Prepared in cooperation with the Minocqua/Kawaguesaga Lakes Protection Association through the Town of Minocqua, Wisconsin

Hydrology, Water Quality, and Response to Changes in Phosphorus Loading of Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin, With Special Emphasis on Effects of Urbanization

Scientific Investigations Report 2010–5196

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

Cover: Aerial photo of Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic ft (ft^3)	0.02832	cubic meter (m^3)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Deposition, application, and yield rate	
pound per square mile (lb/mi^2)	0.175133	kilogram per square kilometer (kg/km^2)
	Soil permeability rate	
inch per hour (in/h)	25.4	millimeter per hour (mm/h)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Datum

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

Water-level elevations in this report refer to distance above the vertical datum.

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Hydrology, Water Quality, and Response to Changes in Phosphorus Loading of Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin, With Special Emphasis on Effects of Urbanization

By Herbert S. Garn, Dale M. Robertson, William J. Rose, and David A. Saad

Abstract

Minocqua and Kawaguesaga Lakes are 1,318- and 690-acre interconnected lakes in the popular recreation area of north-central Wisconsin. The lakes are the lower end of a complex chain of lakes in Oneida and Vilas Counties, Wis. There is concern that increased stormwater runoff from rapidly growing residential/commercial developments and impervious surfaces from the urbanized areas of the Town of Minocqua and Woodruff, as well as increased effluent from septic systems around their heavily developed shoreline has increased nutrient loading to the lakes. Maintaining the quality of the lakes to sustain the tourist-based economy of the towns and the area was a concern raised by the Minocqua/Kawaguesaga Lakes Protection Association. Following several small studies, a detailed study during 2006 and 2007 was done by the U.S. Geological Survey, in cooperation with the Minocqua/Kawaguesaga Lakes Protection Association through the Town of Minocqua to describe the hydrology and water quality of the lakes, quantify the sources of phosphorus including those associated with urban development and to better understand the present and future effects of phosphorus loading on the water quality of the lakes.

The water quality of Minocqua and Kawaguesaga Lakes appears to have improved since 1963, when a new sewage-treatment plant was constructed and its discharge was bypassed around the lakes, resulting in a decrease in phosphorus loading to the lakes. Since the mid-1980s, the water quality of the lakes has changed little in response to fluctuations in phosphorus loading from the watershed. From 1986 to 2009, summer average concentrations of near-surface total phosphorus in the main East Basin of Minocqua Lake fluctuated from 0.009 mg/L to 0.027 mg/L but generally remained less than 0.022 mg/L, indicating that the lake is mesotrophic. Phosphorus concentrations from 1988 through 1996, however, were lower than the long-term average, possibly the result of an extended drought in the area. Water-quality data for Kawaguesaga Lake had a similar pattern to that of Minocqua Lake. Summer average chlorophyll *a* concentrations and Secchi depths also indicate that the lakes generally are mesotrophic but occasionally borderline eutrophic, with no long-term trends.

During the study, major water and phosphorus sources were measured directly, and minor sources were estimated to construct detailed water and phosphorus budgets for the lakes for monitoring years (MY) 2006 and 2007. During these years, the Minocqua Thoroughfare contributed about 38 percent of the total inflow to the lakes, and Tomahawk Thoroughfare contributed 34 percent; near-lake inflow, precipitation, and groundwater contributed about 1, 16, and 11 percent of the total inflow, respectively. Water leaves the lakes primarily through the Tomahawk River outlet (83 percent) or by evaporation (14 percent), with minor outflow to groundwater. Total input of phosphorus to both lakes was about 3,440 pounds in MY 2006 and 2,200 pounds in MY 2007. The largest sources of phosphorus entering the lakes were the Minocqua and Tomahawk Thoroughfares, which delivered about 39 and 26 percent of the total, respectively. The near-lake drainage area, containing most of the urban and residential developments, disproportionately accounted for about 12 percent of the total phosphorus input but only about 1 percent of the total water input (estimated with WinSLAMM). The next largest contributions were from septic systems and precipitation, each contributing about 10 percent, whereas groundwater delivered about 4 percent of the total phosphorus input.

Empirical lake water-quality models within BATHTUB were used to simulate the response of Minocqua and Kawaguesaga Lakes to 19 phosphorus-loading scenarios.

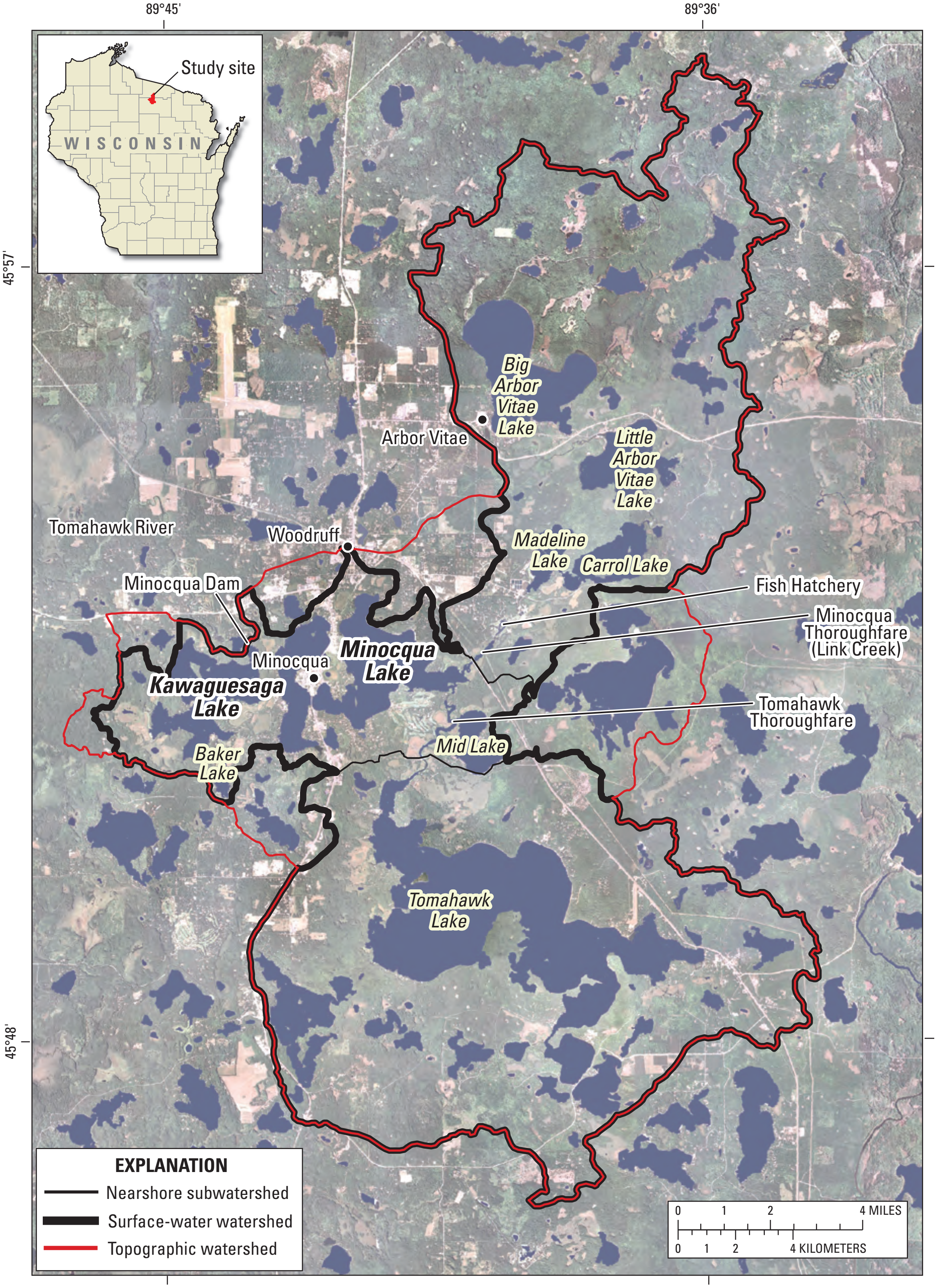
These scenarios included the current base years (2006–07) for which lake water quality and loading were known, nine general increases or decreases in phosphorus loading from controllable external sources (inputs from the tributaries and nearshore areas around the lakes and input from septic systems), and nine scenarios corresponding to future changes in phosphorus loading from residential and urban development, referred to as “2030 buildout,” and removal of septic system inputs. The 2030 buildout scenario with existing stormwater controls resulted in a degradation in water quality: phosphorus concentrations increased by about 0.001 mg/L, chlorophyll *a* concentrations increased by 0.2–0.8 µg/L, and Secchi depths decreased slightly. The largest degradation in water quality was estimated to occur in Kawaguesaga Lake. If 2030 buildout occurred with implementation of best management practices to achieve a 50-percent reduction in loading from near-lake drainages, it is possible that water quality would change very little from existing conditions. Numerous noncontributing areas exist within the watershed that help minimize surface runoff and nutrient loading to the lakes; however, if future development included extending or connecting drainage from these areas into the lakes, loading to the lakes could greatly increase and cause a degradation in the water quality of the lakes. Simulations of removal of phosphorus loading from septic systems around Minocqua Lake improved the water quality of the lakes: in simulations for that scenario, phosphorus concentrations decreased by about 0.001 mg/L, chlorophyll *a* concentrations decreased by 0.5–0.7 µg/L, and Secchi depths increased by 0.3–0.7 ft. If all controllable external phosphorus loading could be reduced by 50 percent, the lakes would become oligotrophic with respect to phosphorus concentration but would still remain mesotrophic with respect to chlorophyll *a* concentration and Secchi depth. Improvements in the water quality of the lakes are likely only with a combination of management actions that decrease inputs from the developed near-lake drainage areas and from septic systems.

