2
7	N 47° 56' 57.5"	W 89° 49' 22.5"	8/27/2003	10:54	23	21	2.0	4.3
8	N 47° 56' 58"	W 89° 49' 22.5"	8/27/2003	11:08	23	19	3.0	3.2
9	N 47° 56' 58.5"	W 89° 49' 23"	8/27/2003	11:18	23	21	2.5	3.5
10	N 47° 56' 58.5"	W 89° 49' 23.5"	8/27/2003	11:27	23	15	2.0	4.6
11	N 47° 56' 59"	W 89° 49' 24"	8/27/2003	11:43	24	21	2.0	4.8
12	N 47° 56' 59"	W 89° 49' 25"	8/27/2003	11:55	25	21	2.0	4.9
13	N 47° 56' 59"	W 89° 49' 25.5"	8/27/2003	12:06	23	15	3.5	3.5
14	N 47° 56' 59"	W 89° 49' 27"	8/27/2003	12:22	23	20	2.3	4.0
15	N 47° 56' 59.5"	W 89° 49' 28"	8/27/2003	12:29	24	25	3.0	1.6
16	N 47° 56' 59.5"	W 89° 49' 28.5"	8/27/2003	12:36	25	21	3.4	2.8
17	N 47° 56' 59.5"	W 89° 49' 29.5"	8/27/2003	12:47	24	16	2.3	4.3
18	N 47° 57' 0"	W 89° 49' 30"	8/27/2003	13:20	24	22	2.3	4.1
19	N 47° 57' 00.5"	W 89° 49' 31"	8/27/2003	13:31	24	22	4.0	1.4
20	N 47° 57' 00.5"	W 89° 49' 31.5"	8/27/2003	13:43	24	18	5.0	1.0
21	N 47° 57' 00.0"	W 89° 49' 33.0"	8/27/2003	13:54	23	20	3.0	2.6
22	N 47° 57' 00.5"	W 89° 49' 34"	8/27/2003	14:02	23	19	1.2	3.8
23	N 47° 57' 01.5"	W 89° 49' 36.5"	8/27/2003	14:13	23	22	2.0	1.0
24	N 47° 57' 01.5"	W 89° 49' 35.5"	8/27/2003	14:20	22	21	2.0	2.0
25	N 47° 57' 01.5"	W 89° 49' 36.5"	8/27/2003	14:26	23	22	.2	2.2
26	N 47° 57' 0.0"	W 89° 49' 35.5"	8/27/2003	14:34	24	19	2.5	3.8
27	N 47° 56' 59.0"	W 89° 49' 35.0"	8/27/2003	14:45	23	18	2.0	4.2
28	N 47° 56' 58.5"	W 89° 49' 34.5"	8/27/2003	14:56	23	17	3.4	2.6
29	N 47° 56' 58.0"	W 89° 49' 34.0"	8/27/2003	15:06	22	18	2.0	4.0
30	N 47° 56' 57.0"	W 89° 49' 33.5"	8/27/2003	15:17	23	19	3.0	3.2

Table 3. Temperature measurements made in surface water and lake sediment of North Lake, Grand Portage Reservation, northeastern Minnesota, August 2003 and May 2004.—Continued

[ft, feet; °C, degrees Celsius; --, no data]

Map number (fig. 3)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Date (month/day/year)	Time (24-hour)	Surface-water temperature in North Lake (°C)	Lake-sediment temperature (°C)	Probe depth into lake sediment (ft)	Water depth (ft)
31	N 47° 56' 56.5"	W 89° 49' 33.5"	8/27/2003	15:27	23	15	2.7	3.3
32	N 47° 56' 55.5"	W 89° 49' 31.0"	8/27/2003	15:39	22	21	1.5	4.6
33	N 47° 56' 56.0"	W 89° 49' 29.5"	8/27/2003	15:45	23	22	4.0	1.8
34	N 47° 56' 56.0"	W 89° 49' 28.5"	8/27/2003	15:53	24	21	5.0	1.4
35	N 47° 56' 55.0"	W 89° 49' 27.5"	8/27/2003	16:01	23	17	1.7	2.3
36	N 47° 57' 1.0"	W 89° 49' 24"	5/18/2004	12:17	9	6	4.5	1.5
37	N 47° 57' 2.0"	W 89° 49' 36"	5/18/2004	13:29	13	12	2.5	1.5
38	N 47° 57' 1.0"	W 89° 49' 35"	5/18/2004	14:07	17	12	.5	1.0
39	N 47° 57' 1.0"	W 89° 49' 33"	5/18/2004	14:53	14	9	.5	1.5
40	N 47° 57' 1.0"	W 89° 49' 31"	5/18/2004	15:15	15	9	1.0	1.5
41	N 47° 57' 2.0"	W 89° 49' 28"	5/18/2004	15:33	11	6	1.0	1.5
42	N 47° 57' 1.0"	W 89° 49' 37"	5/19/2004	9:55	13	6	1.5	2.0
43	N 47° 56' 59.0"	W 89° 49' 37"	5/19/2004	10:23	12	8	2.0	1.5
44	N 47° 56' 58.0"	W 89° 49' 37"	5/19/2004	10:50	14	12	1.0	.5
45	N 47° 56' 57.0"	W 89° 49' 37"	5/19/2004	11:10	14	7	1.5	1.0
46	N 47° 56' 56.0"	W 89° 49' 38"	5/19/2004	11:50	15	7	1.5	2.0
47	N 47° 56' 55.0"	W 89° 49' 27"	5/19/2004	13:37	13	6	2.0	2.0
48	N 47° 56' 56.0"	W 89° 49' 24"	5/19/2004	14:09	11	7	1.0	1.0
49	N 47° 56' 57.0"	W 89° 49' 21"	5/19/2004	14:35	11	6	1.0	2.0
50	N 47° 56' 58.0"	W 89° 49' 21"	5/19/2004	15:00	11	6	1.5	2.5

temperatures were present in the northwest and west. These warmer temperatures ranged from 9 to 12 °C, falling into the range of measured surface-water temperatures (table 3).

Teal Lake

Surface-water temperatures varied from 14 to 22 °C (table 4). Because of poor weather conditions and limited time, no temperature measurements were made along the southeastern shore of Teal Lake (fig. 4). A total of 18 lake-sediment temperature measurements were made along the lakeshore during September 2003, whereas one temperature measurement was made near the center of the lake and close to the surface-water sampling site (fig. 4). Lake-sediment temperatures along the shore of Teal Lake ranged from 4 to 19 °C with all but one of the temperatures between 11 and 19 °C (table 4).

Statistical analysis of the lake-sediment temperature, probe depth into lake sediment, and lake-water depth data for Teal Lake implied that probe depth into lake sediment and lake-water depth were unlikely factors affecting the lake-sediment temperature measurements at Teal Lake. Results from multiple regression analysis of the data indicated that no relation (p -value = 0.76) existed between lake-sediment temperature and probe depth into lake sediment and a weak relation (p -value = 0.08) existed between lake-sediment temperature and water depth of the lake. However, this weak relation was affected mainly by the data point with the coolest lake-sediment temperature (4 °C) measured at Teal Lake and was not existent when the single data point was removed from the regression analysis (p -value = 0.72).

Lake-sediment temperatures between 4 to 14 °C occurred along the south, west, and northwest shores, and portions of the north shore of Teal Lake (fig. 4). Similar to the north

Table 4. Temperature measurements made in surface water and lake sediment of Teal Lake, Grand Portage Reservation, northeastern Minnesota, September 2003.

[ft, feet; ° C, degrees Celsius; --, no data]

Map number (fig. 4)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Date (month/ day/ year)	Time (24-hour)	Surface- water temperature, in Teal Lake (°C)	Lake- sediment temperature (°C)	Probe depth into lake sediment (ft)	Water depth (ft)
1	N 47° 59' 29"	W 89° 39' 23"	9/3/2003	10:24	18	17	2.0	4.0
2	N 47° 59' 34.5"	W 89° 39' 14.5"	9/3/2003	10:41	19	17	2.0	4.2
3	N 47° 59' 36"	W 89° 39' 15.5"	9/3/2003	10:55	22	15	2.5	3.5
4	N 47° 59' 35.5"	W 89° 39' 16"	9/3/2003	11:08	21	18	2.5	2.3
5	N 47° 59' 35.5"	W 89° 39' 16.5"	9/3/2003	11:19	22	17	2.0	2.8
6	N 47° 59' 36"	W 89° 39' 17.5"	9/3/2003	11:35	21	16	2.5	3.5
7	N 47° 59' 32.5"	W 89° 39' 13.5"	9/3/2003	13:33	20	16	1.5	2.8
8	N 47° 59' 30.5"	W 89° 39' 13.5"	9/3/2003	13:53	21	19	1.0	3.0
9	N 47° 59' 38.5"	W 89° 39' 32"	9/3/2003	14:55	20	13	2.5	2.5
10	N 47° 59' 38"	W 89° 39' 33"	9/4/2003	10:05	17	12	3.0	3.0
11	N 47° 59' 38"	W 89° 39' 34.5"	9/4/2003	10:19	17	14	4.0	2.0
12	N 47° 59' 38.5"	W 89° 39' 26.5"	9/4/2003	11:00	19	11	--	--
13	N 47° 59' 37"	W 89° 39' 36.5"	9/4/2003	10:45	18	15	3.5	2.5
14	N 47° 59' 35.5"	W 89° 39' 40.5"	9/4/2003	11:00	19	11	3.0	2.5
15	N 47° 59' 32.5"	W 89° 39' 42.5"	9/4/2003	11:14	20	16	2.5	3.5
16	N 47° 59' 30.5"	W 89° 39' 44"	9/4/2003	11:31	22	13	3.0	3
17	N 47° 59' 24"	W 89° 39' 41.5"	9/4/2003	13:51	19	14	3.5	2.5
18	N 47° 59' 21.5"	W 89° 39' 35.5"	9/4/2003	14:02	19	15	3.8	2.2
19	N 47° 59' 19"	W 89° 39' 33.5"	9/4/2003	14:35	14	4	2.5	.1

shore of North Lake, cool lake-sediment temperatures in the northwest and north were found in or near channels that ran through the fens and swamps surrounding Teal Lake. Beaver dens and activity were prevalent in these channels. The extent of these drainage channels were identified in the analyses of existing aerial photographs. A cool-temperature measurement along the west shore at site 16 was near a drainage channel found at a topographic low point in a northwest-trending diabase dike west of Teal Lake (fig. 4). A very cold lake-sediment temperature (4 °C) was measured at site 19 in a drainage channel located along the south shore where an upwelling spring was present. This temperature was 8 degrees cooler than the second coolest temperature measured in lake sediment at Teal Lake (table 4) and may represent the low end member of the temperature-mixing range between lake and ground-water temperatures. Iron-oxide precipitates originat-

ing from an upgradient spring were present at the bottom of drainage channel upgradient from the upwelling spring.

Warmer lake-sediment temperatures between 15 and 19 °C were present in the northeast, southwest, and portions of the northwest shore of Teal Lake (fig. 4). This temperature range falls within the range of measured surface-water temperatures. The warmer temperatures in lake sediment of the northeast shore were located at or near a surface-water outflow channel (fig. 4). A warm temperature (17 °C) also was found for lake sediment near the center of the lake close to where surface-water samples were collected (fig. 4).

Taylor Lake

Surface-water temperatures ranged from 13 to 17 °C, with temperature differences between the surface water and lake sediment ranging only from 0 to 3 °C (table 5). A total

Table 5. Temperature measurements made in surface water and lake sediment of Taylor Lake, Grand Portage Reservation, northeastern Minnesota, August and September 2004.

[ft, feet; ° C, degrees Celsius; --, no data]

Map number (fig. 5)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Date (month/ day/ year)	Time (24-hour)	Surface- water temperature (°C)	Lake- sediment temperature in Taylor Lake (°C)	Probe depth into lake sediment (ft)	Water depth (ft)
1	N 47° 56' 9.5"	W 89° 50' 0"	8/31/2004	11:00	16	16	1.0	2.0
2	N 47° 56' 9"	W 89° 50' 1"	8/31/2004	11:15	14	14	1.0	1.5
3	N 47° 56' 9"	W 89° 50' 0.5"	8/31/2004	11:25	14	13	.5	2.0
4	N 47° 56' 9"	W 89° 49' 59.5"	8/31/2004	11:35	14	14	1.0	2.0
5	N 47° 56' 9"	W 89° 50' 0"	8/31/2004	11:45	16	13	1.5	3.0
6	N 47° 56' 9"	W 89° 50' 0.5"	8/31/2004	12:00	16	13	2.0	3.5
7	N 47° 56' 7.5"	W 89° 49' 59.5"	8/31/2004	12:10	16	14	1.0	3.5
8	N 47° 56' 8"	W 89° 49' 58.5"	8/31/2004	12:15	16	13	2.0	3.0
9	N 47° 56' 3.5"	W 89° 49' 24"	8/31/2004	13:55	15	15	.3	3.0
10	N 47° 56' 5"	W 89° 49' 56.5"	8/31/2004	14:20	15	15	.5	1.5
11	N 47° 56' 7"	W 89° 49' 57.5"	9/1/2004	9:50	15	15	.5	1.5
12	N 47° 56' 7.5"	W 89° 49' 57"	9/1/2004	10:00	15	15	.5	2.0
13	N 47° 56' 5"	W 89° 49' 56.5"	9/1/2004	10:05	16	16	1.0	1.8
14	N 47° 56' 5"	W 89° 49' 56"	9/1/2004	10:10	15	14	1.0	1.0
15	N 47° 56' 5"	W 89° 49' 55.5"	9/1/2004	10:17	15	15	.5	1.0
16	N 47° 56' 4.5"	W 89° 49' 55"	9/1/2004	10:23	15	15	.8	1.0
17	N 47° 56' 3.5"	W 89° 49' 54.5"	9/1/2004	10:28	15	14	1.3	1.0
18	N 47° 56' 2.5"	W 89° 49' 53"	9/1/2004	10:45	16	15	1.3	1.0
19	N 47° 56' 2"	W 89° 49' 51"	9/1/2004	11:00	16	16	.5	2.0
20	N 47° 56' 1"	W 89° 49' 49"	9/1/2004	11:05	16	16	1.5	1.5
21	N 47° 56' 1"	W 89° 49' 48"	9/1/2004	11:15	13	12	1.0	1.0
22	N 47° 56' 0"	W 89° 49' 46"	9/1/2004	13:00	16	15	.5	1.5
23	N 47° 56' 1"	W 89° 49' 44.5"	9/1/2004	13:25	15	13	.8	.5
24	N 47° 56' 1.5"	W 89° 49' 43.5"	9/1/2004	13:45	16	15	.3	.5
25	N 47° 56' 2"	W 89° 49' 41.5"	9/1/2004	13:55	16	15	.5	.5
26	N 47° 56' 1.5"	W 89° 49' 39"	9/1/2004	14:00	16	14	1.0	1.0
27	N 47° 56' 2"	W 89° 49' 38.5"	9/1/2004	14:05	16	13	1.0	1.5
28	N 47° 56' 2"	W 89° 49' 37"	9/1/2004	14:15	15	13	1.0	1.0
29	N 47° 56' 2"	W 89° 49' 36.5"	9/1/2004	14:20	16	14	.5	.8
30	N 47° 56' 2"	W 89° 49' 35"	9/1/2004	14:30	16	14	.5	1.0

Table 5. Temperature measurements made in surface water and lake sediment of Taylor Lake, Grand Portage Reservation, northeastern Minnesota, August and September 2004.—Continued

[ft, feet; ° C, degrees Celsius; --, no data]

Map number (fig. 5)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Date (month/ day/ year)	Time (24-hour)	Surface- water temperature (°C)	Lake- sediment temperature in Taylor Lake (°C)	Probe depth into lake sediment (ft)	Water depth (ft)
31	N 47° 56' 2.5"	W 89° 49' 34.5"	9/1/2004	14:40	16	14	1.0	0.8
32	N 47° 56' 3"	W 89° 49' 26"	9/1/2004	14:55	17	14	1.0	1.0
33	N 47° 56' 3"	W 89° 49' 24"	9/1/2004	15:00	15	13	.5	1.0
34	N 47° 56' 7.5"	W 89° 49' 30.5"	9/2/2004	9:50	14	13	.5	.5
35	N 47° 56' 8.5"	W 89° 49' 33"	9/2/2004	10:00	14	13	.5	.5
36	N 47° 56' 8.5"	W 89° 49' 34.5"	9/2/2004	10:10	13	13	.5	1.0
37	N 47° 56' 8"	W 89° 49' 36.5"	9/2/2004	10:15	16	16	1.0	1.5

of 37 lake-sediment temperature measurements were made at Taylor Lake. Cooler-than-normal August 2004 air temperatures resulted in small temperature differences between surface water and lake sediment (fig. 5, table 5). Lake-sediment temperatures along the shore of Taylor Lake varied from 12 to 16 °C. Because of this small range in temperature differences, it was more difficult to use lake-sediment temperatures to identify the location of ground-water inflow.