Introduction

Minocqua and Kawaguesaga Lakes (fig. 1) are the lower lakes in a complex chain of lakes in the Northern Lake and Forests ecoregion of north-central Wisconsin (Omernik and others, 2000). Water levels of both lakes are controlled by the Minocqua Dam at the outlet of Kawaguesaga Lake. Water flows from the lakes into the Tomahawk River and eventually into the Wisconsin River. These lakes are popular for fishing, swimming, and other outdoor activities. The lakes are adjacent to the Towns of Minocqua and Woodruff and about 65 mi north of Wausau, Wis. Because of the many uses for the lakes, the area has become a major vacation and retirement destination, a tourist-oriented commercial center, and an important resource for Oneida County. This popularity, however, has resulted in rapid urbanization in Minocqua and Woodruff and the areas around the lakes. This urbanization may affect the hydrology and nutrient loading to the lakes and ultimately the water quality of the lakes. Therefore, understanding the factors affecting the water quality of Minocqua and Kawaguesaga Lakes, especially those factors associated with the increased pressure from urbanization, is very important and is addressed in this report.

In the early 1800s, a Chippewa Indian Village was located between Minocqua and Kawaguesaga Lakes. By 1886, the village had been moved to the peninsula extending out into Minocqua Lake, referred to as the “Island” (P. Garrison and J. Hurley, Wisconsin Department of Natural Resources, written commun., 1992). Growth in the area, other than the Indian Village, began with the extension of the railway from Merrill, Wis., to Minocqua in 1887, and shortly thereafter the area was logged. The Town of Minocqua was platted in 1888. Water levels have been controlled on the chain of lakes since 1889, when the Minocqua Dam (fig. 1) was constructed as part of logging operations to transport logs downstream. The dam increased lake levels by about 4 ft (Minocqua/Kawaguesaga Lakes Protection Association, 2003). The original earthen dam washed out and was rebuilt several times. In 1907, the dam was acquired by the Wisconsin Valley Improvement Company (WVIC), a private corporation, to enable the lakes to be operated as a headwater reservoir. In 1917, the existing earth and wood-frame dam was replaced by a concrete dam with wood slide gates. The wood outlet structure was then replaced in 1954 with steel tainter gates and steel gate sills (D. Coon, Wisconsin Valley Improvement Company, written commun., 2007). The dam and lake levels continue to be managed by WVIC for storage to augment the flow of the Wisconsin River that benefits hydroelectric generation, flood control, water quality, and recreation. The dam generally is operated to store runoff during spring and to release water during winter (January to March), with exceptions for dry years. The maximum water level is set at 1585.05 ft year-round, and the minimum is set at 1582.72 ft during winter and 1584.05 ft during summer (Wisconsin Valley Improvement Company, 2007). The lake level is maintained at a relatively stable level throughout summer.

The water quality of the lakes has been a public concern for many years. Water-quality data have been collected by the Wisconsin Department of Natural Resources (WDNR) as early as 1973. The Minocqua Area Lake Improvement Association was established in 1994 to preserve and protect the welfare of the Minocqua area lakes. In 1997, the organization changed its name to the Minocqua/Kawaguesaga Lakes Protection Association (referred to hereafter as “Lakes Association” for brevity). In 2000, the Lakes Association revived a lakes protection program and began participation in the WDNR lake data-collection program. The WDNR and Lakes Association have done various studies of the two lakes and their watersheds over the past 15 years. Much of the technical information available about the system is generally not in a form that is easily used by the Lakes Association, towns, and other local governments for making management decisions.



Aerial image from U.S. Department of Agriculture, 2006

Figure 1. Surface-water and topographic watersheds of Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin. The topographic watershed includes areas that do not contribute to overland flow to the lakes.

Lake-bottom sediment cores were collected in 1991 and 1992 from Minocqua Lake by the WDNR for analysis of historical sedimentation (Young, 1994; P. Garrison, Wisconsin Department of Natural Resources, written commun., 2003). Cores were collected from the East, Northwest, and Southwest Basins of Minocqua Lake (fig. 2). That study found that development since about 1890 had caused an increase in the rates of sediment and phosphorus accumulation, with largest increases in rates occurring after about 1960. The study also concluded that water quality in the lake had degraded at a slow rate since the late 1800s but that the rate of degradation accelerated around 1950 (P. Garrison and J. Hurley, Wisconsin Department of Natural Resources, written commun., 1992).

The WDNR surveyed macrophyte occurrence and distribution in 1989, 1993, and 1996 as part of the long-term-trend lake monitoring program (Wisconsin Department of Natural Resources, written commun., 1996). The most common species of macrophyte was coontail (*Ceratophyllum demersum* L.), which had increased in the frequency of occurrence since 1989. The percentage of littoral area vegetated also increased from 87 percent in 1989 to 92 percent in 1996. The macrophyte community is characterized by high diversity and primarily submergent species. Soil fertility of the littoral zone sediments was surveyed in 2002 (S. McComas, Blue Water Science, written commun., 2002) to evaluate the potential to support growth of the nuisance Eurasian watermilfoil (*Myriophyllum spicatum* L.). Eurasian watermilfoil was found only in several small patches in Minocqua Lake covering only a few acres. Nitrogen concentrations in littoral sediments were low to moderate, and the potential for supporting nuisance growth was limited to only a few small areas totaling less than 20 acres.

The impacts from septic systems on groundwater and surface water were evaluated in 1996 by the University of Wisconsin-Stevens Point (Lindemann and others, 1997). The study evaluated about half of the 160 homes on Minocqua Lake that had onsite sewage-disposal systems. The researchers found that high groundwater levels and highly permeable sandy soils can cause incomplete onsite wastewater treatment and loading of nutrients to be a concern. They also found high concentrations of ammonium, nitrate, phosphorus, and chloride in groundwater entering the lake at several sites with septic systems. The study did not, however, attempt to quantify the nutrients contributed to the lake by septic systems. The majority of septic systems studied were more than 25 years old (installed during the 1970s or earlier), and any problems associated with them were likely to increase in the future as they aged further.

Stormwater runoff from the residential/commercial developments and impervious surfaces in the urbanized area on the Island (fig. 2), as well as septic systems in the heavily developed shoreline area of Minocqua, may be sources of increased nutrient loading to the lakes. Prior to 1935, the sewage system for the Island discharged raw sewage into Minocqua Lake from multiple outfalls. In 1935, the first treatment facility was constructed on the south side of the pond on the Island, but it still discharged directly into the Northwest Basin of Minocqua Lake. In 1963, a new treatment plant was built west of Minocqua, discharging effluent into the Tomahawk River downstream and bypassing the lakes (Minocqua/Kawaguesaga Lakes Protection Association, 2003). The treatment plant started receiving wastewater from the Town of Woodruff in 1965. The consolidated Lakeland Sanitary District No. 1 was formed in 1975 and currently provides sanitary-sewer service to Minocqua/Woodruff and areas to the north and south of the Island. The Town of Arbor Vitae was added to the sanitary district in 1991. The areas served have expanded since 1965, and in 1996 the district served about 40 percent of properties on Minocqua Lake (Lindemann and others, 1997). In 2001, the sanitary district was reported to be nearing its treatment capacity (Minocqua/Kawaguesaga Lakes Protection Association, 2003). The sanitary district began construction of an upgraded wastewater facility in 2008 to provide additional treatment capacity for the next 20 years. As part of that design process, a 20-year planned area of service was identified that includes almost all of the shoreline of Minocqua Lake and the north and northwest shore of Kawaguesaga Lake (R. Groth, Lakeland Sanitary District No. 1, written commun., 2009).