Statistical analysis of the lake-sediment temperature, probe depth into lake sediment, and lake-water depth data for Taylor Lake implied that probe depth into lake sediment and lake-water depth were unlikely factors affecting the lake-sediment temperature measurements at Taylor Lake. Results from multiple regression analysis of the data indicated that no relation existed between lake-sediment temperature and water depth of the lake and that a relation (p -value = 0.01) existed between lake-sediment temperature and probe depth into lake sediment. However, this relation was affected mainly by two data points occurring at the deepest probe depth into lake sediment (2.0 ft) at Taylor Lake and was not existent when the two data points were removed from the regression analysis (p -value = 0.17).

Lake sediment along large portions of the north, northeast, east, and southeast shores of Taylor Lake were impossible to penetrate with the hand-driven, thermometer probe because of the presence of impermeable bedrock at or near the lakebed. Where the probe could be used, it only could be inserted to relatively shallow depths at Taylor Lake. The lakeshore in these areas consists of submerged logs, boulders, gravels, and hard bedrock. Thermometer-probe penetration depths were much less at Taylor Lake than at North and Teal Lakes (tables 3, 4, and 5).

Cooler lake-sediment temperatures at several locations were found downgradient from valleys and other topographic

low. Lake-sediment temperatures ranging from 12 to 14 °C were located in the northeast, east, southeast, portions of the south, and the far western shores of Taylor Lake (fig. 5). Upgradient from the northeast shore location is a lowland that trends to the northeast to a bog and wooded swamp, which may be sources of ground-water inflow (fig. 5). A steep valley also is located upgradient from the far west shore of Taylor Lake where lake-sediment temperatures range from 12 to 14 °C (fig. 5).

Lake-sediment temperatures between 14 and 16 °C were found along the south and southwest shores and portions of the north and east shores of Taylor Lake (fig. 5). Warmer lake-sediment temperatures (15 °C) in the south (site 22) were found near a beaver dam and channel where surface water discharges to a bog to the south (table 5; fig. 5).

Surface-Water and Pore-Water Quality

Surface-water and pore-water quality differences were observed at Taylor and Teal Lakes, and to a lesser extent at North Lake. Differences were observed in onsite water-quality measurements and constituent concentrations. Some of these differences resulted from the presence of ground-water inflow, whereas others resulted from chemical reactions occurring in the surrounding fens and swamps. Specific conductance values for surface water ranged from 47 to 129 $\mu\text{S}/\text{cm}$ (table 6), whereas values for pore water where ground-water inflow occurred ranged from 123 to 504 $\mu\text{S}/\text{cm}$. The low dissolved oxygen and high total ammonia plus organic nitrogen concentrations in most of the pore-water samples indicated that reducing conditions are present along the shores of the three lakes.

Poor ionic balances (large percentage differences in cation and anion concentrations) were found in several pore-

Table 6. Water-quality data for surface water and pore water collected from North Lake area, August 2003 and May 2004, Teal Lake area, September 2003, and Taylor Lake area, August and September 2004, Grand Portage Reservation, northeastern Minnesota.

[mm, millimeter; Hg, mercury; $\mu\text{S}/\text{cm}$ at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; $\mu\text{g}/\text{L}$, micrograms per liter; °C, degrees Celsius; per mil, parts per thousand; <, less than; E, estimated; --, no data; values in blue, surface water; values in red, pore water]

Water-quality sampling site (figs. 3–5)	Site number	Date (month/day/ year)	Time (24-hour)	Sample type	Baromet- ric pres- sure (mm of Hg)	Specific conduc- tance, onsite ($\mu\text{S}/\text{cm}$ at 25 °C)
North Lake, August 2003						
North Lake near Mineral Center	475658089492701	8/26/2003	11:00	Surface water	722	101
Southwest channel (SW)	475656089493301	8/26/2003	14:30	Pore water	722	163
Northwest shore (NW)	475700089493401	8/26/2003	16:00	Pore water	722	126
North shore (N)	475660089493001	8/27/2003	15:00	Pore water	727	124
South shore (S)	475655089492801	8/27/2003	10:30	Pore water	727	157
North Lake, May 2004						
North Lake near Mineral Center	475658089492701	5/18/2004	11:30	Surface water	730	86
Southwest channel (SW)	475656089493301	5/19/2004	13:00	Pore water	730	162
South shore (S)	475655089492801	5/19/2004	12:00	Pore water	730	147
North-northwest shore (NNW)	475702089493602	5/18/2004	16:00	Pore water	730	132
Northeast shore (NE)	475701089492401	5/18/2004	12:30	Pore water	730	136
Southeast shore (SE)	475657089492201	5/19/2004	14:30	Pore water	728	79
Teal Lake, September 2003						
Teal Lake near Grand Portage	475930089392301	9/3/2003	10:30	Surface water	736	129
Northeast shore (NE)	475935089391601	9/3/2003	12:30	Pore water	735	335
North shore (N)	475938089392601	9/4/2003	11:00	Pore water	744	53
Northwest shore (NW)	475935089394101	9/4/2003	12:30	Pore water	743	71
West shore (W)	475931089394401	9/4/2003	13:30	Pore water	743	73
Southwest shore (SW)	475924089394101	9/4/2003	14:30	Pore water	743	72
South-southwest (SSW)	475919089393301	9/4/2003	15:30	Pore water	743	504
Taylor Lake, August and September 2004						
Taylor Lake - east near Mineral Center	475604089492901	8/31/2004	11:30	Surface water	722	47
Taylor Lake - west near Mineral Center	475605089494701	8/31/2004	12:30	Surface water	722	47
North-northeast shore (NNE)	475609089493201	9/1/2004	11:30	Pore water	728	61
Northeast shore (NE)	475609089493001	9/1/2004	10:30	Pore water	727	46
South shore (S)	475601089494801	9/1/2004	13:30	Pore water	728	211
North shore (N)	475608089493701	9/1/2004	12:00	Pore water	728	285
West shore (W)	475609089500001	9/1/2004	15:00	Pore water	728	245
Southeast shore (SE)	475602089493801	9/2/2004	12:30	Pore water	721	74
East shore (E)	475604089492201	9/2/2004	10:30	Pore water	722	123

Table 6. Water-quality data for surface water and pore water collected from North Lake area, August 2003 and May 2004, Teal Lake area, September 2003, and Taylor Lake area, August and September 2004, Grand Portage Reservation, northeastern Minnesota.—Continued

[mm, millimeter; Hg, mercury; $\mu\text{S}/\text{cm}$ at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; $\mu\text{g}/\text{L}$, micrograms per liter; °C, degrees Celsius; per mil, parts per thousand; <, less than; E, estimated; --, no data; values in blue, surface water; values in red, pore water]

Water-quality sampling site (figs. 3–5)	Date (month/ day/ year)	Sample type	Specific conduc- tance, laboratory ($\mu\text{S}/\text{cm}$ at 25 °C)	pH, onsite (standard units)	pH, labora- tory (standard units)	Air tem- perature (°C)	Water tempera- ture (°C)
North Lake, August 2003							
North Lake near Mineral Center	8/26/2003	Surface water	100	7.0	6.8	--	21.9
Southwest channel (SW)	8/26/2003	Pore water	162	6.0	6.4	--	17.7
Northwest shore (NW)	8/26/2003	Pore water	124	6.1	6.5	--	22.9
North shore (N)	8/27/2003	Pore water	116	5.9	6.4	22.0	18.6
South shore (S)	8/27/2003	Pore water	152	5.6	6.4	21.5	18.6
North Lake, May 2004							
North Lake near Mineral Center	5/18/2004	Surface water	94	6.9	6.7	15.0	11.8
Southwest channel (SW)	5/19/2004	Pore water	150	5.8	6.7	24.0	9.9
South shore (S)	5/19/2004	Pore water	137	5.4	6.0	24.5	10.6
North-northwest shore (NNW)	5/18/2004	Pore water	114	5.7	6.5	16.5	13.1
Northeast shore (NE)	5/18/2004	Pore water	139	5.5	6.4	17.0	8.0
Southeast shore (SE)	5/19/2004	Pore water	80	5.8	6.7	20.5	9.6
Teal Lake, September 2003							
Teal Lake near Grand Portage	9/3/2003	Surface water	130	7.1	7.4	18.0	18.8
Northeast shore (NE)	9/3/2003	Pore water	309	5.6	6.9	--	20.2
North shore (N)	9/4/2003	Pore water	E 57	3.6	3.9	17.0	10.8
Northwest shore (NW)	9/4/2003	Pore water	75	3.9	4.2	18.0	13.7
West shore (W)	9/4/2003	Pore water	77	4.5	5.2	20.0	13.2
Southwest shore (SW)	9/4/2003	Pore water	71	5.3	5.8	20.0	14.1
South-southwest (SSW)	9/4/2003	Pore water	490	5.4	6.3	20.0	10.6
Taylor Lake, August and September 2004							
Taylor Lake - east near Mineral Center	8/31/2004	Surface water	48	7.0	7.8	17.5	17.2
Taylor Lake - west near Mineral Center	8/31/2004	Surface water	49	7.3	7.9	17.5	17.1
North-northeast shore (NNE)	9/1/2004	Pore water	62	6.0	6.4	13.5	14.7
Northeast shore (NE)	9/1/2004	Pore water	49	6.4	6.6	13.0	15.1
South shore (S)	9/1/2004	Pore water	152	5.9	6.5	14.0	13.6
North shore (N)	9/1/2004	Pore water	270	5.9	6.3	15.5	16.2
West shore (W)	9/1/2004	Pore water	146	5.7	6.0	14.0	14.2
Southeast shore (SE)	9/2/2004	Pore water	63	6.2	6.3	16.5	14.1
East shore (E)	9/2/2004	Pore water	80	5.6	5.9	15.0	15.1

Table 6. Water-quality data for surface water and pore water collected from North Lake area, August 2003 and May 2004, Teal Lake area, September 2003, and Taylor Lake area, August and September 2004, Grand Portage Reservation, northeastern Minnesota.—
Continued[mm, millimeter; Hg, mercury; $\mu\text{S}/\text{cm}$ at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; $\mu\text{g}/\text{L}$, micrograms per liter; ° C, degrees Celsius; per mil, parts per thousand; <, less than; E, estimated; --, no data; values in blue, surface water; values in red, pore water

Water-quality sampling site (figs. 3–5)	Date (month/day/ year)	Sample type	Dissolved oxygen (mg/L)	Dissolved oxygen (percent saturation)	Dissolved calcium (mg/L as Ca)	Dissolved magnesium (mg/L as Mg)
North Lake, August 2003						
North Lake near Mineral Center	8/26/2003	Surface water	6.3	74	13.6	2.76
Southwest channel (SW)	8/26/2003	Pore water	.2	3	21.6	4.43
Northwest shore (NW)	8/26/2003	Pore water	.6	7	18.1	3.19
North shore (N)	8/27/2003	Pore water	.4	4	15.4	3.12
South shore (S)	8/27/2003	Pore water	.3	3	23.0	2.66
North Lake, May 2004						
North Lake near Mineral Center	5/18/2004	Surface water	7.0	66	14.8	2.42
Southwest channel (SW)	5/19/2004	Pore water	.3	2	24.6	4.89
South shore (S)	5/19/2004	Pore water	.2	2	24.9	2.49
North-northwest shore (NNW)	5/18/2004	Pore water	5.4	52	19.5	3.62
Northeast shore (NE)	5/18/2004	Pore water	.2	2	17.2	5.19
Southeast shore (SE)	5/19/2004	Pore water	.2	1	12.3	2.24
Teal Lake, September 2003						
Teal Lake near Grand Portage	9/3/2003	Surface water	8.5	94	10.1	4.46
Northeast shore (NE)	9/3/2003	Pore water	.6	7	26.6	10.7
North shore (N)	9/4/2003	Pore water	.3	3	2.39	1.27
Northwest shore (NW)	9/4/2003	Pore water	.2	2	2.51	1.62
West shore (W)	9/4/2003	Pore water	.2	2	5.76	2.32
Southwest shore (SW)	9/4/2003	Pore water	1.8	18	11.4	3.64
South-southwest (SSW)	9/4/2003	Pore water	2.1	19	30.4	11.7
Taylor Lake, August and September 2004						
Taylor Lake - east near Mineral Center	8/31/2004	Surface water	8.8	95	6.55	1.46
Taylor Lake - west near Mineral Center	8/31/2004	Surface water	8.6	91	6.58	1.47
North-northeast shore (NNE)	9/1/2004	Pore water	.8	8	8.80	2.20
Northeast shore (NE)	9/1/2004	Pore water	2.9	29	7.07	1.65
South shore (S)	9/1/2004	Pore water	1.8	17	16.2	4.50
North shore (N)	9/1/2004	Pore water	.9	9	30.1	13.4
West shore (W)	9/1/2004	Pore water	.3	3	24.5	4.80
Southeast shore (SE)	9/2/2004	Pore water	1.3	13	11.0	1.83
East shore (E)	9/2/2004	Pore water	.2	2	12.0	2.69

Table 6. Water-quality data for surface water and pore water collected from North Lake area, August 2003 and May 2004, Teal Lake area, September 2003, and Taylor Lake area, August and September 2004, Grand Portage Reservation, northeastern Minnesota.—Continued

[mm, millimeter; Hg, mercury; $\mu\text{S}/\text{cm}$ at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; $\mu\text{g}/\text{L}$, micrograms per liter; °C, degrees Celsius; per mil, parts per thousand; <, less than; E, estimated; --, no data; values in blue, surface water; values in red, pore water]

Water-quality sampling site (figs. 3–5)	Date (month/day/ year)	Sample type	Dissolved sodium (mg/L as Na)	Dis- solved potassi- um (mg/L as K)	Bicarbo- nate, filtered water, on- site (mg/L as HCO_3)	Alkalinity, filtered wa- ter, onsite (mg/L as CaCO_3)	Dissolved sulfate (mg/L as SO_4)
North Lake, August 2003							
North Lake near Mineral Center	8/26/2003	Surface water	0.96	E 0.09	62	51	0.6
Southwest channel (SW)	8/26/2003	Pore water	1.32	.39	92	75	E .1
Northwest shore (NW)	8/26/2003	Pore water	1.00	.18	71	58	.2
North shore (N)	8/27/2003	Pore water	1.06	.24	67	55	.5
South shore (S)	8/27/2003	Pore water	1.15	.40	95	78	.2
North Lake, May 2004							
North Lake near Mineral Center	5/18/2004	Surface water	1.17	< .16	54	44	2.5
Southwest channel (SW)	5/19/2004	Pore water	1.42	.22	93	76	1.4
South shore (S)	5/19/2004	Pore water	1.34	< .16	90	73	< .2
North-northwest shore (NNW)	5/18/2004	Pore water	1.45	< .16	78	64	< .2
Northeast shore (NE)	5/18/2004	Pore water	1.75	.19	86	71	< .2
Southeast shore (SE)	5/19/2004	Pore water	1.04	E.10	49	40	1.2
Teal Lake, September 2003							
Teal Lake near Grand Portage	9/3/2003	Surface water	7.58	.84	28	23	3.6
Northeast shore (NE)	9/3/2003	Pore water	7.75	.97	171	140	.6
North shore (N)	9/4/2003	Pore water	1.03	E .16	0	0	.4
Northwest shore (NW)	9/4/2003	Pore water	3.12	.45	0	0	.3
West shore (W)	9/4/2003	Pore water	4.91	< .16	11	9	E .2
Southwest shore (SW)	9/4/2003	Pore water	2.28	.49	24	20	.7
South-southwest (SSW)	9/4/2003	Pore water	38.7	.65	40	33	2.0
Taylor Lake, August and September 2004							
Taylor Lake - east near Mineral Center	8/31/2004	Surface water	.71	E .12	27	22	.7
Taylor Lake - west near Mineral Center	8/31/2004	Surface water	.65	.17	27	22	.7
North-northeast shore (NNE)	9/1/2004	Pore water	.80	.20	34	28	.2
Northeast shore (NE)	9/1/2004	Pore water	.68	E .12	27	22	.5
South shore (S)	9/1/2004	Pore water	1.32	.77	114	93	.3
North shore (N)	9/1/2004	Pore water	1.75	1.73	188	154	.2
West shore (W)	9/1/2004	Pore water	.25	< .16	136	111	< .9
Southeast shore (SE)	9/2/2004	Pore water	.77	.33	37	31	.31
East shore (E)	9/2/2004	Pore water	1.14	<.16	54	44	E .1