Another point source of nutrient loading identified in the watershed (Blake, 1996; Minocqua/Kawaguesaga Lakes Protection Association, 2003) is the WDNR-operated Woodruff Fish Hatchery on Minocqua Thoroughfare below Madeline Lake (fig. 1). The hatchery and rearing ponds were established in 1901 and discharged effluent into the Minocqua Thoroughfare on a seasonal basis. In 1991, the hatchery was estimated to contribute about 80 lb of phosphorus per year (about 2 percent of the total annual load) to Minocqua Lake (Blake, 1996). The fish hatchery was enlarged and modernized in 1993; improvements included construction of a facility to treat and infiltrate water before it is discharged to the Thoroughfare.

Like communities around many northern Wisconsin lakes undergoing urbanization, Minocqua has experienced a population boom that doubled from 1960 to 1980 and grew by an additional 38 percent from 1990 to 2000 (fig. 3; U.S. Census Bureau, 2003). Vacant lands on lakes in the northern lakes region are disappearing—the number of lakefront homes has more than doubled since the 1960s. By 1994, vacant lots around the lakes were a rarity (Minocqua/Kawaguesaga Lakes Protection Association, 2003). More than 80 percent of northern Wisconsin's lakeshore frontage is privately owned, and the WDNR estimated that all of the remaining privately owned shoreland would be developed by 2015 (Wisconsin State Journal, 2005). In addition, in many cases, small summer cottages have been replaced by large urban-style homes accompanied by larger impervious surfaces, clearing of natural vegetation from shorelines, and creation of lawns down to the edge of water (fig. 4).

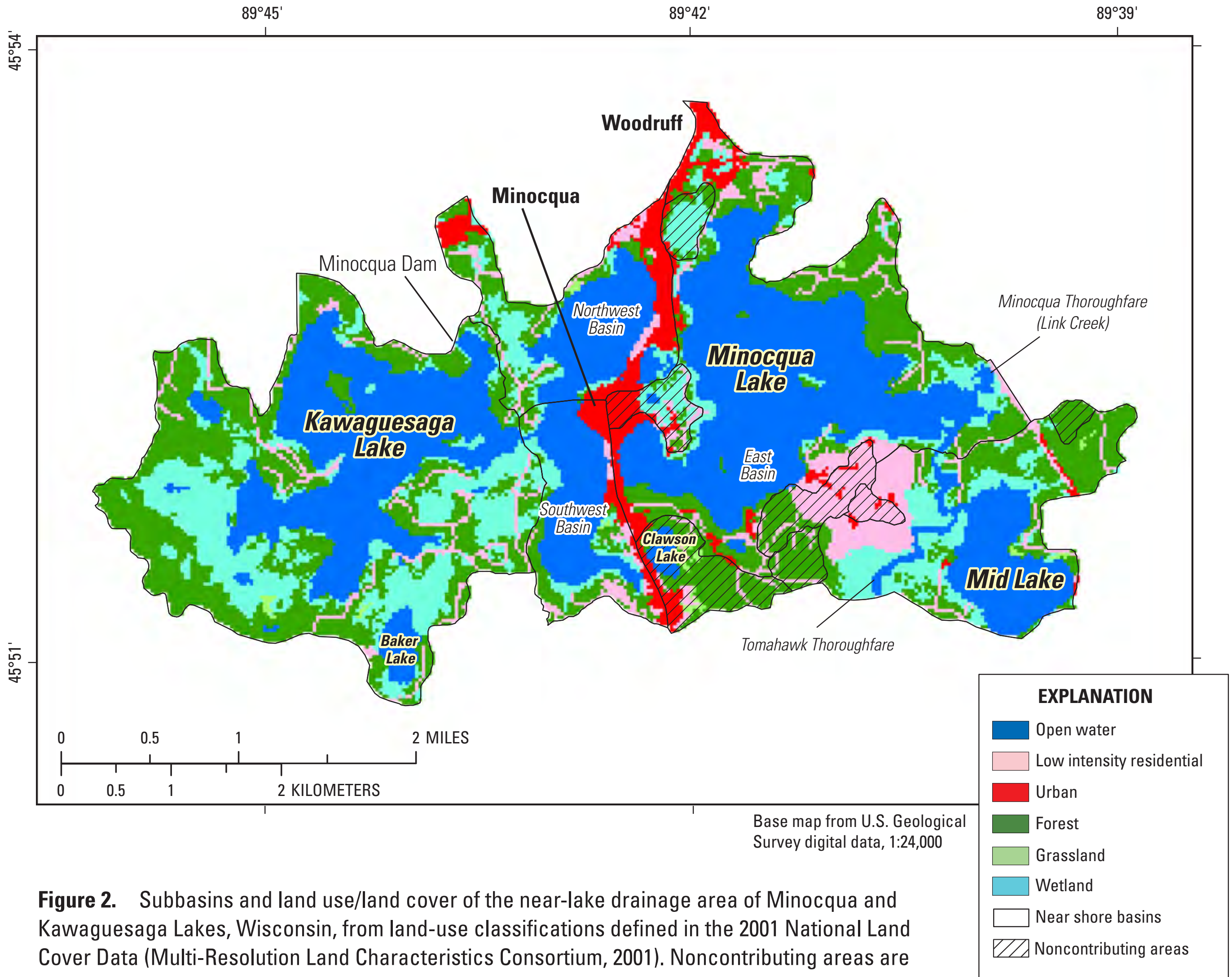


Figure 2. Subbasins and land use/land cover of the near-lake drainage area of Minocqua and Kawaguesaga Lakes, Wisconsin, from land-use classifications defined in the 2001 National Land Cover Data (Multi-Resolution Land Characteristics Consortium, 2001). Noncontributing areas are areas with internal drainages that do not drain to the lake.

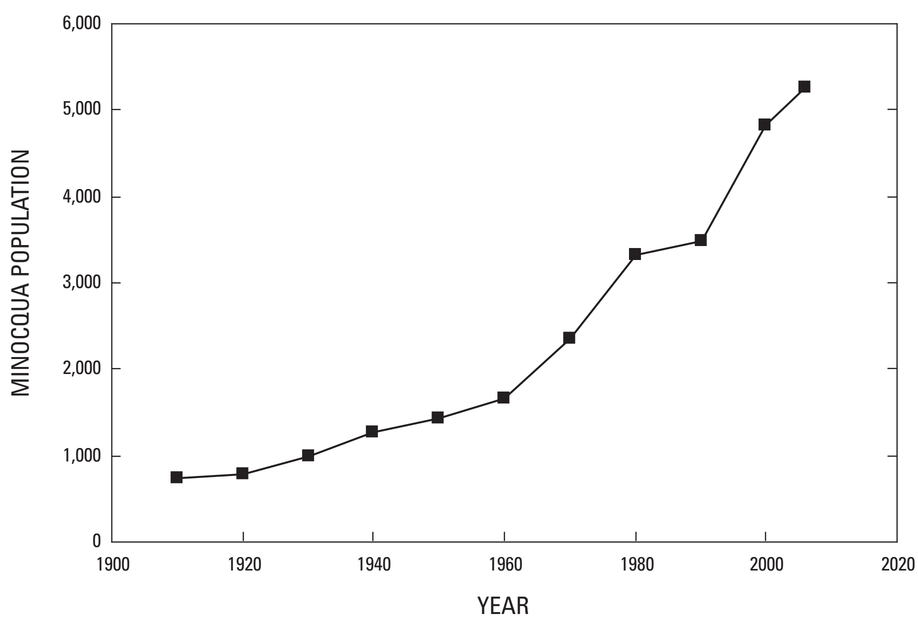


Figure 3. Population of Minocqua, Wisconsin, 1910–2006 (U.S. Census Bureau, 2003; J. Kumbera, Oneida County Economic Development Corporation, written comun., 2007).

A

B

Figure 4. (*A*) Typical lakeshore residential development prior to the 1970s and (*B*) around 2000 at Minocqua Lake, Wisconsin.

Urbanization commonly affects the hydrology of the area. It not only affects the type and the magnitude of runoff but also stream-channel stability, sedimentation/erosion, and water quality. These changes result from initial clearing of vegetation, soil disturbance and compaction, and ditching and draining, followed by covering parts of the land surface with impervious roofs, parking lots, and roads. Gutters, drains and storm sewers convey runoff rapidly to stream channels, which are often extended, straightened or lined to make them more efficient at transferring water. Natural storage areas, swales, drainageways, and wetlands may be altered or eliminated by urban development. These actions can increase downstream flooding by forcing more water into drainage networks. Each of these changes can result in a substantial increase in peak discharge and duration of a given flow magnitude—transmitting the floodwave downstream faster and with less retardation, thereby destabilizing channels and increasing sediment and other pollutant loads (Booth and Jackson, 1997; Tang and others, 2005). As a result of these changes, channels become unstable, and their widths and depths typically increase in response to urban development. Booth and Jackson (1997), in a study of various watersheds in Kings County, Wash., found that at low levels of watershed urbanization—beyond about 8–10 percent of contributing effective impervious area—channels generally became unstable, and downstream aquatic systems were degraded.

Graczyk and others (2003) monitored and compared nutrient yields from developed (homes with lawns) and forested sites in nearshore areas of four northern Wisconsin lakes. For all constituents, median nutrient yields in surface runoff from developed sites were greater than those from wooded sites. Annual median total phosphorus yield from lawns (0.026 lb/acre) was greater than that from wooded catchments (0.003 lb/acre) by about a factor of 10. Median surface runoff from lawns was generally about a factor of 10 greater than that from the wooded catchments. Thus, the increased water volumes from lawns resulted in greater nutrient loads and annual yields from the developed sites.

Various best management practices (BMPs) are commonly used to control stormwater runoff; among these are wet and dry detention ponds, created wetlands, grassed swales, filtration practices, and infiltration practices. Pollutant-removal efficiencies, expressed as a percentage, are commonly used to describe the ability of a practice to reduce pollutant levels between the inflow and the outflow of the control structure. Median pollutant-removal percentages by these BMPs for total phosphorus generally range from 0 to 70 percent (Pennington and others, 2003; U.S. Environmental Protection Agency, 2009). Use of these efficiencies as a measure may be misleading, however, because it does not take into account the importance of runoff-volume reduction and its effect on total load. Land-use-planning approaches (commonly referred to as “smart growth”) designed to minimize the increase in runoff from urbanization by optimally selecting the placement and pattern of development may reduce the increase in runoff from projected development by as much as 20 percent (Tang and others, 2005). To assist in the selection of effective BMPs, comparative information about the performance of BMP categories may be obtained from a Web-based tool: the Urban BMP Performance Tool created by the U.S. Environmental Protection Agency (2009), which provides access to studies and data pertinent to pollutant removal and stormwater-volume reduction.

The long-term management and protection of Minocqua and Kawaguesaga Lakes in the face of increased development and urbanization is a major concern to local and state government. Maintaining the quality of area lakes is key to sustaining the highly successful tourist-based economy of the towns. In 1994, the WDNR approved the Minocqua–Woodruff Priority Lakes Project Plan, prepared under the provisions of the Wisconsin Nonpoint Source Pollution Abatement Program, which recognized the lakes as high-quality resource values because of their water quality, trophy fishery, and quality multiuse recreation (Blake, 1996). In the plan, it was concluded that the lakes have experienced an increase in nonpoint-source pollution over the last several decades, including construction-site erosion, urban stormwater runoff, and impacts from lakeside development. It was also concluded that the water quality of the lakes was declining, as indicated by the perception that populations of algae and aquatic plants were increasing. The plan presented watershed-management recommendations to reduce the delivery phosphorus and sediment to the lakes and provided financial support by WDNR to achieve water-quality objectives for the lakes. The plan included estimates of phosphorus input quantities from the various sources, including septic systems (as of 1991), to target management efforts. The accuracy and reliability of these estimates, however, were questionable and based upon limited data and the methods available at that time. For various reasons, the implementation of the plan was terminated by the Town of Minocqua in 1996 (Minocqua/Kawaguesaga Lakes Protection Association, 2003).

Degradation in the water quality of lakes may have an economic impact on an area. What is the economic value of a high-quality lake? Monies are commonly allocated for lake management and protection with little or no information about the economic effects of lake water quality. Several studies have investigated the effects of accelerated eutrophication, and resulting decrease in lake water quality, on local economies and property values (Dodds and others, 2009). In addition to biological effects, reduced water clarity and increased algae and plant growth can reduce a lake’s aesthetic appeal, lower recreational benefits, and lower prices of lakefront properties around the lake. Studies in Maine estimated the effect of water clarity on lakefront property prices for a variety of lakes (Michael and others, 1996; Boyle and others, 1998). The authors found that part of the property value can be attributed to water clarity. An improvement of about 3 ft in lake water clarity as measured with a Secchi disk resulted in increased property prices ranging from $11 to $200 per frontage foot

(1990–94 Maine prices). These increases, when aggregated over all properties around a lake, could equate to several million dollars in increased property values per lake (Michael and others, 1996). The authors also found that the change in property value was greater when water clarity declined than when it improved, thus suggesting that it may be better to protect existing water clarity than to try to improve it after it has declined (Boyle and others, 1998). A study of lakes in Minnesota found a 15 percent decrease in property values for every 3 ft loss in clarity (Dodds and others, 2009).

Eisworth and others (2005) investigated the economic effects of restoring degraded Delavan Lake in Walworth County, Wis. More than $7 million was spent on restoring the quality of the 2,000-acre lake in the late 1980s to early 1990s. Property values increased 350 percent between 1987 and 1995, compared to 280 percent for nearby lakes. The Delavan Lake restoration was estimated to increase the average lake property by $177,000 from 1987 to 2003, an aggregated increase in valuation of over $99 million. In addition, the study found that degradation of water quality reduced regional economic activity by 8 to13 percent, or $5 million to $6 million per year. In summary, the studies clearly showed that lake-water clarity significantly affects the local economy and property prices and that lakefront property owners place a high economic value on good water clarity.

The Town of Minocqua, the Lakes Association, and area residents are concerned about water quality of the lakes, frequency of algal blooms, excessive weed growth, and effects of additional development and urbanization. The sensitivity of the lakes' water quality to changes in nutrient loading associated with additional development within the watershed is unknown. Quantitative information needs to be refined and updated with regard to actual rates of phosphorus loading from the various sources so that the significance of stormwater or septic-system loading as a percentage of total loading to the lakes can be evaluated. To establish realistic water-quality goals for the lakes, historical water-quality data need to be assembled, and accurate nutrient loading estimates are needed to enable water-quality models to be calibrated and used to simulate the future response of the lakes. With calibrated models, the lakes' response to incremental increases or decreases in phosphorus loading can be evaluated and be useful for determining practices or actions to help protect and improve the lakes as part of an updated lake-management plan.

To provide a better understanding of the factors that affect the water quality of Minocqua and Kawaguesaga Lakes, a detailed study of the lakes and their watersheds was begun in 2005 by the U.S. Geological Survey (USGS). This study, in cooperation with the Minocqua/Kawaguesaga Lakes Protection Association through the Town of Minocqua, was partially funded through the Lake Protection Grant Program of the WDNR and the Cooperative Water Program of the USGS. The study had the following objectives:

- Describe the hydrology and water quality of the lakes.
- Quantify the major inflows and determine a detailed phosphorus budget by quantifying the phosphorus loading associated with each source, including loading from urban areas and septic systems.
- Provide a better understanding of the problems and sources of phosphorus for developing future lake-management actions.
- Evaluate and relate the measured water and phosphorus loads to observed and modeled water-quality responses within the lakes by using available lake water-quality models.
- Assess how the water quality of the lakes should respond to increases or decreases in phosphorus loading from the watershed and changes in loading associated with specific future management actions, including some that are aimed at reducing phosphorus loads to the lakes.

Minocqua and Kawaguesaga Lakes and Their Watersheds

The Minocqua–Woodruff Priority Lakes Project Plan (Blake, 1996) includes a description of the lakes, their watersheds and water-resource conditions, and an estimate of the phosphorus budgets (sources of phosphorus loading) for the lakes based on unit-area loading data and simple models available at the time (1991). Rapid land-use changes, however, have occurred since the analysis in 1993–94, and new data, information, and techniques are now available.