Table 6. Water-quality data for surface water and pore water collected from North Lake area, August 2003 and May 2004, Teal Lake area, September 2003, and Taylor Lake area, August and September 2004, Grand Portage Reservation, northeastern Minnesota.—Continued

[mm, millimeter; Hg, mercury; $\mu\text{S}/\text{cm}$ at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; $\mu\text{g}/\text{L}$, micrograms per liter; ° C, degrees Celsius; per mil, parts per thousand; <, less than; E, estimated; --, no data; values in blue, surface water; values in red, pore water]

Water-quality sampling site (figs. 3–5)	Date (month/day/ year)	Sample type	Dissolved chloride (mg/L as Cl)	Dissolved fluoride (mg/L as F)	Dissolved bromide ($\mu\text{g}/\text{L}$ as Br)	Dissolved silica (mg/L as SiO_2)
North Lake, August 2003						
North Lake near Mineral Center	8/26/2003	Surface water	E 0.12	< 0.2	--	7.02
Southwest channel (SW)	8/26/2003	Pore water	.43	< .2	--	22.6
Northwest shore (NW)	8/26/2003	Pore water	E .15	< .2	--	23.3
North shore (N)	8/27/2003	Pore water	E .19	< .2	--	17.3
South shore (S)	8/27/2003	Pore water	.35	< .2	--	27.9
North Lake, May 2004						
North Lake near Mineral Center	5/18/2004	Surface water	.25	< .2	--	6.16
Southwest channel (SW)	5/19/2004	Pore water	.48	< .2	0.03	13.9
South shore (S)	5/19/2004	Pore water	E .12	< .2	.05	19.4
North-northwest shore (NNW)	5/18/2004	Pore water	.65	< .2	.37	16.3
Northeast shore (NE)	5/18/2004	Pore water	.22	< .2	.02	31.3
Southeast shore (SE)	5/19/2004	Pore water	E .12	< .2	< .02	10.4
Teal Lake, September 2003						
Teal Lake near Grand Portage	9/3/2003	Surface water	19.6	< .2	--	.74
Northeast shore (NE)	9/3/2003	Pore water	14.6	< .2	E .12	44.4
North shore (N)	9/4/2003	Pore water	.89	< .2	E .38	16.8
Northwest shore (NW)	9/4/2003	Pore water	12.3	< .2	--	3.89
West shore (W)	9/4/2003	Pore water	12.1	< .2	--	4.74
Southwest shore (SW)	9/4/2003	Pore water	4.50	< .2	E .17	8.09
South-southwest (SSW)	9/4/2003	Pore water	125	< .2	--	15.0
Taylor Lake, August and September 2004						
Taylor Lake - east near Mineral Center	8/31/2004	Surface water	< .20	< .2	--	.93
Taylor Lake - west near Mineral Center	8/31/2004	Surface water	E .10	< .2	--	.92
North-northeast shore (NNE)	9/1/2004	Pore water	< .20	< .2	.08	2.80
Northeast shore (NE)	9/1/2004	Pore water	< .20	< .2	< .02	1.89
South shore (S)	9/1/2004	Pore water	.67	< .2	.49	19.0
North shore (N)	9/1/2004	Pore water	.36	< .2	< .80	29.2
West shore (W)	9/1/2004	Pore water	< .20	< .2	.73	27.3
Southeast shore (SE)	9/2/2004	Pore water	.26	< .2	.08	3.30
East shore (E)	9/2/2004	Pore water	E .16	< .2	.35	5.82

Table 6. Water-quality data for surface water and pore water collected from North Lake area, August 2003 and May 2004, Teal Lake area, September 2003, and Taylor Lake area, August and September 2004, Grand Portage Reservation, northeastern Minnesota.—Continued

[mm, millimeter; Hg, mercury; $\mu\text{S}/\text{cm}$ at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; $\mu\text{g}/\text{L}$, micrograms per liter; °C, degrees Celsius; per mil, parts per thousand; <, less than; E, estimated; --, no data; values in blue, surface water; values in red, pore water]

Water-quality sampling site (figs. 3–5)	Date (month/day/ year)	Sample type	Dissolved nitrite nitrogen (mg/L as N)	Dissolved nitrite and nitrate nitrogen (mg/L as N)	Dissolved ammonia nitrogen (mg/L as N)	Total am- monia plus organic nitrogen (mg/L as N)	Dissolved organic nitrogen (mg/L as N) ¹
North Lake, August 2003							
North Lake near Mineral Center	8/26/2003	Surface water	< 0.008	< 0.06	< 0.04	0.65	¹ 0.65
Southwest channel (SW)	8/26/2003	Pore water	< .008	< .06	2.48	2.9	¹ 4.1
Northwest shore (NW)	8/26/2003	Pore water	< .008	< .06	1.05	1.5	¹ 4.8
North shore (N)	8/27/2003	Pore water	< .008	< .06	1.95	2.6	¹ 6.1
South shore (S)	8/27/2003	Pore water	< .008	< .06	2.76	3.4	¹ 5.9
North Lake, May 2004							
North Lake near Mineral Center	5/18/2004	Surface water	< .008	< .06	E .02	¹ 3.1	¹ 2.9
Southwest channel (SW)	5/19/2004	Pore water	< .008	< .06	.24	¹ 5.2	¹ 2.8
South shore (S)	5/19/2004	Pore water	< .008	< .06	.76	¹ 1.2	¹ 4.39
North-northwest shore (NNW)	5/18/2004	Pore water	< .008	< .06	.12	¹ 1.0	¹ 9.2
Northeast shore (NE)	5/18/2004	Pore water	< .008	< .06	2.19	¹ 2.4	¹ 2.4
Southeast shore (SE)	5/19/2004	Pore water	< .008	< .06	.12	¹ 3.2	¹ 2.0
Teal Lake, September 2003							
Teal Lake near Grand Portage	9/3/2003	Surface water	< .008	< .06	< .04	.76	¹ 7.6
Northeast shore (NE)	9/3/2003	Pore water	< .008	< .06	8.85	11	¹ 2.2
North shore (N)	9/4/2003	Pore water	.018	< .12	1.05	2.2	¹ 1.1
Northwest shore (NW)	9/4/2003	Pore water	E .005	< .06	.84	1.5	¹ 6.6
West shore (W)	9/4/2003	Pore water	E .005	< .06	.06	.66	¹ 6.0
Southwest shore (SW)	9/4/2003	Pore water	E .015	< .12	.97	2.1	¹ 1.2
South-southwest (SSW)	9/4/2003	Pore water	< .008	< .06	1.16	1.8	¹ 5.9
Taylor Lake, August and September 2004							
Taylor Lake - east near Mineral Center	8/31/2004	Surface water	< .008	< .06	< .04	.33	¹ 3.3
Taylor Lake - west near Mineral Center	8/31/2004	Surface water	< .008	< .06	< .05	.33	¹ 3.3
North-northeast shore (NNE)	9/1/2004	Pore water	< .008	< .06	< .06	1.50	¹ 4.4
Northeast shore (NE)	9/1/2004	Pore water	< .008	< .06	< .07	1.43	¹ 4.1
South shore (S)	9/1/2004	Pore water	.012	< .06	< .08	14.4	¹ 4.4
North shore (N)	9/1/2004	Pore water	< .008	< .06	< .09	13.0	.62
West shore (W)	9/1/2004	Pore water	E .004	< .06	< .10	1.82	¹ 8.2
Southeast shore (SE)	9/2/2004	Pore water	< .008	< .06	< .11	1.70	¹ 4.8
East shore (E)	9/2/2004	Pore water	.01	< .06	< .12	11.2	¹ 9.5

Table 6. Water-quality data for surface water and pore water collected from North Lake area, August 2003 and May 2004, Teal Lake area, September 2003, and Taylor Lake area, August and September 2004, Grand Portage Reservation, northeastern Minnesota.— Continued

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Water-quality sampling site (figs. 3–5)	Date (month/day/ year)	Sample type	Total nitrogen (mg/L as N)	Total phospho- rus (mg/L as P)	Dissolved phosphate (mg/L as P)	Dissolved orthophos- phorus (mg/L as P)
North Lake, August 2003						
North Lake near Mineral Center	8/26/2003	Surface water	1.65	0.012	E 0.004	< 0.02
Southwest channel (SW)	8/26/2003	Pore water	2.89	--	.099	.07
Northwest shore (NW)	8/26/2003	Pore water	1.53	--	.018	E .01
North shore (N)	8/27/2003	Pore water	2.56	--	.211	.19
South shore (S)	8/27/2003	Pore water	3.35	--	.240	.21
North Lake, May 2004						
North Lake near Mineral Center	5/18/2004	Surface water	1.31	.007	E .003	< .02
Southwest channel (SW)	5/19/2004	Pore water	.52	--	.021	.02
South shore (S)	5/19/2004	Pore water	1.2	--	.027	.02
North-northwest shore (NNW)	5/18/2004	Pore water	1.0	--	.027	.01
Northeast shore (NE)	5/18/2004	Pore water	2.4	--	.123	.11
Southeast shore (SE)	5/19/2004	Pore water	.32	--	.004	< .02
Teal Lake, September 2003						
Teal Lake near Grand Portage	9/3/2003	Surface water	1.76	.010	E .003	< .02
Northeast shore (NE)	9/3/2003	Pore water	11.0	--	.802	.79
North shore (N)	9/4/2003	Pore water	2.18	--	.148	.12
Northwest shore (NW)	9/4/2003	Pore water	1.51	--	.099	.08
West shore (W)	9/4/2003	Pore water	1.67	--	.029	.02
Southwest shore (SW)	9/4/2003	Pore water	2.14	--	.145	.12
South-southwest (SSW)	9/4/2003	Pore water	1.75	--	.051	.04
Taylor Lake, August and September 2004						
Taylor Lake - east near Mineral Center	8/31/2004	Surface water	1.33	.011	.005	<.02
Taylor Lake - west near Mineral Center	8/31/2004	Surface water	1.33	.010	E .003	<.02
North-northeast shore (NNE)	9/1/2004	Pore water	.50	--	.015	.01
Northeast shore (NE)	9/1/2004	Pore water	.43	--	.010	< .02
South shore (S)	9/1/2004	Pore water	4.42	--	.323	.40
North shore (N)	9/1/2004	Pore water	2.97	--	.521	.02
West shore (W)	9/1/2004	Pore water	.82	--	.045	.04
Southeast shore (SE)	9/2/2004	Pore water	.70	--	.053	.04
East shore (E)	9/2/2004	Pore water	1.20	--	.099	.08

Table 6. Water-quality data for surface water and pore water collected from North Lake area, August 2003 and May 2004, Teal Lake area, September 2003, and Taylor Lake area, August and September 2004, Grand Portage Reservation, northeastern Minnesota.—
Continued

[mm, millimeter; Hg, mercury; $\mu\text{S}/\text{cm}$ at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; $\mu\text{g}/\text{L}$, micrograms per liter; ° C, degrees Celsius; per mil, parts per thousand; <, less than; E, estimated; --, no data; values in blue, surface water; values in red, pore water]

Water-quality sampling site (figs. 3–5)	Date (month/ day/year)	Sample type	Dissolved boron ($\mu\text{g}/\text{L}$ as B)	Dis- solved iron ($\mu\text{g}/\text{L}$ as Fe)	Dis- solved manga- nese ($\mu\text{g}/\text{L}$ as Mn)	Ionic balance (per- centage differ- ence) ²	Oxy- gen-18/ oxygen- 16 ratio, unfiltered water, per mil	Deute- rium/ protium ratio, unfiltered water, per mil
North Lake, August 2003								
North Lake near Mineral Center	8/26/2003	Surface water	9.6	100	1.50	-3.9	-7.22	-62.10
Southwest channel (SW)	8/26/2003	Pore water	16	1,030	27.5	1.7	-9.31	-72.20
Northwest shore (NW)	8/26/2003	Pore water	16	931	33.0	4.2	-7.88	-66.10
North shore (N)	8/27/2003	Pore water	15	951	20.9	.9	-7.56	-63.20
South shore (S)	8/27/2003	Pore water	24	1,580	49.8	-1.9	-8.95	-70.90
North Lake, May 2004								
North Lake near Mineral Center	5/18/2004	Surface water	E 6.3	32	E .7	2.7	-11.12	-80.80
Southwest channel (SW)	5/19/2004	Pore water	E 5.2	581	30.6	5.2	-9.58	-73.10
South shore (S)	5/19/2004	Pore water	7.5	1,040	65.1	3.5	-8.79	-67.40
North-northwest shore (NNW)	5/18/2004	Pore water	< 7.0	11,800	638	21.1	-8.16	-67.90
Northeast shore (NE)	5/18/2004	Pore water	14	636	20.9	-.8	-10.75	-77.60
Southeast shore (SE)	5/19/2004	Pore water	E 5.7	329	5.4	2.2	-12.14	-84.80
Teal Lake, September 2003								
Teal Lake near Grand Portage	9/3/2003	Surface water	11	43	< .4	5.9	-5.01	-50.3
Northeast shore (NE)	9/3/2003	Pore water	18	2,480	63.0	-8.6	-8.44	-68.5
North shore (N)	9/4/2003	Pore water	E 5.6	563	5.9	80	-11.02	-72.2
Northwest shore (NW)	9/4/2003	Pore water	7.5	483	13.0	9.9	-8.48	-63.9
West shore (W)	9/4/2003	Pore water	E 6.6	186	2.3	15	-7.25	-59.8
Southwest shore (SW)	9/4/2003	Pore water	E 6.5	319	3.7	30	-9.97	-70
South-southwest (SSW)	9/4/2003	Pore water	15	1,400	34.5	.4	-11.31	-78.2
Taylor Lake, August and September 2004								
Taylor Lake - east near Mineral Center	8/31/2004	Surface water	E 5.6	46	< .8	2.5	-5.82	-57.80
Taylor Lake - west near Mineral Center	8/31/2004	Surface water	E 5.8	38	< .8	2.6	-5.92	-57.40
North-northeast shore (NNE)	9/1/2004	Pore water	E 4.0	1,930	94.2	16	-6.01	-58.00
Northeast shore (NE)	9/1/2004	Pore water	E 4.8	303	41.4	8.7	-6.02	-58.40
South shore (S)	9/1/2004	Pore water	< 21	17,600	287	8.1	-8.12	-67.00
North shore (N)	9/1/2004	Pore water	< 35	31,200	541	18	-7.10	-61.70
West shore (W)	9/1/2004	Pore water	< 7.0	35,400	345	23	-6.84	-62.30
Southeast shore (SE)	9/2/2004	Pore water	E 5.7	1,240	95.3	13	-6.30	-59.10
East shore (E)	9/2/2004	Pore water	E 4.5	9,430	130	22	-6.50	-60.10

¹Estimated from the concentrations of other nitrogen constituents.

²Represents percentage difference between total cation and total anion concentrations.

water samples from the North, Teal, and Taylor Lake areas (table 6). These poor ionic balances were all positive, indicating that the total cation concentrations were greater than the total anion concentrations. These high percentage differences indicate that either the samples were not in equilibrium during sampling, biases occurred during analysis, or anions that are major contributors to the overall major constituent chemistry of the water were not measured. For some of the pore-water samples with poor ionic balances, dissolved oxygen concentrations were relatively high, indicating that some water from the lake may have been drawn into the sampling tube during sample collection. The mixing of drawn-in surface water and pore water in the sampled water could result in a state of chemical disequilibrium in the sample, potentially causing problems with the ionic balance. The smell of hydrogen sulfide gas was noted during the collection of some pore-water samples at the three lakes. The loss of sulfate ions in the water because of the production of hydrogen sulfide gas and other non-gaseous, sulfide complexes could be responsible for poor ionic balances in the water samples. Concentrations of hydrogen sulfide gas and non-gaseous, sulfide complexes were not measured onsite or in the collected water samples.

North Lake

One surface-water sample and four pore-water samples were collected in August 2003, and one surface-water sample and five pore-water samples were collected in May 2004 at North Lake (table 6). The surface-water samples were collected in the east-central part of the lake, whereas pore-water samples were collected at various locations along the shore (fig. 3). Most of the pore-water samples were collected near locations where cooler lake-sediment temperatures were measured.

Specific conductance values for the surface- and pore-water samples from the North Lake area were all less than 200 $\mu\text{S}/\text{cm}$ (table 6). Specific conductance values for the southwest channel and south shore pore-water samples collected in August 2003 and May 2004 were the highest of all of the samples collected. The higher pH values for surface water may be caused by chemical reactions and biological activity in the lake. pH values for the pore water were within the pH range for water in *Picea mariana* (black spruce) stands of northwestern Minnesota alkaline peatlands (Bares and Wali, 1979). Water temperatures of pore water sampled in August 2003 and May 2004 were all cooler than the surface-water samples, except for pore-water temperatures from the northwest and north-northwest shores, which were similar to temperature data collected for North Lake surface water. Surface water in North Lake generally had lower specific conductance values, higher onsite pH values, and higher dissolved oxygen concentrations than pore water collected from the area (table 6). The dissolved oxygen concentrations for the pore-water samples were all less than 0.7 mg/L, except for the pore-water sample collected from the north-northwest shore in May 2004. The water temperature and dissolved oxygen con-

centration for the north-northwest pore-water sample collected in May 2004 were much higher than the other pore-water samples collected in May 2004 (table 6).

Surface-water alkalinity and bicarbonate values were less than most pore-water values, with the exception of the pore-water sample from the southeast shore collected in May 2004. Specific conductance, alkalinity, and bicarbonate values for the southeast shore pore-water sample were slightly less than the surface-water values. However, pH values and dissolved oxygen concentrations for the southeast shore pore-water sample were much less than surface-water values and concentrations (table 6). Alkalinity and bicarbonate values for the pore-water samples collected from the northwest and north shores in August 2004 were only slightly more than values for the surface-water sample, with low dissolved oxygen concentrations (table 6).

Total nitrogen and dissolved phosphorus concentrations in surface water were less than in pore-water samples, with notable variability in nitrogen concentrations among the pore-water samples (table 6). Measurable concentrations of total nitrogen in surface water consisted only of dissolved organic nitrogen, whereas total nitrogen in pore water consisted of total ammonia plus organic nitrogen. Total ammonia plus organic nitrogen concentrations were greater than 1.0 mg/L for all of the pore-water samples collected in August 2003 (table 6), indicating reduced conditions in the lake sediment. In May 2004, total ammonia plus organic nitrogen concentrations were greater in pore-water samples from the south and northeast shores than in the other pore-water samples (table 6). Total nitrogen and ammonia plus nitrogen concentrations were less than 0.60 mg/L as nitrogen for the southwest channel and southeast shore pore-water samples collected in May 2004, which is equal to or less than one-half of the total nitrogen concentrations in the other pore-water samples (table 6). In August 2003, the total nitrogen concentration in southwest channel pore water was higher, 2.9 mg/L as nitrogen. In general, total nitrogen and phosphorus concentrations in pore-water samples collected in May 2004 were less than in pore-water samples collected in August 2003. This decrease in concentrations is likely because of the flushing of spring snowmelt water through the lake sediment.

The percentage differences between the total cation and anion concentrations for the surface-water and pore-water samples from the North Lake area were between -5 and +5 percent for the surface-water samples and for eight of the nine pore-water samples (table 6). The difference in the ionic balance for the May 2004 pore-water sample collected from the north-northwest shore was +21.1 percent, with the positive difference indicating higher total cation concentration than total anion concentration. A sulfate concentration below the detection level and a strong hydrogen-sulfide smell during sampling indicate an underestimate of the total sulfur concentration, resulting in the highly positive ionic balance difference. The total sulfur concentrations may include sulfate, hydrogen sulfide gas, and other non-gaseous, sulfide complexes. The small difference between onsite and

laboratory specific conductance values for the north-northwest pore-water sample (table 6) indicates that the sampled water may have been in chemical disequilibrium when sampled and that changes in the dissolved major constituent concentrations could have occurred between the time of onsite water-quality measurement and sample collection and (or) analysis. At surface-water outseepage locations, chemical disequilibrium may be a common occurrence as oxygenated surface water seeps into low-oxygenated pore water.

Differences in major constituent concentrations were small between the surface water and pore water in the North Lake area relative to differences observed in the Teal and Taylor Lake areas (figs. 7 and 8, table 6). Both the surface water and pore water in the North Lake area are a predominantly calcium bicarbonate type, with large calcium and bicarbonate concentrations in most of the pore-water samples (figs. 7 and 8). The only exception was the pore-water sample collected along the southeast shore in May 2004. The calcium and bicarbonate concentrations in this sample were less than in the surface-water samples for both August 2003 and May 2004 (table 6). Calcium concentrations in the pore water ranged from 12 to 25 mg/L as calcium, with concentrations of 14 and 15 mg/L as calcium in the surface water. Pore water from the south shore and southwest channel sampled in August 2003 and May 2004 had the highest calcium and bicarbonate concentrations and indicates potential locations for ground-water inflow (fig. 8). Pore water from the northwest shore sampled in August 2003 and from the north-northwest shore sampled in May 2004 was only slightly higher in calcium and bicarbonate concentrations than the surface water (fig. 8, table 6). The distribution of cation and anion concentrations in the surface-water sample for North Lake (fig. 8) was very similar to the distribution for surface-water samples from Swamp Lake (fig. 1) collected by Winterstein (2000) and presented in Winterstein (2002).

Dissolved chloride concentrations were less than 0.7 mg/L for all of the surface-water and pore-water samples (table 6). The low specific conductance values and chloride concentrations of the pore water indicated that the residence time of the water likely is small or that the parent materials are highly resistant to dissolution, with the lake water obtained from local sources.

Dissolved silica, iron, and manganese concentrations were higher in all of the pore-water samples than in the surface-water samples from the North Lake area, being notably higher in the south pore-water samples collected in August 2003 and May 2004 and the north-northwest pore-water sample collected in May 2004 (table 6). Dissolved silica concentrations ranged from 6.2 to 7.0 mg/L in the two surface-water samples and from 10 to 31 mg/L in pore water. In seven of the nine pore-water samples, both dissolved iron and manganese concentrations were an order of magnitude higher than concentrations in the surface-water samples (table 6). Similar to total nitrogen and phosphorus concentrations, dissolved boron concentrations in the pore-water samples were lower in May 2004 than in pore-water samples in August 2003, with

concentrations in the August 2003 pore-water samples higher than in the surface-water sample. The flushing of spring snowmelt water through the lake sediment is the likely cause for these concentration reductions.

Oxygen-18/oxygen-16 and deuterium/protium ratios for surface-water and pore-water samples collected in the North Lake area in August 2003 and May 2004 lie along an evaporation line with a slope of 4.6 and a y-intercept of -29.4 (fig. 6B). For the August 2003 samples, the most evaporative signature was for the surface-water sample collected at North Lake because the oxygen-18/oxygen-16 and deuterium/protium ratios lie the farthest from the meteoric waterline relative to other samples (fig. 6B). This is to be expected because evaporation rates are high off the lake surface in the summer, increasing the stable isotope ratios over time. In May 2004, the surface water had an isotopic composition that plotted close to the meteoric waterline (fig. 6B), along a portion of the line where late winter and early spring precipitation from northern Wisconsin plotted (Krabbenhoft and others, 1994). Snowmelt water that entered the lake in late April and early May likely had lower oxygen-18/oxygen-16 and deuterium/protium ratios and was a major contributor to the spring water budget of the small, shallow lake. The isotopic ratios for the August 2003 and May 2004 pore-water samples collected along the north and northeast shores, respectively, were similar to the ratios for the August 2003 and May 2004 surface-water samples, respectively (fig. 6B), potentially indicating surface-water outseepage at those locations.

The least evaporative signature for the August 2003 samples is for the southwest channel sample, falling closer to the meteoric waterline than the other pore-water samples (fig. 6B). However, the oxygen-18/oxygen-16 and deuterium/protium ratios for this sample do not fall along the meteoric waterline, indicating that some evaporation, probably from an upgradient wetland or lake, affected the water contributed to the lake at that location. The stable isotope ratios for samples collected in August 2003 and May 2004 at the southwest channel are very similar, indicating a relatively constant isotopic composition over time (fig. 6B). This temporal conservative nature also can be seen in the south, northwest, and north-northwest pore-water samples, but these samples have a more evaporative signature than the southwest channel sample (fig. 6B).

Teal Lake

One surface-water sample and six pore-water samples were collected in September 2003 from the Teal Lake area (table 6). The surface-water sample was collected just east of the center of the lake, and pore-water samples were collected at various locations along the shore (fig. 4). Pore-water samples collected along the northwest, west, southwest, and south-southwest shores were located at or near drainage channels identified in the analyses of existing aerial photographs (fig. 4). No pore-water samples were collected along the southeast shore of Teal Lake because no lake-sediment temperature data were collected along that part of the lakeshore.

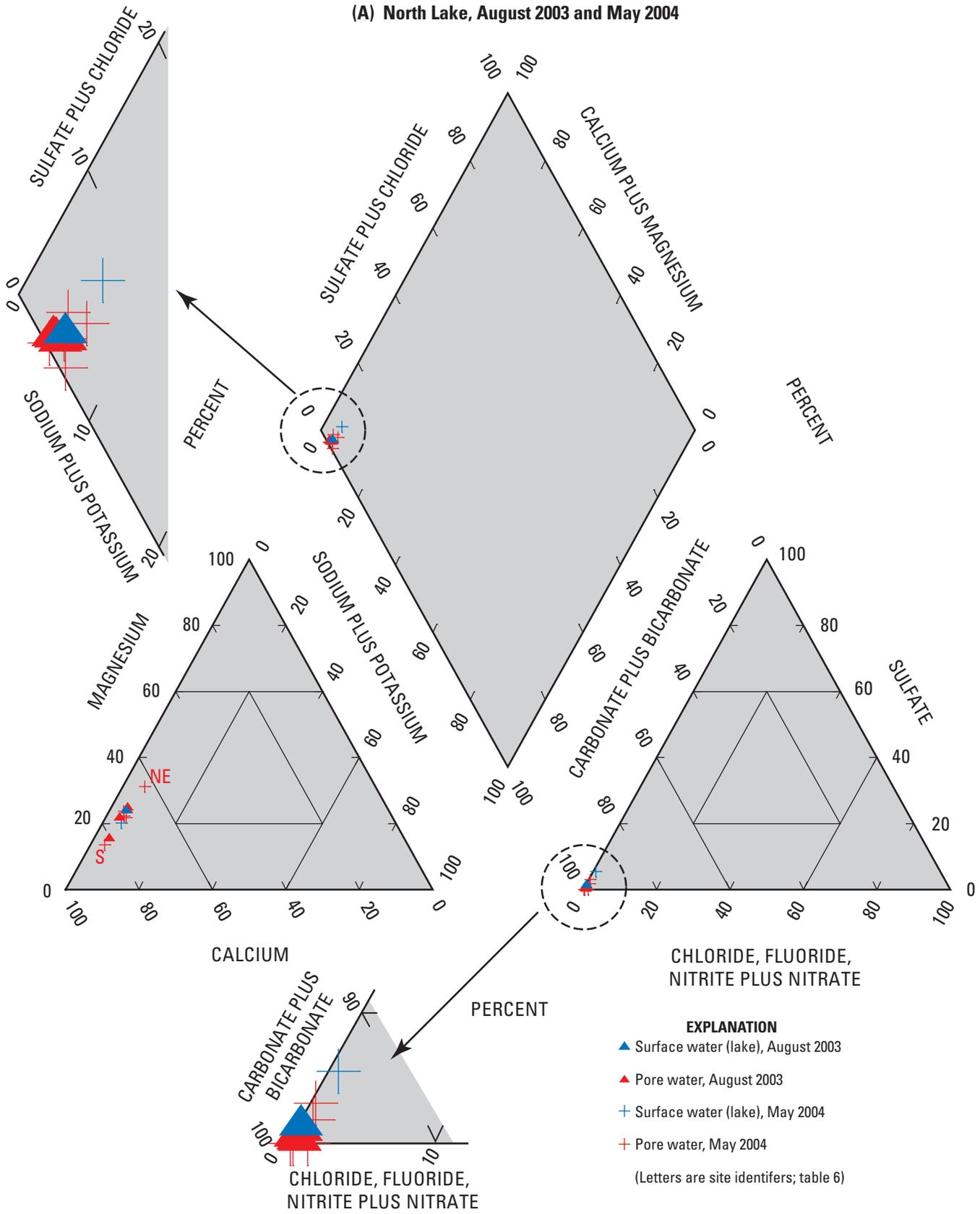


Figure 7. Percentage distribution of major ion concentrations determined for surface water and pore water sampled from (A) North Lake, August 2003 and May 2004, (B) Teal Lake, September 2003, and Taylor Lake, August and September 2004, Grand Portage Reservation, northeastern Minnesota.