Minocqua and Kawaguesaga Lakes are natural-drainage lakes, with water level controlled by a low-head dam at their outlet, in the headwaters of the Tomahawk River. Minocqua Lake is about 2.7 mi long and has a maximum width of about 2.0 mi; Kawaguesaga Lake is about 1.8 mi long and has a maximum width of about 1.7 mi. Both Minocqua and Kawaguesaga Lakes have complex, varied shorelines with multiple basins and islands that add to their scenic beauty. Minocqua Lake is divided into three distinct basins, having a maximum depth of 60 ft in the main East Basin, 30 ft in the Northwest Basin, and 40 ft in the Southwest Basin (fig. 2). Kawaguesaga Lake, whose maximum depth is 44 ft, has a less developed shoreline than Minocqua Lake. Most of the undeveloped shoreline around Minocqua Lake is due to adjacent wetlands. Kawaguesaga Lake also has a 120-acre pine forest—a State Natural Area—on the southwest side of the lake. The physical characteristics of the lakes, by basin, are summarized in table 1.

Table 1. Morphometric characteristics of Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin.

Basin	Area (acres)	Shoreline length (miles)*	Developed shoreline (percent)	Depth (feet)		Volume (acre-feet)
				Maximum	Mean	
Minocqua						
East Basin	888	10.37	83	60	24	21,716
Northwest Basin	209	3.24	86	30	17	3,573
Southwest Basin	221	3.65	100	40	23	5,184
Entire lake	**1,318**	**17.26**	**87**	**60**	**23**	**30,473**
Kawaguesaga						
Entire lake	**690**	**9.72**	**71**	**44**	**17**	**11,538**

* Excluding islands.

The area and volume of Minocqua Lake are 1,360 acres and 31,765 acre-ft and of Kawaguesaga Lake are 670 acres and 11,881 acre-ft, as given on the 1972 WDNR lake survey maps. Mean depths of the two lakes are 23 ft and 18 ft (Wisconsin Department of Natural Resources, 2001). In this study, the morphometries of the lakes were reevaluated on the basis of an aerial image obtained from the 2005 National Agricultural Imagery Program (U.S. Department of Agriculture, 2006). By using geographic information system (GIS) techniques, the resulting surface areas of Minocqua and Kawaguesaga Lakes were determined to be 1,318 and 690 acres and the volumes to be 30,473 and 11,538 acre-ft, respectively. The surface delineation of adjacent wetland areas for this study may have been different from the previous delineations and may account for the slight differences in the two determinations of area and volume. The area and volume values determined in this study were used for all of the computations in this report.

Minocqua Lake receives inflows from two major tributaries: Minocqua Thoroughfare, which drains an upstream chain of lakes from the northeast including Big Arbor Vitae, through Link Creek to Little Arbor Vitae, Carrol and Madeline Lakes; and Tomahawk Thoroughfare, which drains the area from the southeast, including Tomahawk Lake (fig. 1). An adjacent groundwater-discharge lake, Mid Lake, also discharges into the Tomahawk Thoroughfare channel upstream from its mouth with Minocqua Lake (fig. 1). Baker Lake, on the south side of Kawaguesaga Lake, has a small outlet and is the only tributary that flows into Kawaguesaga Lake (fig. 2). The total contributing area upstream from the outlet dam is 58.5 mi^2 (37,400 acres).

The surface-water contributing area of the Minocqua Thoroughfare at State Highway 47 at the inlet to Minocqua Lake is 23.8 mi^2 (15,200 acres; table 2). The second tributary, Tomahawk Thoroughfare, including flows from Tomahawk and Mid Lakes (fig. 2), has a surface-water contributing area above its mouth of 30.1 mi^2 (19,300 acres). The ungaged near-lake area, lacking any distinct stream channels, has a combined contributing area of 2,950 acres: 1,370 acres around Minocqua Lake and 1,580 acres around Kawaguesaga Lake. Surface-water contributing areas to each of the basins in Minocqua and Kawaguesaga Lakes are described in table 2.

Table 2. Land use/land cover in the contributing areas to Minocqua and Kawaguesaga Lakes, from 2001 National Land Cover Data.

[Data from the Multi-Resolution Land Characteristics Consortium, 2001]

Basin/drainage*	Area (acres)	Agriculture (percent)	Forest (percent)	Shrub/grassland (percent)	Wetland (percent)	Low-density residential (percent)	Urban (percent)	Water (percent)
Gaged watersheds								
Tomahawk Thoroughfare	18,700	0.2	56.4	2.0	6.7	5.1	1.2	28.4
Minocqua Thoroughfare	15,200	0.0	62.5	1.0	10.1	5.2	0.3	20.9
Subwatersheds of individual lakes and basins								
Mid Lake	598	0.0	38.6	1.7	29.9	20.8	1.6	7.3
Minocqua Lake	1,370	0.0	43.3	3.1	17.1	12.6	17.9	5.9
East Basin	818	0.0	50.3	1.7	14.0	14.2	12.1	7.6
Northwest Basin	355	0.0	30.3	3.3	21.6	9.4	30.1	5.4
Southwest Basin	199	0.0	37.8	8.8	21.6	11.8	20.0	0.0
Kawaguesaga Lake	1,580	0.0	51.8	1.0	34.3	6.4	0.0	6.5
Entire watershed								
Entire drainage above dam	37,400	0.1	57.9	1.6	10.0	5.8	1.4	23.2

* Not including areas of Mid, Minocqua, and Kawaguesaga Lakes.

Land use/land cover in the area contributing surface water to the lakes is primarily a mixture of forest (57.9 percent), open water (23.2 percent), and wetland (10.0 percent), with areas of low-density residential (5.8 percent, including the golf course) and smaller areas of urban (1.4 percent), shrub and grassland (1.6 percent), and agriculture (0.1 percent) (table 2). Most of the headwaters are within the Northern Highland-American Legion State Forest. Land-cover data were retrieved from the 2001 National Land Cover Data (Multi-Resolution Land Characteristics Consortium, 2001), and rural residential development was updated from 2005 aerial photographs. Agricultural uses are not a factor in this area, but urban and low-density residential uses take on greater significance, especially in the drainage areas of the Northwest and Southwest Basins of Minocqua Lake. Land uses in subwatersheds draining into each of the basins are given in table 2.

The contributing watershed consists of surficial glacial deposits, including pitted outwash and other ice-contact deposits and end moraines composed of sand and gravel. The mostly hilly, rolling terrain has flat to steep slopes. Depth of the surficial materials may be as much as 150–300 ft over igneous and metamorphic bedrock (Oakes and Cotter, 1975; Mudrey and others, 1982). The stratified glacial drift is the only important source of groundwater, yielding moderate to large quantities of water. Soils of the rolling to undulating uplands are primarily loamy sand and sand with permeabilities of 2.5 to 5 in/h or more, and muck or peat soils occur in the wetlands (Hole and others, 1968; Oakes and Cotter, 1975). Scattered throughout the area are many small closed depressions (internally drained areas (fig. 2), commonly with ponds or wetlands but without outlets) that do not contribute surface runoff to the lakes. Clawson Lake is an example of larger closed basin adjacent to the main lakes. Several smaller depressions are within the urban areas of Minocqua and Woodruff. The total noncontributing area within the entire upstream watershed was not determined, but closed basins (noncontributing areas) were taken into account in runoff estimates from the urban and other nearshore areas of Kawaguesaga and Minocqua Lakes (fig. 2).

Purpose and Scope

This report describes the water quality of Minocqua and Kawaguesaga Lakes, quantifies the water and phosphorus budgets for the lakes on the basis of data collected from November 2005 through October 2007, gives estimates of the phosphorus loading from the urbanized areas and septic systems, and presents the results of model simulations that demonstrate the potential effects that changes in phosphorus inputs may have on the water quality of the lakes.