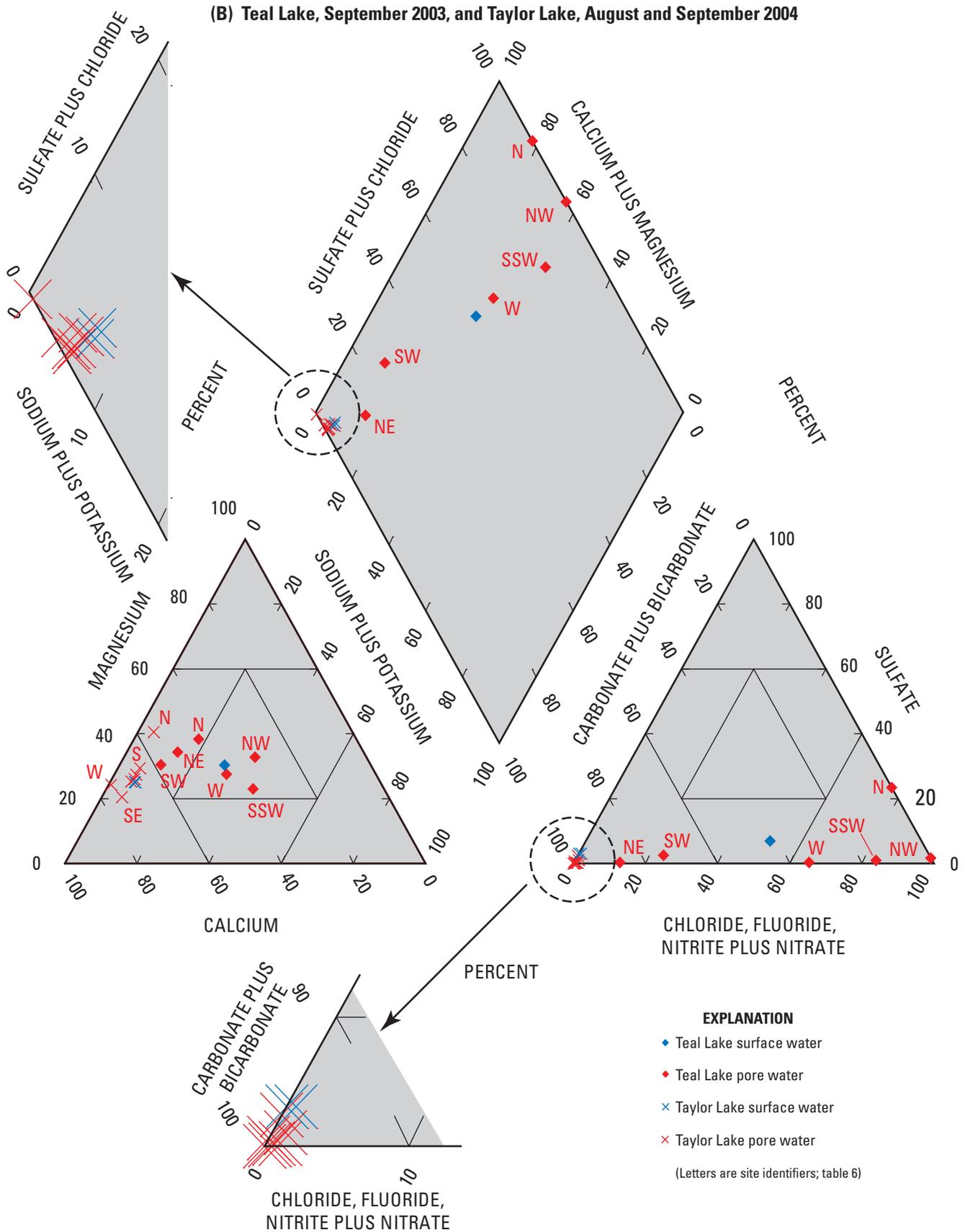


Figure 7. Percentage distribution of major ion concentrations determined for surface water and pore water sampled from (A) North Lake, August 2003 and May 2004, (B) Teal Lake, September 2003, and Taylor Lake, August and September 2004, Grand Portage Reservation, northeastern Minnesota.—Continued

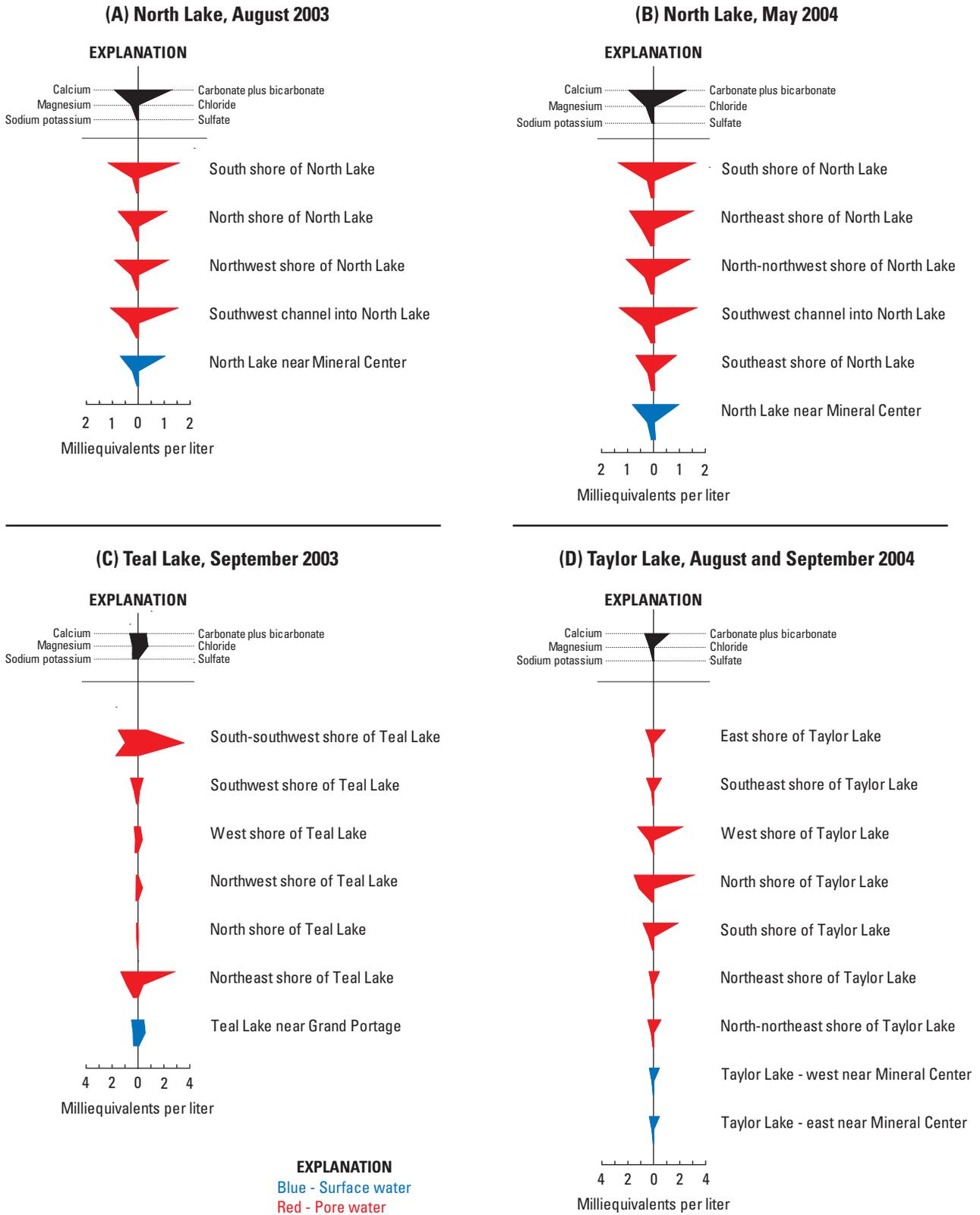


Figure 8. Concentrations of cations and anions in surface water and pore water sampled from (A) North Lake, August 2003, (B) North Lake, May 2004, (C) Teal Lake, September 2003, and (D) Taylor Lake, August and September 2004, Grand Portage Reservation, northeastern Minnesota.

The specific conductance value for the surface-water sample was 129 $\mu\text{S}/\text{cm}$. Specific conductance values for the pore-water samples ranged widely from 53 to 504 $\mu\text{S}/\text{cm}$ (table 6). The lowest values occurred in pore-water samples from along the north, northwest, west, and southwest shores, with all of the values less than 75 $\mu\text{S}/\text{cm}$. Alkalinity values for these four samples were less than 21 mg/L as calcium carbonate. The highest specific conductance values occurred in the northeast and south-southwest pore-water samples, with values of 335 and 504 $\mu\text{S}/\text{cm}$, respectively.

The pH values for the pore-water samples were lower than the surface-water value for Teal Lake. The pH for the surface-water sample from Teal Lake (7.1 standard units) was similar to the surface-water samples collected at North Lake (table 6), whereas pH values for the pore-water samples tended to be divided into two pH ranges. Pore-water samples collected along the northeast, southwest, and south-southwest shores had pH values ranging from 5.3 to 5.6 standard units, which were similar to values for pore-water samples from the North Lake area and values determined by Bares and Wali (1979) for water in *Picea mariana* (black spruce) stands of northwestern Minnesota alkaline peatlands. Pore-water samples collected along the north, northwest, and west shores had pH values ranging from 3.6 to 4.5 standard units (table 6).

The low specific conductance and low pH values for the north, northwest, and west pore-water samples likely are associated with the well-developed fen along these shores, which has high organic content (fig. 4). As organic content increases with fen development, the capacity of the soil to adsorb and exchange cations increases, resulting in sharp declines in cation concentrations and leading to a dominance of hydrogen ions in pore water (Mitsch and Gosselink, 1993). Any ground water flowing into the fen environment has ionic strengths too low to increase the low pH conditions in the pore water. These processes result in low specific conductance and pH values in the pore water. Wilde and Randall (1951) found similar low specific conductance and pH values for black spruce/tamarack bog water in Wisconsin. Pore water in poor (low-mineral input) fens in northern Minnesota tend to have similar low pH values and low calcium concentrations (Glaser, 1992).

Water temperatures for the pore-water samples were notably colder than for the surface-water sample from Teal Lake, except for the pore-water sample collected along the northeast shore (table 6). The water temperature for the northeast pore-water sample was 20.2 °C, 1.4 °C higher than the water temperature of the surface-water sample. Temperatures for the other pore-water samples ranged from 10.6 to 14.1 °C. The warmer water temperature for the northeast pore-water sample is similar to other relatively warm lake-sediment temperatures measured along the northeast shore (fig. 4).

Dissolved oxygen concentrations for the pore-water samples were much lower than the concentration in the surface-water sample, with values ranging from 0.2 to 2.1 mg/L (table 6). Concentrations for the southwest and south-southwest pore-water samples are notably higher than concentrations for the other pore-water samples, indicating that a

small volume of surface water may have been drawn through the sediment and into the sampling tube during sampling.

Total nitrogen and phosphorus concentrations were higher in the pore-water samples than in the surface-water sample from the Teal Lake area, with the exception of the west pore-water sample (table 6). The total nitrogen and total ammonia plus organic nitrogen concentrations for the west pore-water sample were similar to concentrations present in the surface-water sample. As with the North Lake pore-water samples, dissolved nitrogen in the surface water consisted only of dissolved organic nitrogen, whereas dissolved nitrogen in the pore water consisted mainly of total ammonia plus organic nitrogen. Pore-water sampled from the northeast shore had much higher total nitrogen and total ammonia plus organic nitrogen concentrations than the other pore-water samples (table 6). These high concentrations may be associated with the presence of detritus and decomposition associated with a beaver dam at that location (Naiman and others, 1994).

The major constituent chemistry of the pore water at Teal Lake varied substantially because of chemical reactions occurring in the surrounding fens and swamps. Percentage differences for ionic balances were greater than 10 percent for the north, west, and southwest pore-water samples, whereas percentage differences for the other pore-water samples and the surface-water sample were between -10 and +10 percent (table 6). The ionic balances for the north, west, and southwest pore-water samples are positive, indicating that the total cation concentrations are greater than the total anion concentrations. Similar to the May 2004 north-northwest pore-water sample from the North Lake area, the low sulfate concentrations and strong hydrogen-sulfide smell during sampling indicate an underestimate of the total sulfur concentrations under unstable, changing chemical conditions.

Dissolved calcium, magnesium, sodium, sulfate, and chloride concentrations in pore-water samples collected along the north, northwest, west, and southwest shores were lower or similar to concentrations in the Teal Lake surface-water sample (fig. 8, table 6). The low calcium, magnesium, and sodium concentrations in the north, northwest, and west pore-water samples, and to a lesser extent the southwest pore-water sample, are likely a result of cation exchanges with hydrogen ions, cation adsorption, and chelation occurring in the fen surrounding the lake as discussed earlier (Mitsch and Gosselink, 1993). Dissolved silica, iron, and manganese concentrations were higher in pore-water samples than in the surface-water sample (table 6). These ions are less likely to be exchanged with other ions in the fen soils and, therefore, would be expected to be more concentrated in the pore water. The low sulfate concentrations are likely a result of the conversion of sulfate to hydrogen sulfide gas and other non-gaseous, sulfide complexes. The low chloride concentrations along the north and southwest shores indicate that dilution may be causing the lower cation and anion concentrations at these locations.

Major chemical constituents are widely disseminated in the pore water of the Teal Lake area, with the major constituent chemistry of the surface-water sample being generally a

mix of the chemistry of all of the pore-water samples (figs. 7 and 8). The southwest and northeast pore-water samples are generally calcium magnesium bicarbonate water, with major constituent concentrations much higher in the northeast pore-water sample (table 6). Of all the Teal Lake pore-water samples, the major constituent chemistry of the northeast pore-water sample was most similar to major constituent chemistry of the North Lake pore-water samples (figs. 7 and 8). South-southwest, west, north, and northwest pore-water samples consisted of a mixture of calcium, magnesium, and sodium, with chloride being the dominant anion (figs. 7 and 8). Of these four samples, iron, manganese, and boron concentrations are notably higher in the south-southwest pore-water sample. This sample was collected at an upwelling spring where iron-oxide precipitates were present in a channel bottom upgradient of the spring. The relatively high chloride and boron concentrations in the pore-water sample from the south-southwest shore were much lower than concentrations measured by Allen and others (1997) and Tipping and Allen (1997) in ground water of the North Shore Volcanics Group. The west pore-water sample was the most similar in major constituent chemistry to the surface-water sample collected at Teal Lake (fig. 7). The percentage distributions of cations for the southwest, northeast, and north pore-water samples were similar to the cation distribution for rock samples collected from the diabase dike at the Grand Portage National Monument (Laurel Woodruff, U.S. Geological Survey, oral commun., March 8, 2005).

Oxygen-18/oxygen-16 and deuterium/protium ratios for surface-water and pore-water samples collected from the Teal Lake area lie along an evaporation line with a slope of 3.9 and a y-intercept of -31.8 (fig. 6C). The most evaporative signature was for the surface-water sample (fig. 6C). The pore-water samples collected along the south-southwest, north, and southwest shores had isotopic compositions that lie closest to the meteoric waterline (fig. 6C). These samples lie along portions of the meteoric waterline where spring precipitation isotope ratios for northern Wisconsin plotted, indicating that the ground water potentially discharging to these shores entered the ground-water system from spring recharge. Oxygen-18/oxygen-16 and deuterium/protium ratios for the northeast, northwest, and west pore-water samples lie along the evaporation line between the surface-water sample ratio and the meteoric waterline (fig. 6C).

Taylor Lake

Two surface-water samples and seven pore-water samples were collected in August 2004 from the Taylor Lake area (table 6). The surface-water samples were collected in the southeast and west-central parts of the lake (fig. 5). Only minor differences occurred in the water chemistry of the two surface-water samples (table 6). Pore-water samples were collected at various locations along the lakeshore (fig. 5).

Obtaining representative samples for the pore water was difficult in many shore locations of Taylor Lake because lake sediment was thin. Similar to the thermocouple probe, the

stainless-steel sampling tube could not be driven into lake sediment along the northeast, north, east, and southeast shores of Taylor Lake because the lake bottom consisted only of logs, boulders, gravels, and bedrock. Therefore, no pore-water samples were collected at those locations. Where present, lake sediment was generally less than 2.0 ft thick along the shores (table 5). As a result, the stainless-steel sampling tube could penetrate only to relatively shallow depths in the sediment at many of the sampling locations. During initial attempts to collect pore-water samples along the north-northeast and northeast shores, the specific conductance decreased and dissolved oxygen concentrations increased during pumping to values similar to the surface water. These results indicate that water from the lake may have penetrated through the thin lake sediment into the sampling tube during sampling. Therefore, as the samples were collected at each site, the percentages of infiltrating surface water and pore water varied in the samples. In those instances water samples probably do not represent the actual pore-water chemistry.

Onsite specific conductance values for the two surface-water samples collected from Taylor Lake were 47 $\mu\text{S}/\text{cm}$, whereas pore-water specific conductance values were grouped into two ranges, one between 46 and 74 $\mu\text{S}/\text{cm}$ and the other between 211 and 285 $\mu\text{S}/\text{cm}$ (table 6). The onsite specific conductance value for the east pore-water sample was 123 $\mu\text{S}/\text{cm}$, lying between the two ranges. Pore-water samples in the lower specific conductance range (north-northeast, northeast, and southeast shores) had specific conductance values, alkalinity, and major constituent concentrations, except for iron and manganese concentrations, similar to the surface-water samples. However, because of the highly conductive nature of the fractures located along the shoreline, pumping during sample collection may have temporarily drawn in lake water directly to the sampling location through the fractures. Seasonal sampling of the sites would need to be done to determine if these are surface-water-outseepage locations. Alkalinity concentrations for the north-northeast, northeast, and southeast pore-water samples ranged from 22 to 31 mg/L as calcium carbonate (table 6).

Similar to North and Teal Lakes, pH values for the surface-water samples from Taylor Lake were higher than the pH values for the pore-water samples (table 6). The surface-water samples had in-situ pH values of 7.0 and 7.3 standard units, similar to North and Teal Lakes (table 6). The pH values for all Taylor Lake pore-water samples ranged from 5.6 to 6.4 standard units, within the pH range for *Picea mariana* (black spruce) stands determined by Bares and Wali (1979) for a peatland in northwestern Minnesota. pH differences of more than 1.0 standard unit were found during initial attempts to collect pore-water samples along the east shore within relatively short horizontal distances, roughly 1 ft.