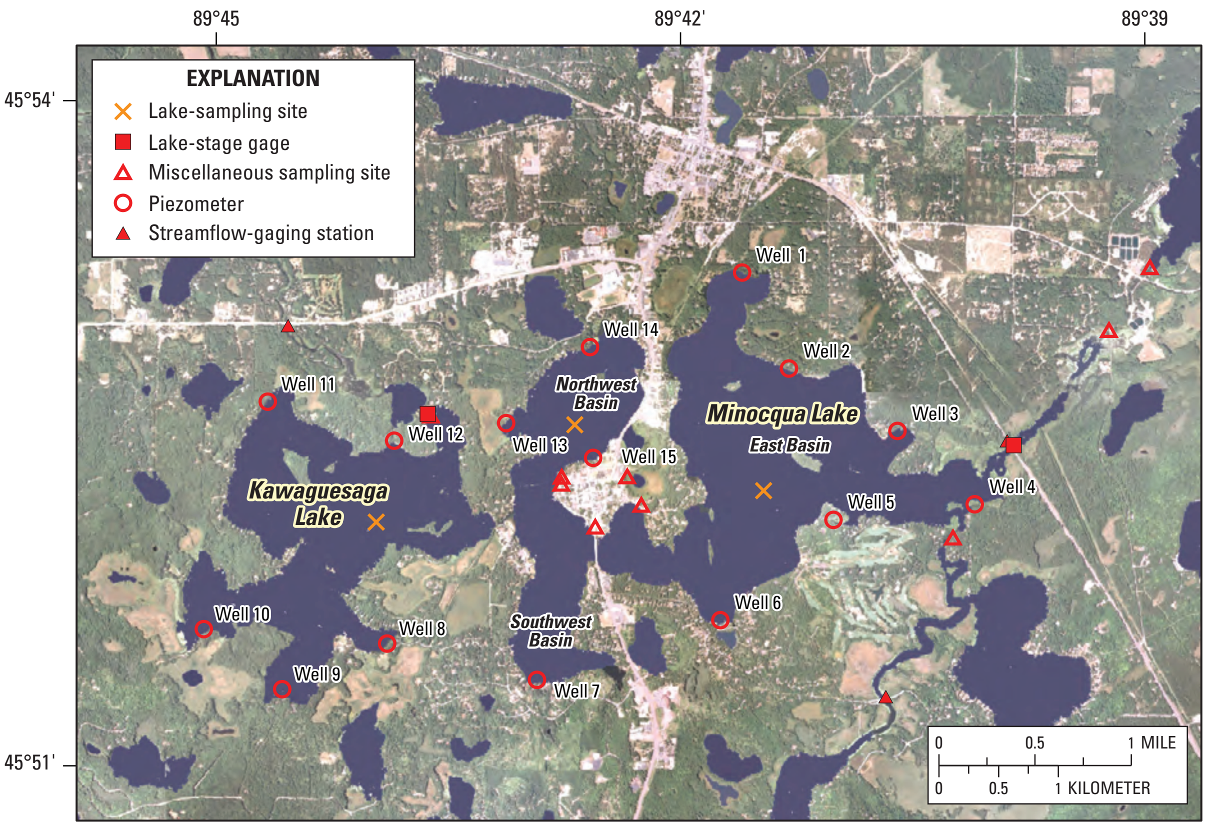
Water-quality data and detailed water and phosphorus budgets described in this report improve the understanding of the hydrologic system of the lakes and aid in the understanding of how lakes in general respond to changes in nutrient inputs. The data and interpretations herein should be useful to the lake organizations and to county and local officials in the preparation of a comprehensive lake-management plan. In addition, this report adds to the Wisconsin literature on lakes for which detailed hydrologic, phosphorus-loading, and water-quality information are available to compare with other lakes in the region.

Data-Collection Methods and Sites

USGS personnel collected stream and lake data from November 2005 through October 2007 as part of this study and had collected detailed lake water-quality data previously in 2003. In addition, earlier water-quality data for the lakes were collected by the WVIC, WDNR, and volunteers from the Lakes Association as part of the WDNR's Wisconsin Citizen Lake Monitoring Program (Wisconsin Department of Natural Resources, 2008). Data collected by the WDNR were supplied by J. Vennie (Wisconsin Department of Natural Resources, written commun., 2003), and WVIC data were supplied by C. Wendt (Wisconsin Valley Improvement Company, written commun., 2003). More recent Citizen Lake Monitoring data were obtained from the WDNR's World Wide Web page (Wisconsin Department of Natural Resources, 2008). All available data, but primarily near-surface concentrations of total phosphorus and chlorophyll *a*, plus Secchi depths, were used to characterize long-term changes in the water quality of the lakes; however, only data collected from November 1, 2005, to October 31, 2007, were used to describe the hydrology and phosphorus inputs to the lakes. This latter period was divided into two monitoring years (MY): November 2005 through October 2006 (hereafter referred to as "MY 2006") and November 2006 through October 2007 (hereafter referred to as "MY 2007").

Lake-Stage and Water-Quality Monitoring

A continuously recording (at 15-minute intervals) lake-stage gage was installed as part of the streamflow-gaging station operated on Minocqua Thoroughfare (Link Creek) at State Highway 47 on the east side of Minocqua Lake (fig. 5). WVIC also collected daily lake-stage data manually at the Minocqua Dam on Kawaguesaga Lake; these data were supplied by S. Morgan (Wisconsin Valley Improvement Company, written commun., 2007).



Aerial image from U.S. Department of Agriculture, 2006

Figure 5. Locations and types of data-collection sites at Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin.

Water-quality data for the lakes were collected by the WDNR from 1973 to 1974 as part of a statewide assessment and from 1986 to 1999 as part of their Long-Term Trend monitoring program, by the WVIC from 1979 to 1983, by volunteers from the local community and Lakes Association (Citizen Monitoring) from 1993 to 2009, and by the USGS in 2003 and from 2006 to 2007 as part of this study. In 2003, the USGS collected data in spring and monthly from May through September at the deep-hole site in the East Basin of Minocqua Lake, near the deepest location in the Southwest Basin of Minocqua Lake, and at the deep-hole site in Kawaguesaga Lake (fig. 5). In 2006 and 2007, USGS sampling supplemented the Citizen Monitoring and was done at the deep-hole sites in both lakes and near the deepest part of the Northwest Basin in spring and monthly from May through September. USGS protocols were similar to those of the WDNR Long-Term Trend monitoring program. These protocols involved collecting profiles of water temperature, dissolved oxygen, specific conductance, and pH with a multiparameter meter, and water clarity (Secchi depth) with a standard 8-in.-diameter black and white Secchi disk during each visit. Near-surface samples were collected with a Van Dorn sampler and were analyzed for total phosphorus and chlorophyll *a* concentrations and, during midsummer, for various nitrogen species (nitrite plus nitrate and Kjeldahl nitrogen). Near-bottom samples were collected about 1 m above the sediment-water interface and analyzed for total phosphorus concentration. In addition, water samples collected at the deep-hole sites in each lake during spring turnover in 2003 were analyzed for common ions and other characteristics such as color, turbidity, alkalinity, total dissolved solids, and silica.

All of the lake-stage, water-quality, and quality-assurance data collected by the USGS were published in the USGS annual data report series “Water Quality and Lake-Stage Data for Wisconsin Lakes,” water years 2003, 2006, and 2007 (U.S. Geological Survey, Wisconsin Water Science Center Lake-Studies Team, 2004, 2007, 2008).

Lake Classification

One method of classifying the water quality of a lake is with trophic state index (TSI) values based on near-surface concentrations of total phosphorus and chlorophyll *a*, plus Secchi depths, as developed by Carlson (1977). The indices were developed to place these three characteristics on similar scales to allow comparison of different lakes. TSI values based on total phosphorus concentrations (TSI_P), chlorophyll *a* concentrations (TSI_C), and Secchi depths (TSI_{SD}) were computed for each sampling by use of equations 1–3. The individual index values were averaged monthly, and the monthly average values were then used to compute summer (June through September) average TSI values:

$$TSI_P = 4.15 + 14.42 * \ln(\text{total phosphorus}) \qquad (1)$$

[total phosphorus in micrograms per liter * 1,000]

$$TSI_C = 30.6 + 9.81 * \ln(\text{chlorophyll } a) \qquad (2)$$

[chlorophyll *a* in micrograms per liter]

$$TSI_{SD} = 77.12 - 14.41 * \ln(\text{Secchi depth}). \qquad (3)$$

[Secchi depth in feet]

Oligotrophic lakes (TSI values less than 40) have a limited supply of nutrients; typically have low phosphorus concentrations, low algal populations, and high water clarity; and contain oxygen throughout the year in their deepest zones (Wisconsin Department of Natural Resources, 1992). Mesotrophic lakes (TSI values between 40 and 50) have a moderate supply of nutrients, a tendency to produce moderate algal blooms, and moderate clarity: occasional oxygen depletions in the deepest zones of the lake are possible. Eutrophic lakes (TSI values greater than 50) are nutrient rich and have correspondingly severe water-quality problems, such as frequent seasonal algal blooms and poor clarity; oxygen depletion is common throughout the deeper zones of the lake. Eutrophic lakes with TSI values greater than 60 are often further classified as hypereutrophic lakes, and they typically have even more severe water-quality problems, with frequent extensive algal blooms.