The range in pore-water temperatures was much smaller in the Taylor Lake area than in the North and Teal Lake areas due in part to the relatively cool air temperatures in August 2004. Pore-water temperatures ranged from 13.6 to 16.2 $^{\circ}\text{C}$, whereas surface-water temperatures were 17.1 and 17.2 $^{\circ}\text{C}$

(table 6). The coolest temperatures were measured in pore-water samples collected along the south, west, and southeast shores.

Dissolved oxygen concentrations were less than 3.0 mg/L for all of the pore-water samples, with concentrations less than 1.0 mg/L for four of the seven pore-water samples (table 6). These low dissolved oxygen concentrations indicate that reducing conditions likely occur in the lake sediment. Dissolved oxygen concentrations for the northeast, south, and southeast pore-water samples were slightly higher than concentrations for the other pore-water samples, indicating that a volume of surface water may have been drawn through the sediment and into the sampling tube during sampling. The relatively high specific conductance values for the south pore-water sample indicate that the volume of surface water that may have been drawn into the sampling tube was very small.

Total nitrogen concentrations were greater in the pore-water samples than in the surface-water samples of the Taylor Lake area, but the concentrations were generally lower than concentrations in pore-water samples from North and Teal Lakes (table 6). These lower total nitrogen concentrations may be because of the greater lake depth and a lower amount of beaver activity at Taylor Lake. Total ammonia plus organic nitrogen concentrations were greater in the south and north pore-water samples than in the other pore-water samples from the Taylor Lake area (table 6). The south and north pore-water samples were collected near beaver dams and dens, respectively, where nutrient concentrations tend to be relatively high (Naiman and others, 1994).

Percentage differences for ionic balances were greater than 10 percent for five of the seven pore-water samples collected in the Taylor Lake area (table 6). All of these balances were positive, indicating that the total cation concentrations were greater than the total anion concentrations. As indicated earlier, some water from the lake may have been drawn into the sampling tube while collecting several of the pore-water samples from the Taylor Lake area, potentially resulting in chemical disequilibrium in the samples and causing problems with the ionic balance. Also, the smell of hydrogen sulfide gas was present in all of the pore-water samples, indicating that the amount of total dissolved sulfur may have been underestimated in the ionic balances.

All of the surface-water and pore-water samples collected in the Taylor Lake area were a calcium magnesium bicarbonate type water (figs. 7 and 8). The percentage distributions of major ions for the surface water and pore water were similar to the water samples collected from the North Lake area, with only minor differences in the distributions between the samples for the Taylor Lake area (fig. 7). Sulfate, chloride, fluoride, nitrate, and nitrite concentrations were relatively low in all of the surface-water and pore-water samples compared to bicarbonate concentrations (figs. 7 and 8, table 6). The cation distributions for the north, west, and southeast pore-water samples were slightly different from the distributions of the other surface-water and pore-water samples. The south

and west samples had higher percentages of calcium, whereas the north sample had a lower percentage of calcium compared to the other samples (fig. 7). The west pore-water sample also had a lower percentage of sodium and potassium than the other samples. The distribution of cation and anion concentrations in the surface-water sample for Taylor Lake was very similar to the distribution for surface-water samples for nearby Speckled Trout and Loon Lakes presented in Winterstein (2002) (figs. 1 and 8).

Iron and manganese concentrations were higher for the pore-water samples than concentrations in the surface-water samples (table 6). Concentrations were notably higher in the pore-water samples collected along the south, north, and west shores of Taylor Lake. Some iron-oxide precipitates, likely bacteria-oxidized iron (Wetzel, 1983), were observed at these locations.

Oxygen-18/oxygen-16 and deuterium/protium ratios for surface-water and pore-water samples collected in the Taylor Lake area lie along an evaporation line with a slope of 4.1 and a y-intercept of -33.7 (fig. 6D). This slope value is between values obtained from North and Teal Lakes. A comparison between the three slope values indicates an apparent negative relation between the slope values and lake-surface area for the three lakes. However, this relation does not consider the effect of temporal variations in sample collection because the samples were collected during different years for Teal and Taylor Lakes.

The two surface-water samples for Taylor Lake were the most evaporative because they plotted farthest from the meteoric waterline, with stable isotope ratios for the two samples lying close to each other along the evaporation line (fig. 6D). Stable isotope ratios for north-northeast and northeast pore-water samples lie near the surface-water samples (fig. 6D).

The least evaporative isotope ratios for the Taylor Lake samples were for the south, north, and west pore-water samples (fig. 6D). The pore-water samples collected along the east and southeast shores of Taylor Lake had similar stable isotope ratios, lying between the ratios for the surface-water and least-evaporative isotope ratio samples (fig. 6D). However, the major constituent concentrations differ between the two samples, with specific conductance values and the major constituent concentrations being higher in the east pore-water sample (table 6).

Quality Assurance

The percentage differences between original and replicate samples for major constituents, nutrient, and stable isotope concentrations were better than ± 5 percent for all of the constituents except for dissolved potassium and dissolved chloride in one original/replicate sample set and dissolved phosphorus and total phosphorus in another original/replicate set (table 7). Hem (1992) stated that for constituent concentrations greater than 100 mg/L, percentage differences should be better than ± 5 percent, whereas for concentrations less than 1 mg/L, percentage differences generally are not better than ± 10 per-

Table 7. Sequential replicate samples from North Lake, August 2003, Teal Lake, September 2003, and Taylor Lake, September 2004, Grand Portage Reservation, northeastern Minnesota.

[Values in parentheses are percentage differences between concentrations in onsite samples and replicate samples; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than; E, estimated; --, no data]

Constituent	Southwest channel of North Lake, 475656089493301, 8/26/2003, 14:32 hours	Teal Lake near Grand Portage, 475930089392301, 9/3/2003, 10:32 hours	Southeast shore of Taylor Lake, 475602089493801, 9/2/2004, 12:35 hours
Dissolved calcium (mg/L as Ca)	20.8 (1.9)	9.40 (3.6)	10.6 (1.9)
Dissolved magnesium (mg/L as Mg)	4.55 (-1.3)	4.40 (0.7)	1.80 (0.8)
Dissolved potassium (mg/L as K)	.42 (-3.7)	.77 (4.3)	.25 (13.8)
Dissolved sodium (mg/L as Na)	1.34 (-0.8)	7.55 (0.2)	.75 (1.3)
Dissolved chloride (mg/L as Cl)	.42 (1.2)	20.0 (-1.0)	E .17 (20.9)
Dissolved fluoride (mg/L as F)	< .2 (--)	< .2 (--)	< .2 (--)
Dissolved silica (mg/L as SiO ₂)	23.2 (-1.3)	.76 (-1.3)	3.33 (-0.5)
Dissolved sulfate (mg/L as SO ₄)	E .1 (0)	3.7 (-1.4)	.3 (0)
Total nitrogen (mg/L as N)	--	--	.69 (0.7)
Total ammonia plus organic nitrogen (mg/L as N)	2.9 (-0.3)	.79 (-1.9)	--
Dissolved ammonia nitrogen (mg/L as N)	2.46 (0.4)	< .04 (--)	.23 (-2.2)
Dissolved nitrite nitrogen (mg/L as N)	< .008 (--)	< .008 (--)	< .008 (--)
Dissolved phosphorus (mg/L as P)	.100 (-0.5)	E .004 (-14.3)	.055 (-1.9)
Dissolved ortho-phosphorus (mg/L as P)	.08 (-2.0)	< .02 (--)	.04 (-2.3)
Total phosphorus (mg/L as P)	--	.009 (5.3)	--
Dissolved boron (µg/L as B)	15 (3.0)	11 (-2.7)	< 7.0 (--)
Dissolved iron (µg/L as Fe)	1,010 (1.0)	40 (3.6)	1,190 (2.1)
Dissolved manganese (µg/L as Mn)	28.7 (-2.1)	< .4 (--)	94.8 (0.3)
Dissolved bromide (µg/L as Br)	--	--	.08 (0)
Oxygen-18/oxygen-16 ratio, unfiltered water, per mil	-9.24 (-0.4)	-5.02 (-0.1)	-6.3 (0)
Deuterium/protium ratio, unfiltered water, per mil	-71.40 (-0.6)	-51.40 (-1.1)	-59.90 (0.7)

cent and can be poorer. For the constituents of the replicate samples with high percentage differences between the original and replicate samples, concentrations were less than 1 mg/L, with two of the concentrations low enough to only be estimated values (table 7). At these low concentrations, only small changes in concentrations resulted in large percentage differences. No blank or spike samples were collected in the study.

Ground-Water/Surface-Water Interaction

Water-quality data collected during this study indicate that most of the ground-water inflow to the three lakes likely occurs through fractures or zones of fractures located along the shorelines. This type of ground-water inflow is common in fractured-rock terrains. Beaver dens and activity were common in channels developed near fractures along the shorelines. It could be possible that beavers build their dens in these channels because ground-water inflow to these channels keep water temperatures relatively constant throughout the year.

Analyses of existing aerial photographs, nearshore lake-sediment temperatures, and seasonal isotope ratios of surface-water and pore-water samples were the most valuable data for identifying locations of ground-water inflow. Major constituent chemistry was valuable at Taylor Lake, and to a limited extent at North and Teal Lakes, in confirming results from the isotope and lake-sediment temperature data. However, lake-sediment temperatures were not as useful for identifying areas of ground-water inflow at Taylor Lake because of the cooler-than-normal air temperatures in August 2004. Major constituent chemistry worked well where large concentration differences between surface-water and pore-water chemistry existed, such as in pore-water samples from the south-southwestern shore of Teal Lake.

The lack of notable concentration differences and potential cation exchanges, cation adsorption, and chelation in fens and swamps surrounding lakes confounded the use of major constituent chemistry to identify locations of ground-water inflow to North and Teal Lakes, respectively. Highland lakes, such as North Lake and, to a lesser extent, Taylor Lake, tend to receive localized ground water that has relatively low dissolved-ion concentrations. This localized ground water has a short residence time, less contact time with the formations, and as a result, less time to react chemically with the rock matrix. Therefore, localized ground water tends to have lower ionic concentrations than more regional water. Chemical reactions in upgradient fens and swamps also reduce major constituent concentrations in ground water that discharges from these fens and swamps and eventually recharges the highland lakes.

Variables that were not evaluated at these study sites but that may be valuable in locating areas of ground-water inflow are shoreline vegetation, forest cover, and beaver activity. Tamarack, manna grass, and white cedars commonly were present in areas where ground-water inflow apparently occurs. During pore-water sampling, the location of manna grass commonly was used to locate sampling sites where ground-water discharge was likely to occur.

North Lake

Analyses of existing aerial photographs, lake-sediment temperature, and water-quality data indicate that ground-water inflow to North Lake likely occurs along the southwest and south shores (fig. 9A), and portions of the west, north, southeast, and northeast shores. The southern drainage channel identified in the analyses of existing aerial photographs of North Lake is likely a location for potential ground-water inflow rather than surface-water outseepage because the channel is higher in elevation than the lake, with surface water in the channel following snowmelt and precipitation flowing towards the lake (fig. 3). Relatively cool lake-sediment temperatures along the southeast, south, southwest, and west shores (fig. 3), and in isolated beaver channels in the north and northeast of North Lake indicate potential ground-water inflow

at these locations (fig. 10A). The high specific conductance values and high dissolved calcium and bicarbonate concentrations for the pore-water samples from the southwest channel and south shore in August 2003 and May 2004 indicate that inflowing ground water with higher specific conductance values than the surface water is potentially more of a component of these pore-water samples than of the other pore-water samples (figs. 10B and 10C). The consistent oxygen-18/oxygen-16 and deuterium/protium ratios for the south, southwest channel, and north-northwest pore-water samples indicate a predominance of ground-water inflow at those locations (figs. 6B and 10D). In general, pore water with a consistent isotopic composition over time is affected more by ground water (Krabbenhoft and others, 1994). The more evaporative isotopic compositions of the south and the north-northwest pore-water samples than for the southwest channel pore-water sample indicate that the south and the north-northwest samples either are less affected by ground-water inflow than pore water from the southwest channel location or likely receive ground water from upgradient wetlands where more evaporation occurs (fig. 6B).

Conflicting evidence for ground-water flow conditions exist for the northwest and north-northwest pore-water samples for the North Lake area. Warm lake-sediment temperatures, similar to water temperatures in the lake, relatively high dissolved oxygen concentrations, and low total ammonia plus organic nitrogen concentrations in pore-water samples from the northwest and north-northwest shores indicate that surface-water outseepage or little ground-water and surface-water interaction occurs at the locations (figs. 10A and 10B). The high organic nitrogen concentration in the pore-water sample from the north-northwest shore (table 6) further indicates the potential for surface-water outseepage. However, consistent stable isotope ratios for pore-water samples from the northwest and north-northwest shores indicate a mixing of surface-water and some potential ground-water inflow (figs. 6B and 10D). Possible explanations for the temporal conservative nature in stable isotope ratios are local differences in flow conditions between the August 2003 and May 2004 sampling sites and a lag in the pore-water isotopic response to seasonal isotopic changes in the lake water because of low-permeability sediment. The northwestern drainage channel identified in the analyses of existing aerial photographs is lower in elevation than North Lake and, therefore, is likely a location for more surface-water outseepage rather than ground-water inflow.

A combination of ground-water inflow and surface-water outseepage from North Lake likely occurs along portions of the north, northeast, southeast, and south shores (fig. 9A). Ground-water inflow or surface-water outseepage could be occurring in the northern drainage channel identified in the analyses of existing aerial photographs because the difference in elevation between the channel and lake is small (fig. 3). Similarities in the oxygen-18/oxygen-16 and deuterium/protium ratios for the surface-water samples and the north and northeast pore-water samples of North Lake indicate that surface-water outseepage was occurring or these samples were

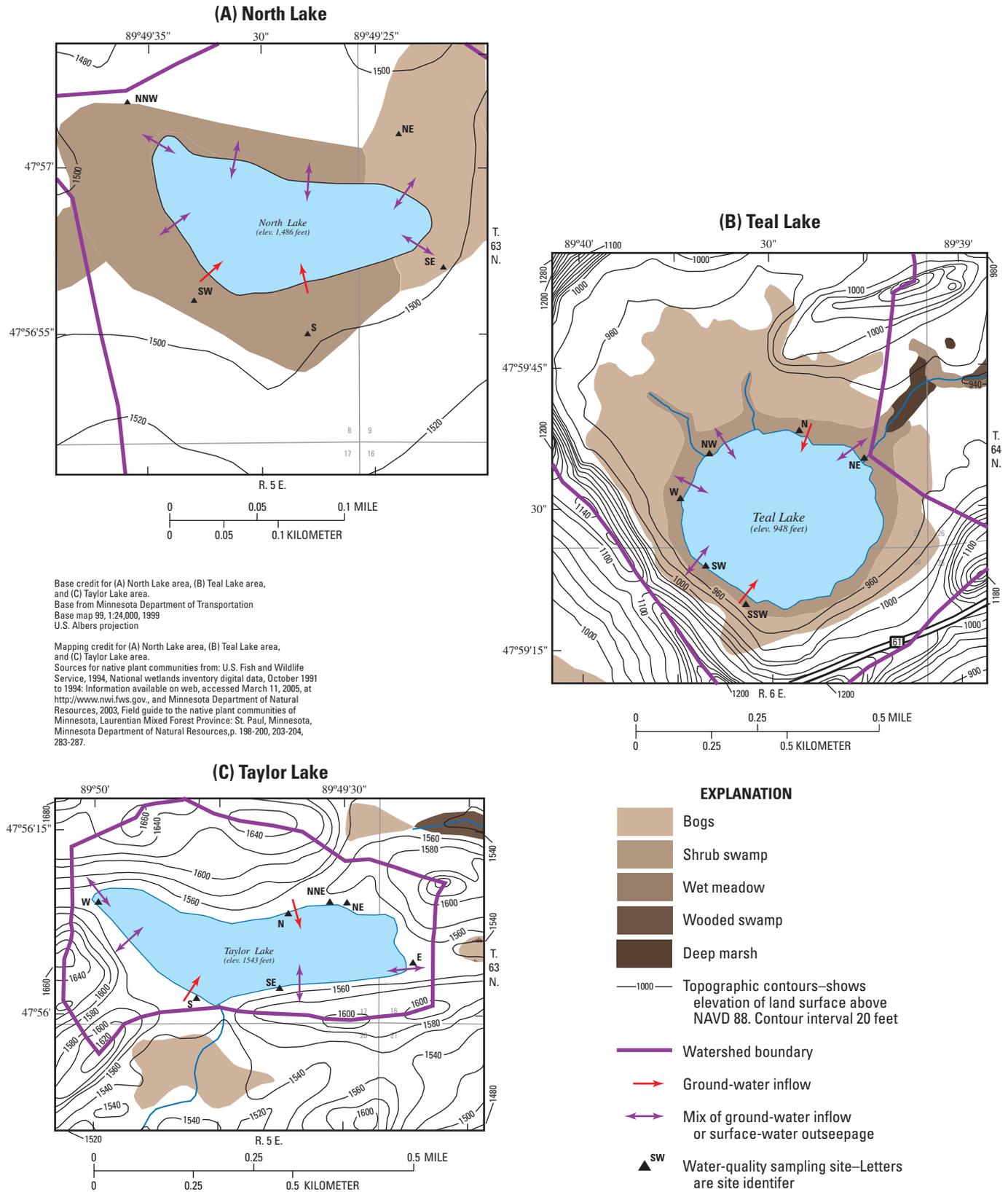


Figure 9. Nearshore locations of ground-water inflow and surface-water outseepage for (A) North Lake, (B) Teal Lake, and (C) Taylor Lake, Grand Portage Reservation, northeastern Minnesota, determined on the basis of lake-sediment temperatures and water-quality data.

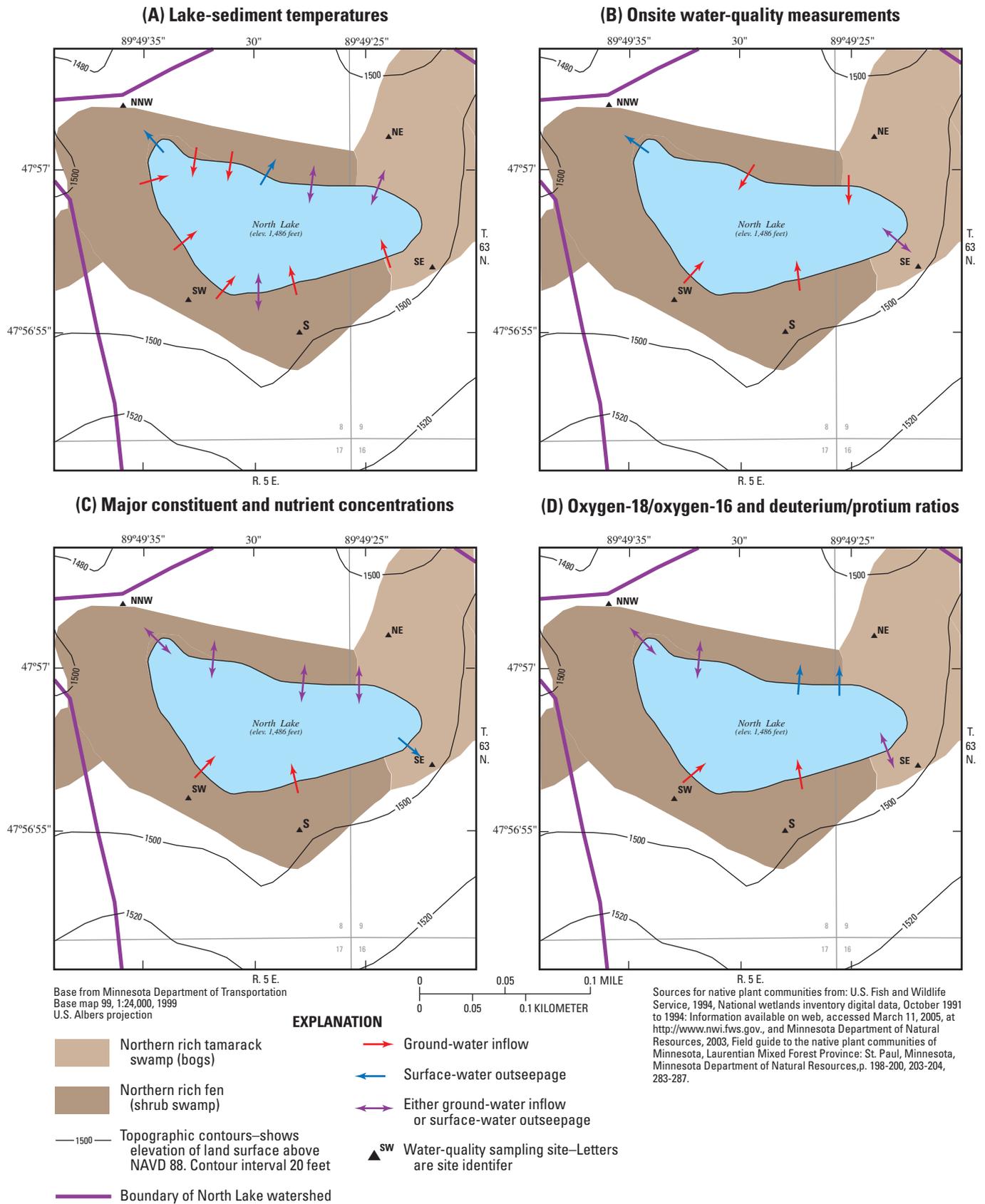


Figure 10. Nearshore locations of ground-water inflow and surface-water outseepage for North Lake, Grand Portage Reservation, northeastern Minnesota, determined on basis of (A) lake-sediment temperatures, (B) onsite water-quality measurements, (C) major constituent and nutrient concentrations, and (D) oxygen-18/oxygen-16 and deuterium/protium ratios.

affected by upgradient surface water (figs. 6B and 10D). The large tamarack swamp located north of the north and northeast shores is likely contributing water to local surface water and pore water of North Lake (fig. 3). The low specific conductance and bicarbonate values for the southeast pore-water sample indicate that this pore water may be from surface-water outseepage or more likely affected by upgradient wetlands (fig. 10B). However, low pH values and dissolved oxygen concentrations for the southeast pore-water sample do not indicate surface-water outseepage. Upgradient wetlands may be affecting isotopic ratios along the southeast shore because the oxygen-18/oxygen-16 and deuterium/protium ratios for the May 2004 sample lie near the meteoric waterline similar to the May 2004 surface-water sample and the northeast pore-water sample (fig. 6B). However, no sample was collected at the southeast location in August 2003 for temporal comparison. Lake-sediment temperatures above 18 °C were found along portions of the south shore and throughout North Lake, indicating potential surface-water outseepage or little ground-water and surface-water interaction at those locations (fig. 10A).

Teal Lake

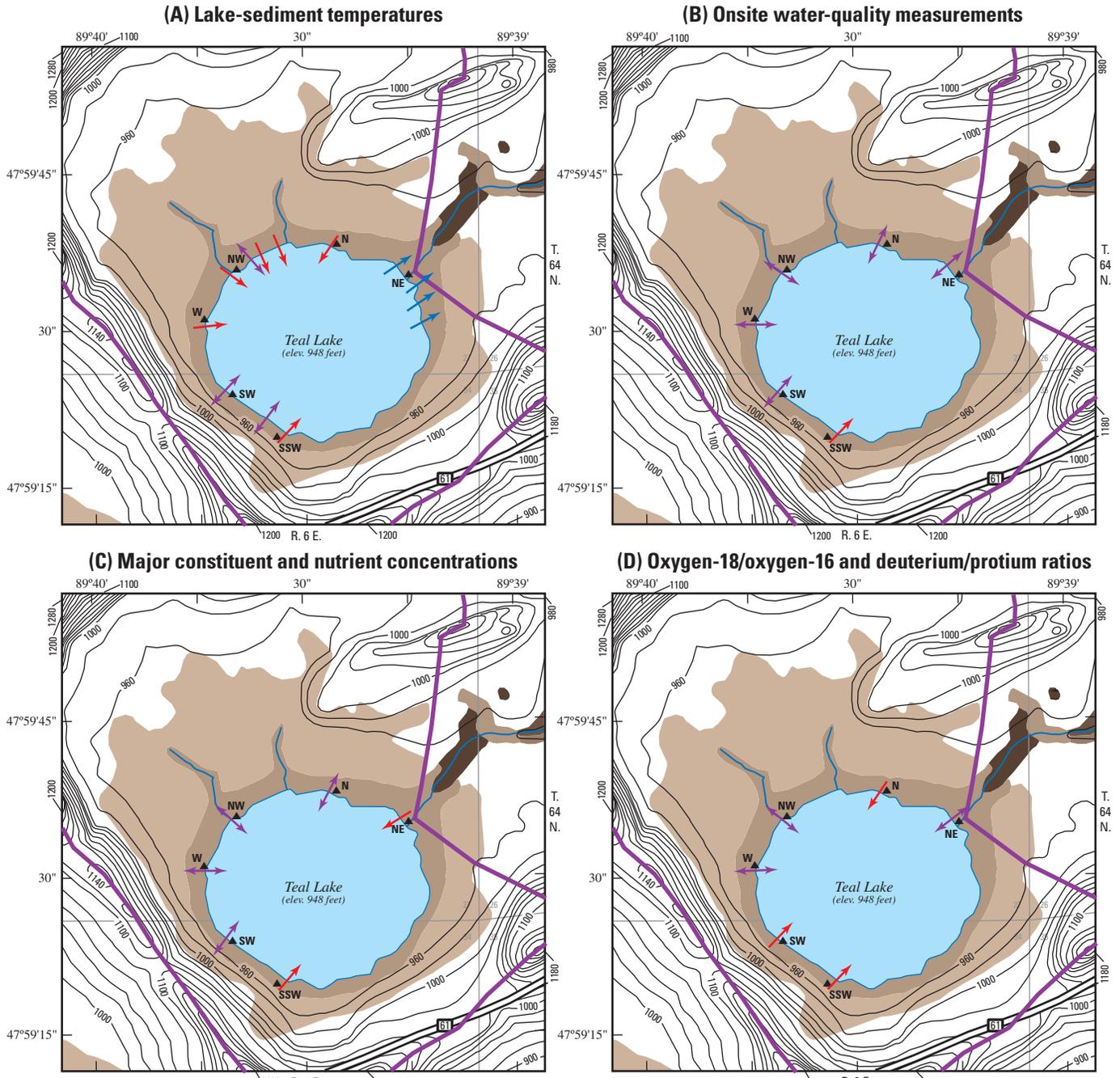
Ground-water inflow likely takes place along the southwest and north shores of Teal Lake, with a mixture of ground-water inflow and surface-water outseepage occurring in other areas of the lake (fig. 9B). Lake-sediment temperatures indicate that ground-water inflow occurs along the south-southwest, west, and northwest shores, portions of the north shore, and in channels identified in the analyses of existing aerial photographs where lake-sediment temperatures were less than 15 °C (figs. 4 and 11A). High major constituent concentrations in the south-southwest pore-water sample further indicate the presence of ground-water inflow at that location (fig. 11C). The pore-water samples from the south-southwest, north, and southwest shores had isotopic compositions that lie closest to the meteoric waterline (fig. 6C), indicating that ground-water inflow occurred at these locations (fig. 11D). The low specific conductance values for the north, northwest, west, and southwest pore-water samples were likely because of cation adsorption or relation between inflowing ground water and soils in the fens and swamps but probably was not the result of surface-water outseepage.

Ground-water inflow and surface-water outseepage from Teal Lake likely occurs along the northeast shore (fig. 9B). Warmer lake-sediment temperatures in the northeast and portions of the southwest and northwest shores of Teal Lake (fig. 4) indicate potential locations where surface-water outseepage or little ground-water and surface-water interaction occurs (fig. 11A). However, surface-water outseepage is unlikely or only localized along the southwest and northwest shores because low-permeability diabase dikes located to the west and south are higher in elevation than Teal Lake, preventing any regional surface-water outseepage (fig. 4).

The low permeabilities of the diabase dikes likely restrict ground-water inflow to the lake from the west and south to within the drainage channels that cross the dikes and the lake's watershed. Warmer water temperatures along the northeast shore indicate potential surface-water outseepage (fig. 11A); however, the high major constituent concentrations in the northeast pore-water sample indicate potential ground-water inflow (fig. 11C). Local beaver activity near the northeast shore may result in the high major constituent concentrations (Naiman and others, 1994). Oxygen-18/oxygen-16 and deuterium/protium ratios for pore-water samples from the northeast, northwest, and west shores indicate that some evaporation has occurred with this water but not as much as with surface water (fig. 6C). The likely source of this pore water is ground water flowing south from fens and swamps to the north (fig. 4) where some evaporation likely occurred but not as much as in the surface-water sample. The warm lake-sediment temperature (17 °C) found near the center of the lake indicates that little ground-water/surface-water interaction occurs at that location (fig. 4).

Taylor Lake

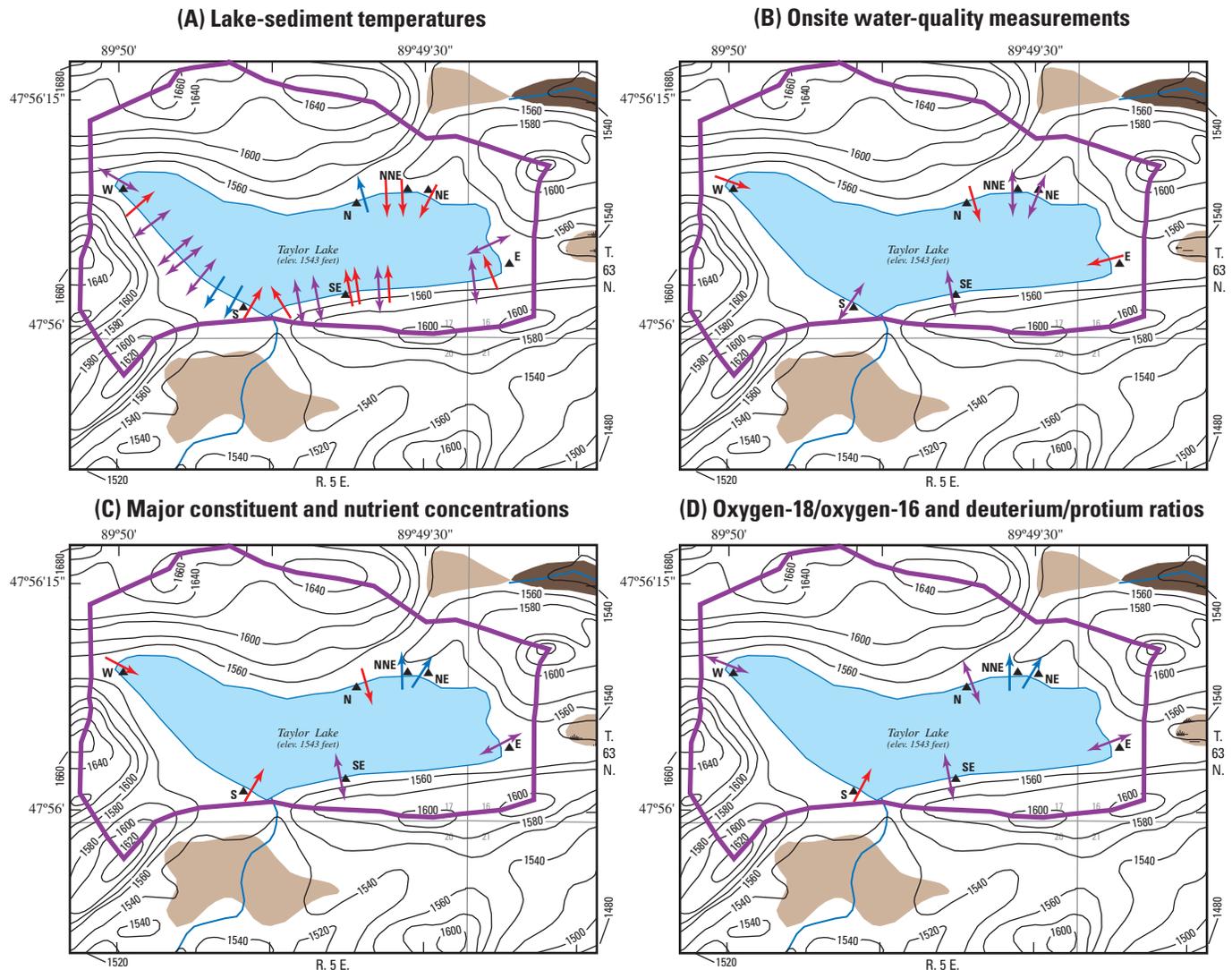
Ground-water inflow to Taylor Lake likely occurs along the north and south shores (fig. 9C). Two lowlands to the north and northeast of Taylor Lake (fig. 5) identified in the analyses of existing aerial photographs are topographically higher than the lake and, therefore, are more likely areas of ground-water inflow rather than surface-water outseepage. Cooler lake-sediment temperatures along the northeast shore of Taylor Lake indicate that ground-water inflow likely is occurring at that location (fig. 12A), with an upgradient lowland, bog, and wooded swamp likely sources of ground water. Warmer lake-sediment temperature along the north shore indicates that some minor surface-water outseepage may occur at that location (fig. 12A). Major constituent chemistry and isotope values for pore-water samples collected in the Taylor Lake area indicate that ground-water inflow is occurring along the south and likely the north and west shores (figs. 12C and 12D). These samples had isotope evaporative signatures most similar to the meteoric waterline, the highest specific conductance values, and the highest calcium, magnesium, bicarbonate, silica, iron, and manganese concentrations for the Taylor Lake pore-water samples. However, the isotopic values for these samples do not fall close to the meteoric waterline (fig. 6D), indicating that some evaporative water, probably from an upgradient wetland or lake, is contributing water to the lake at those locations. The high iron and manganese concentrations in pore-water samples from along the south, north, and west shores of Taylor Lake indicate the presence of iron seeps at those locations (table 6). Iron seeps are common along the shores of lakes and wetlands in northern Minnesota (Harder, 1919; Robbins and others, 1997). A combination of warmer and cooler lake-sediment temperatures along the west lowland indicates that ground-water inflow and surface-water outseepage may occur at that location (fig. 12A).