Stream Monitoring

Three stream sites (fig. 5) were equipped with instrumentation to continuously monitor flow (at 15-minute intervals). At one of the sites, Tomahawk River at State Highway 70 (about 0.5 mi downstream from the Minocqua dam), water level was measured to determine flow by use of standard stage-discharge relations (Rantz and others, 1982). The other two sites, Tomahawk Thoroughfare at Thoroughfare Road and Minocqua Thoroughfare (Link Creek) at State Highway 47 at the inlets to Minocqua Lake, were not suited to flow determination by standard stage-discharge methods because of backwater conditions, slow velocities, and periods of negative flow. These sites were equipped with acoustic Doppler velocity meters and water-level sensors and were operated as velocity-index stations (Sauer, 2002). From the 15-minute data, daily average flows for each site were computed. The data are stored and maintained in the USGS National Water Information System (NWIS) database.

Samples were collected by USGS staff or a local observer approximately monthly and during flow events by use of the Equal-Width-Increment (EWI) method (Edwards and Glysson, 1999) or by grab methods. Tomahawk River at the lake outlet was sampled by the EWI method below the dam on Kawaguesaga Lake rather than at the gaging station farther downstream. Water samples were analyzed for concentrations of total phosphorus. Phosphorus loads for the continuously monitored sites at two inlets and for the Tomahawk River outlet were computed by use of techniques described by Porterfield (1972) for integrating streamflow and concentration.

Intermittent discharge measurements and water samples were collected at several miscellaneous sites. Discharge measurements were made with an acoustic Doppler current profiler, and samples were collected at the mouth of Tomahawk Thoroughfare with Minocqua Lake, about 1.3 mi downstream from the gaging station, which included the outflow from Mid Lake. Discharge measurements and water samples were also collected during periods of runoff at four storm-sewer outlets from the urbanized area of the Island that discharge into Minocqua Lake (fig. 5). Measurements and water samples were also collected at an outfall on the southeast part of the Island that discharges pumped groundwater into Minocqua Lake; this groundwater is pumped to the surface and aerated by flowing over a step cascade as part of a remediation project to clean up dry-cleaning solvent contamination in the shallow aquifer. Other measurements and water samples were collected upstream and downstream from the WDNR fish hatchery on Minocqua Thoroughfare. All water samples were analyzed for total phosphorus. Additional water-quality data collected by the Woodruff Fish Hatchery were supplied by S. Ohm (Wisconsin Department of Natural Resources, written commun., 2007).

All water-quality data and daily flows and loads were published in the annual USGS water-data report series (Waschbusch and others, 2007, 2008) in compact-disk format.

Groundwater Monitoring

Fifteen shallow, small-diameter piezometers (1/2-in.-diameter observation wells) were installed around the periphery of both lakes (fig. 5) to help define areas contributing groundwater to each lake, to determine the phosphorus concentration in the groundwater entering the lakes, and to quantify the phosphorus loading from groundwater. The piezometers were installed approximately 2–3 ft below the water table, to depths of 5–8 ft. Ten piezometers were located along the shoreline of Minocqua Lake, and five along Kawaguesaga Lake. Groundwater gradients (determined from the differences in water elevation in the piezometers and elevation of the lake surface) and dissolved phosphorus concentrations were measured three times each year in 2006 and 2007 for each piezometer. Additional analyses for dissolved chloride and field measurements of water temperature, dissolved oxygen, specific conductance, and pH were also obtained with a flowthrough multiparameter meter during some of these sampling visits.

Water-surface elevations of selected nearby lakes and streams were surveyed in October 2006 with a Real-Time Kinematic Global Positioning System (RTK-GPS) for calibration of a local groundwater model (described in later sections). The elevations surveyed have an expected accuracy of about 0.1 ft. Concurrent base-flow discharge measurements were made at stream sites during the survey.

All lake, stream, and groundwater samples were analyzed by the Wisconsin State Laboratory of Hygiene in accordance with standard analytical procedures described in its “Manual of Analytical Methods, Inorganic Chemistry Unit” (Wisconsin State Laboratory of Hygiene, 1993).

Lake Water Quality

Most of the basins in Minocqua and Kawaguesaga Lakes are dimictic, meaning that they typically undergo two periods of extensive mixing (often referred to as “turnover”) during spring and fall, and thermally stratify during summer and winter. During summer, a thermocline (the depth interval where the temperature decreases abruptly) develops in late June and remains well established through September. The thermocline usually develops from about 13 to 30 ft below the surface in Minocqua Lake and from 16 to 30 ft below the surface in Kawaguesaga Lake (fig. 6). Bottom water temperatures were from about 8 to 10°C in Minocqua Lake and from about 11 to 13°C in Kawaguesaga Lake through the summer; surface water temperatures can approach or exceed 25°C. Dissolved oxygen concentrations are near saturation throughout the lakes just after the ice melts, but oxygen is slowly depleted below the thermocline in both lakes during June and July. By mid-August to mid-September, dissolved oxygen concentrations below the thermocline are near zero (less than 0.5 mg/L) and unable to support fish. Oxygen depletion in the hypolimnion of Kawaguesaga Lake is more rapid and occurs earlier than in Minocqua Lake. This anaerobic condition in bottom waters is fairly common and similar to what occurs in other mesotrophic lakes. During late fall, the lakes completely mix, and dissolved oxygen concentrations at all depths are near saturation again. The Northwest Basin of Minocqua Lake was polymictic, meaning it frequently mixes during all seasons except under the ice. This results in its deep water warming throughout summer and bottom dissolved oxygen concentrations also varying between samplings (fig. 6*B*). The Northwest Basin occasionally mixed to the bottom because of its shallow depth.

Water Chemistry and Trophic Conditions

The water chemistry of Minocqua and Kawaguesaga Lakes is similar and fairly typical for lakes in north-central Wisconsin, reflecting the igneous bedrock and glacial deposits in the area. The hardness of the lake water is about 45 to 50 mg/L as $CaCO_3$, which is classified as soft water (Hem, 1985). Hardness is caused primarily by the presence of calcium and magnesium. According to Lillie and Mason (1983), relatively low concentrations of calcium, magnesium, and alkalinity characterize lakes in this region. They found that for 189 lakes sampled in this region, average concentrations of calcium, magnesium, and alkalinity were 10, 5, and 37 mg/L, respectively. During this study, concentrations of calcium, magnesium, and alkalinity in Kawaguesaga and Minocqua Lakes were 13, 4, and 45 mg/L, respectively.

The specific conductance throughout the lakes during spring and fall overturns and near the surface during other periods is about 110–140 µS/cm but increases to greater than 250 µS/cm near the bottom of the lakes when these areas are anaerobic during late summer. The pH in the upper part of the lakes is typically between 7 and 8 standard units; it is about 6.5 to 7.5 near the bottom when the lakes are stratified. Specific conductance commonly increases and pH decreases in the deep anoxic zones during late summer.

Concentrations of chloride increased in Minocqua Lake from 1.0–2.0 mg/L in 1973 to 6.1 mg/L in 2003, more than a threefold increase. The median concentration of chloride in lakes in this area reported by Lillie and Mason (1983) was 2 mg/L. Concentrations of chloride and sodium are indicators of increasing urban development in the watershed. Increasing use of salt for deicing roads combined with increasing use of water softeners is the likely cause of this increase in Minocqua Lake and other developed/urbanized lakes. The changes in sodium and chloride concentration in Minocqua Lake are similar to the trends observed for many other lakes in the more populated areas of southeastern Wisconsin (Garn and others, 2006). Concentrations of chloride, however, are still very low compared to those in southeastern Wisconsin lakes. According to U.S. Environmental Protection Agency (1988) water-quality criteria, freshwater aquatic organisms should not be affected unacceptably if the 4-day average concentration of dissolved chloride does not exceed 230 mg/L.