Sources for native plant communities from: U.S. Fish and Wildlife Service, 1994, National wetlands inventory digital data, October 1991 to 1994; Information available on web, accessed March 11, 2005, at <http://www.nwi.fws.gov>, and Minnesota Department of Natural Resources, 2003, Field guide to the native plant communities of Minnesota, Laurentian Mixed Forest Province: St. Paul, Minnesota, Minnesota Department of Natural Resources, p. 198-200, 203-204, 283-287.

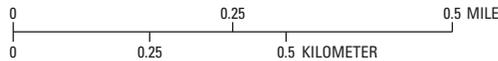
- EXPLANATION**
- Northern cedar swamp (bogs)
 - Northern rich fen (shrub swamp)
 - Wet meadow
 - Wooded swamp
 - Deep marsh
 - Topographic contours—shows elevation of land surface above NAVD 88. Contour interval 20 feet
 - Boundary of Teal Lake watershed
 - Ground-water inflow
 - Surface-water outseepage
 - Either ground-water inflow or surface-water outseepage
 - Water-quality sampling site—Letters are site identifier

Figure 11. Nearshore locations of ground-water inflow and surface-water outseepage for Teal Lake, Grand Portage Reservation, northeastern Minnesota, determined on basis of (A) lake-sediment temperatures, (B) onsite water-quality measurements, (C) major constituent and nutrient concentrations, and (D) oxygen-18/oxygen-16 and deuterium/protium ratios.



Base from Minnesota Department of Transportation
Base map 99, 1:24,000, 1999
U.S. Albers projection

Sources for native plant communities from: U.S. Fish and Wildlife Service, 1994, National wetlands inventory digital data, October 1991 to 1994; Information available on web, accessed March 11, 2005, at <http://www.nwi.fws.gov>, and Minnesota Department of Natural Resources, 2003, Field guide to the native plant communities of Minnesota, Laurentian Mixed Forest Province: St. Paul, Minnesota, Minnesota Department of Natural Resources, p. 198-200, 203-204, 283-287.



- EXPLANATION**
- Bogs
 - Wooded swamp
 - Topographic contours—shows elevation of land surface above NAVD 88. Countour interval 20 feet
 - Boundary of Taylor Lake watershed
 - Ground-water inflow
 - Surface-water outseepage
 - Either ground-water inflow or surface-water outseepage
 - Water-quality sampling site—Letters are site identifier

Figure 12. Nearshore locations of ground-water inflow and surface-water outseepage for Taylor Lake, Grand Portage Reservation, northeastern Minnesota, determined on basis of (A) lake-sediment temperatures, (B) onsite water-quality measurements, (C) major constituent and nutrient concentrations, and (D) oxygen-18/oxygen-16 and deuterium/protium ratios.

Surface-water outseepage likely occurs from Taylor Lake along portions of the south shore through a surface-water drainage channel to a downgradient bog (fig. 5). Warmer lake-sediment temperatures measured along portions of the south and southeast shores (fig. 12A) and the high dissolved oxygen concentrations found along the south and southeast shores indicate a potential for surface-water outseepage. Warmer lake-sediment temperatures also found along the west, southwest, northeast, and portions of the north and east shores of Taylor Lake (fig. 5) indicate that potential surface-water outseepage to local aquifers or little ground-water and surface-water interaction occurs at those locations (fig. 12A).

Similarities between stable isotope ratios, specific conductance values, alkalinity, and major constituent concentrations for surface-water samples and north-northeast and northeast pore-water samples from the Taylor Lake area indicate that surface-water outseepage potentially occurs at these locations (fig. 9C). The high dissolved oxygen concentration for the northeast pore-water samples also indicates that some surface-water outseepage may occur at those locations. However, as discussed earlier, surface water may have been drawn into the sampling tubing from the lake through fractures during sampling along the north-northeast and northeast shores.

Ground-water inflow and surface-water outseepage may occur along the west, southeast, and east shores of Taylor Lake (fig. 9C), varying seasonally or in response to large amounts of precipitation. A lowland to the west of Taylor Lake (fig. 5) either could be a location of ground-water inflow to the lake or surface-water outseepage to the ground-water system because the difference in topography between the lake and the lowland is small and both cool and warm lake-sediment temperatures were measured at that location. Stable isotope ratios, specific conductance values, and bicarbonate and major constituent concentrations for the southeast pore-water sample indicate that a mixture of surface-water outseepage and ground-water inflow may occur along the southeast shore (fig. 9C). Aerial photography analyses identified a lowland to the east of Taylor Lake (fig. 5) that either could be a location of ground-water inflow or surface-water outseepage because the difference in topography between the lake and the lowland is small. The stable isotope ratios for the east pore-water sample (fig. 6D) indicate that the east shore may be a location where a mixture of surface and ground water occurs (fig. 12D). The large differences in onsite water-quality measurements (specific conductance, pH, temperature, and dissolved oxygen) found along the east shore within relatively short horizontal distances further indicate a mixing of surface and ground water or local evapotranspiration effects. The large pH differences could be caused by vegetation factors (Mitsch and Gosselink, 1993). However, no notable changes in vegetation were seen along the east shore.

Implications of Ground-Water/Surface-Water Interactions

Knowledge of general water-flow directions in lake watersheds and how they may change seasonally can help water-quality specialists and lake managers address a variety of water-quality and aquatic habitat protection issues for lakes. Current (2006) concerns over nutrient criteria, impaired waters, and invasive aquatic plants in lakes are all issues where understanding ground-water/surface-water interactions in a lake are needed to make wise management decisions. In fractured-rock settings, identifying ground-water inflow locations to lakes can indicate the location of upgradient springs, which may be valuable sources of water to small communities where finding adequate sources of water is difficult.

Results from this study indicate that ground-water and surface-water interactions at the study lakes are complex, and the ability of the applied techniques to identify ground-water inflow and surface-water outseepage locations varied among the lakes. These variations are in part a result of the complexity of local geology, chemical reactions in fens upgradient and surrounding the lakes, and the fracture-flow bedrock setting. Seasonal variabilities of ground-water inflow and surface-water outflow locations and flow rates were not determined for this study, and should be assessed before determining water balances of a lake.

Measurement of lake-sediment temperatures proved to be a reliable and relatively inexpensive reconnaissance technique that lake managers may apply in complex settings to identify general areas of ground-water inflow and surface-water outseepage. In the complex settings of the three study lakes, nearshore lake-sediment temperatures were shown to be valuable information in identifying ground-water inflow and surface-water outseepage locations, but interpretations of the temperature measurements were most powerful when combined with interpretation of seasonal pore-water-quality data and aerial photographs. Lake-sediment temperatures are relatively simple to measure and can be measured and interpreted within a short period of time. Statistical analyses of the lake-sediment temperatures demonstrated that lake sediment and water depths were unlikely factors in determining the lake-sediment temperature, further simplifying the interpretation of the temperature data.

Summary

The U.S. Geological Survey (USGS), in cooperation with the Grand Portage Band of Chippewa Indians, applied three techniques to assess ground-water/surface-water interaction in nearshore areas of three lakes (North, Teal, and Taylor) on the Grand Portage Reservation in northeastern Minnesota. At each lake, the analyses of existing aerial photographs, in-situ temperature measurements of shoreline lake sediment, and

chemical analysis of surface water and shoreline pore water were conducted. Surface-water and pore-water samples were analyzed for major constituents, nutrients, and stable isotopes of oxygen and hydrogen. No attempt was made to identify areas of ground-water inflow or surface-water outseepage to local aquifers in deeper water beyond the littoral zone of the lake. Bulk precipitation samples were collected and analyzed for nutrient concentrations to determine nutrient input to the lakes through atmospheric deposition and for stable isotope ratios of oxygen and hydrogen to determine a meteoric waterline that was needed for the stable isotope analyses of surface-water and pore-water samples.

Total nitrogen concentrations in the precipitation samples ranged from 0.51 to 8.4 mg/L as nitrogen at the North Lake precipitation station and from 0.42 to 2.3 mg/L as nitrogen at the Grand Portage precipitation station. These concentrations are similar to the total nitrogen concentrations measured for bulk precipitation at the National Atmospheric Deposition Program/National Trends Network precipitation monitoring site at Hovland, Minnesota. Oxygen-18/oxygen-16 and deuterium/protium isotope ratios for most of the bulk precipitation samples lie relatively close to a meteoric waterline for precipitation in northern Wisconsin.

Analyses of existing aerial photographs, nearshore lake-sediment temperatures, and seasonal isotope ratios of surface-water and pore-water samples were the most valuable data for identifying locations of ground-water inflow and surface-water outseepage. Identified drainages and lineaments in the analyses of existing aerial photographs were valuable in directing the location of temperature measurements and pore-water sampling. Lake-sediment temperatures at potential ground-water inflow locations ranged from 4 to 16 °C, varying between lakes, seasons, and climatic conditions. Cooler-than-normal August 2004 air temperatures resulted in only small temperature differences between surface water and lake sediment at Taylor Lake, making it difficult to use lake-sediment temperatures to identify the location of ground-water inflow. Major constituent chemistry was valuable at Taylor Lake, and to a limited extent at North and Teal Lakes, in confirming results from the isotope and lake-sediment temperature data. The major constituent chemistry of inflowing ground water often was affected by cation adsorption, cation exchanges with hydrogen ions, and chelation occurring in the surrounding fens and swamps, in particular for pore-water samples collected from the Teal Lake area.

Ground-water inflow to North Lake likely occurs along the southwest and south shores, and along portions of the west, southeast, north, and northeast shores. Cooler temperatures in August 2003 occurred along the southwest, south, west, and southeast shores, and in isolated channels along the north and northeast shores of North Lake, indicating potential ground-water inflow at these locations. Analyses of oxygen and hydrogen isotopes from pore-water samples collected in August 2003 and May 2004 from North Lake indicate that ground-water inflow was occurring along the south, southwest, and potentially along the southeast shores. A mix of ground-

water inflow and surface-water outseepage from North Lake likely occurs along portions of the north, northeast, southeast, and south shores, varying seasonally. Conflicting evidence for ground-water flow conditions exist for the northwest and north-northwest pore-water samples. Warm lake-sediment temperatures, similar to water temperatures in the lake, high dissolved oxygen concentrations, and relatively low ammonia concentrations along the northwest and north-northwest shores indicate that surface-water outseepage or little ground-water and surface-water interaction occurs at the locations. The high organic nitrogen concentration along the north-northwest shore further indicates the potential for surface-water outseepage. However, consistent stable isotope ratios for pore-water samples from the northwest and north-northwest shores indicate a mixing of surface water and some potential ground-water inflow. Only minor differences in the major constituent concentrations were seen between the surface-water and pore-water samples from North Lake area with the exception of iron and manganese concentrations. Dissolved silica, iron, and manganese concentrations were higher in all of the pore-water samples than in the surface-water samples from North Lake, being notably higher in the south pore-water samples for August 2003 and May 2004 and the north-northwest pore-water sample for May 2004.

Ground-water inflow likely takes place along the south-southwest and north shores of Teal Lake, with a mixture of ground-water inflow and surface-water outseepage occurring in other areas of the lake. Cooler lake-sediment temperatures occurred along the south-southwest, west, and northwest shores, portions of the north shore, and in channels identified in aerial photographs throughout the lake, indicating potential ground-water inflow at those locations. Warmer lake-sediment temperatures along the northeast and portions of the southwest and northwest shores of Teal Lake indicate potential locations where surface-water outseepage or little ground-water and surface-water interaction occurs. The percentage distribution of major constituents is widely dispersed for the pore water in the Teal Lake area, with the major constituent chemistry of the surface-water sample being generally a mix of the chemistry of all of the pore-water samples. Major constituent concentrations were higher in the pore-water samples collected from the south-southwest and northeast shores of Teal Lake. Cation adsorption, cation exchanges with hydrogen ions, and chelation occurring in the fen surrounding the lake likely resulted in the low dissolved calcium, magnesium, and sodium concentrations in north, northwest, and west pore-water samples from the Teal Lake area. Low sulfate concentrations in these samples likely result from sulfate reduction occurring in the fen substrate, with the production of hydrogen sulfide gas. The low chloride concentrations along the north and the southwest shores indicate that dilution may be causing the lower cation and anion concentrations at these locations. Pore-water samples from the south-southwest, north, and southwest shores of Teal Lake had isotopic compositions that plotted closest to the meteoric waterline, indicating that these locations may be where ground-water inflow was occurring.

Surface-water outseepage from Teal Lake likely occurs along the northeast shore, even though major constituent concentrations were high. Major constituent concentrations may be high because of a nearby beaver dam.

Ground-water inflow to Taylor Lake likely occurs along the north and south shores. Higher major constituent concentrations and the least evaporative isotope ratios were found in south, north, and west pore-water samples from the Taylor Lake area, indicating potential locations of ground-water inflow. However, a combination of warmer and cooler lake-sediment temperatures along the west lowland indicate that ground-water inflow and surface-water outseepage may occur at that location. Surface-water outseepage from Taylor Lake likely occurs along the south shore through a surface-water drainage channel to a downgradient bog. Warmer lake-sediment temperatures along portions of the south and southeast shores indicate that surface-water outseepage may occur at those locations. Both ground-water inflow and surface-water outseepage may occur along the west, southeast, and east shores of Taylor Lake, varying seasonally and with local precipitation.

Knowledge of general water-flow directions in lake watersheds and how they may change seasonally can help water-quality specialists and lake managers address a variety of water-quality and aquatic habitat protection issues for lakes. Results from this study indicate that ground-water and surface-water interactions at the study lakes are complex, and the ability of the applied techniques to identify ground-water inflow and surface-water outseepage locations varied among the lakes. Measurement of lake-sediment temperatures proved to be a reliable and relatively inexpensive reconnaissance technique that lake managers may apply in complex settings to identify general areas of ground-water inflow and surface-water outseepage.

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