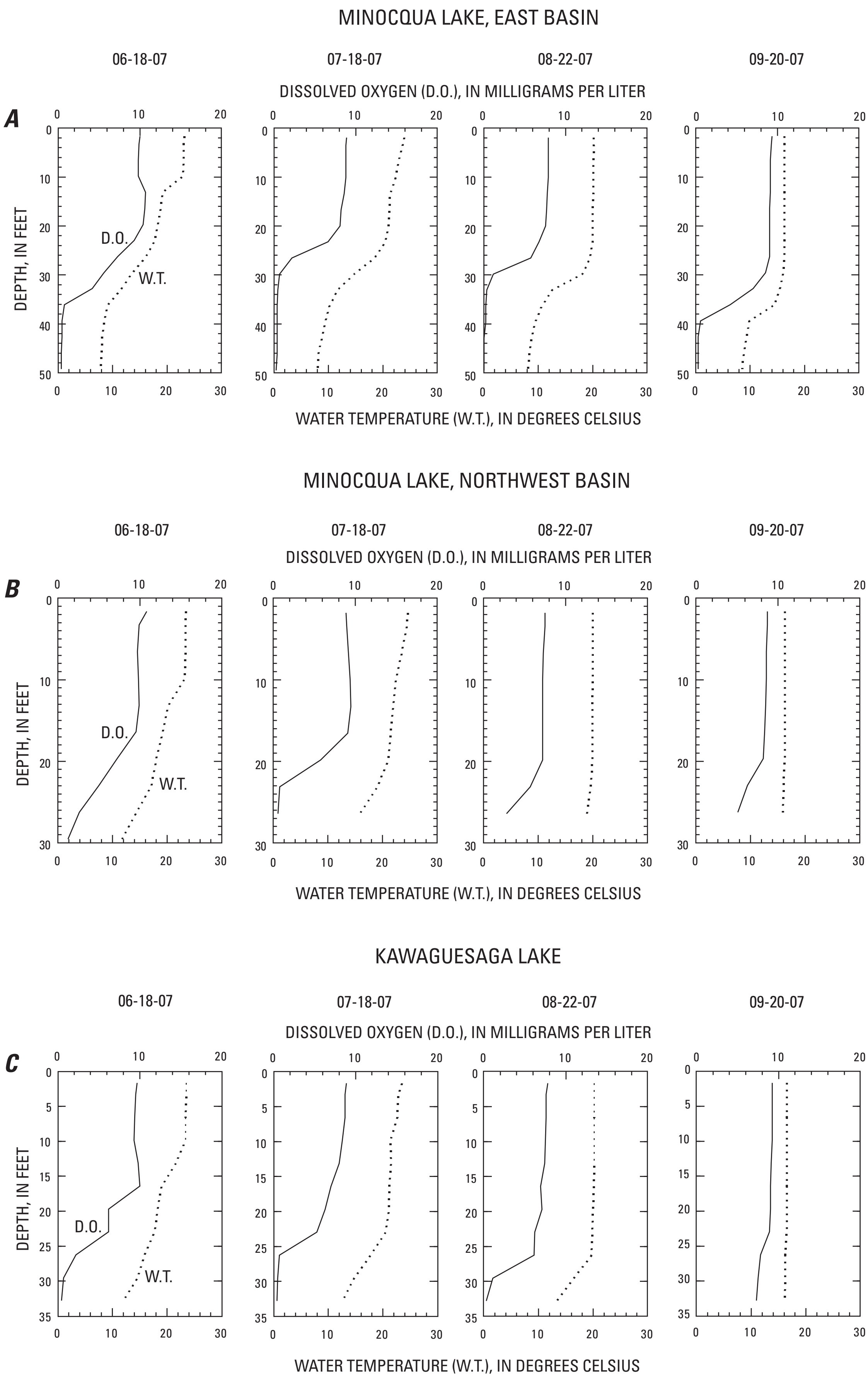


Figure 6. Water temperature and dissolved oxygen profiles on 4 selected days during summer 2007 at the deep holes in (*A*) the main East Basin, (*B*) Northwest Basin of Minocqua Lake, and (*C*) Kawaguesaga Lake, Oneida County, Wisconsin.

Phosphorus and nitrogen are essential nutrients for plant growth and are the nutrients that usually limit algal growth in most lakes. High nutrient concentrations can cause high algal populations (blooms); therefore, increased nutrient loading can be the cause of accelerated eutrophication (that is, aging and increased productivity) of lakes. Near-surface total phosphorus concentrations in the East Basin of Minocqua Lake have ranged from 0.006 mg/L to 0.07 mg/L (fig. 7). In the early 1970s and 1980s, reported total phosphorus concentrations were as high as 0.07 mg/L during fall turnover and ranged from 0.02 to 0.03 mg/L during spring turnover. The high concentrations occurred after 1965, when the new sewage-treatment plant for Minocqua and Woodruff discharged effluent into the Tomahawk River downstream from the lakes. The probable causes for these higher concentrations after diversion are not clear, but the lake may not have recovered fully by that time to reach equilibrium, and the effects of the diversion may have been limited because the initial sewered service area was smaller than at present.

From 1972 to 2009, summer average or growing-season concentrations (June through September) of near-surface total phosphorus in the East Basin fluctuated from 0.009 mg/L in 1989 to a maximum of 0.03 mg/L in 1984, but generally remained less than 0.022 mg/L after 1986 (table 3; fig. 7). There appears to be a gradual increase in phosphorus concentration since 1988; however, the lower concentrations from 1988 through 1996 may have been lower than the long-term average, possibly because of an extended drought that occurred in the late 1980s. During the 2-year study period 2006–07, the average summer concentration of total phosphorus was 0.015 mg/L, and the average concentration during spring overturn was 0.020 mg/L. Total phosphorus concentrations in the Southwest Basin were similar to those of the East Basin, but those of the Northwest Basin were generally greater. From 1991 to 2007, near-surface total phosphorus in the Northwest Basin ranged from 0.007 to a maximum of 0.043 mg/L; summer average concentrations ranged from 0.011 mg/L in 1991 to 0.022 mg/L in 2003, and the average summer concentration was 0.018 mg/L (table 3). During 2006–07, the average summer concentration of near-surface total phosphorus was 0.021 mg/L. Total phosphorus concentrations from 0.012 to 0.024 mg/L indicate mesotrophic conditions; therefore, the summer average total phosphorus concentrations indicate that since 1986, Minocqua Lake has generally been mesotrophic.

Available nutrient data for Kawaguesaga Lake are intermittent over time but exhibit similar patterns in water quality to that of Minocqua Lake. Near-surface concentrations of total phosphorus in Kawaguesaga Lake have ranged from 0.006 mg/L to 0.06 mg/L (fig. 8). In the early 1970s and 1980s, total phosphorus concentrations were as high as 0.06 mg/L in fall and winter, ranged from 0.006 to 0.033 mg/L during spring turnover, and ranged from 0.013 to 0.040 mg/L in summer (table 4; fig 8). From 1991 to 2007, summer average concentrations ranged from 0.009 mg/L in 1991 to a maximum of 0.026 mg/L in 2001 but were less than 0.024 mg/L after 2001. During 2006–07, the average summer concentration was 0.018 mg/L. Therefore, the summer average total phosphorus concentrations indicate that the lake was also generally mesotrophic since 1991.

Concentrations of near-surface total nitrogen (computed as the sum of Kjeldahl nitrogen and dissolved nitrite plus nitrate) ranged from 0.31 to 0.94 mg/L during the 1970s to 1980s in Minocqua Lake and from 0.27 to 1.05 mg/L in Kawaguesaga Lake. During summer 2003, near-surface total nitrogen concentrations were 0.38 mg/L in Minocqua Lake and 0.28 mg/L in Kawaguesaga Lake; relatively low concentrations compared to the earlier data.

The ratio of the near-surface concentrations of total nitrogen to total phosphorus (N:P ratio) is often used to determine the potential limiting nutrient in a lake. The specific value of this ratio that determines which nutrient potentially is limiting differs under varied conditions such as water temperature, light intensity, and nutrient deficiencies (Correll, 1998); however, a ratio greater than about 16:1 by weight usually indicates that phosphorus should be the potentially limiting nutrient. Ratios less than 10:1 are generally considered to indicate nitrogen limitation. The N:P ratios for the 1970s through 1980s summer data for Minocqua Lake ranged from 15:1 to 94:1, with an average of 35:1. The N:P ratios for the 1970s and 1991 summer data for Kawaguesaga Lake ranged from 11:1 to 52:1, with an average of 29:1. This indicates that phosphorus was the potentially limiting nutrient. In 2003, the N:P ratios during spring turnover for Minocqua and Kawaguesaga Lakes were 15:1 and 13:1; which indicate that algal productivity may be colimited by nitrogen and phosphorus. Reductions in phosphorus concentrations should not only increase the N:P ratio but also favor the growth of green algae over the growth of blue-green algae. Blue-green algae usually are not limited by nitrogen because they can fix nitrogen from the atmosphere. Blue-green algae are the least desirable type of algae because they commonly form extensive blooms, are potentially toxic, and are usually the least preferred by grazing zooplankton. Therefore, phosphorus should be the nutrient of concern when considering management efforts to improve the water quality of these lakes.

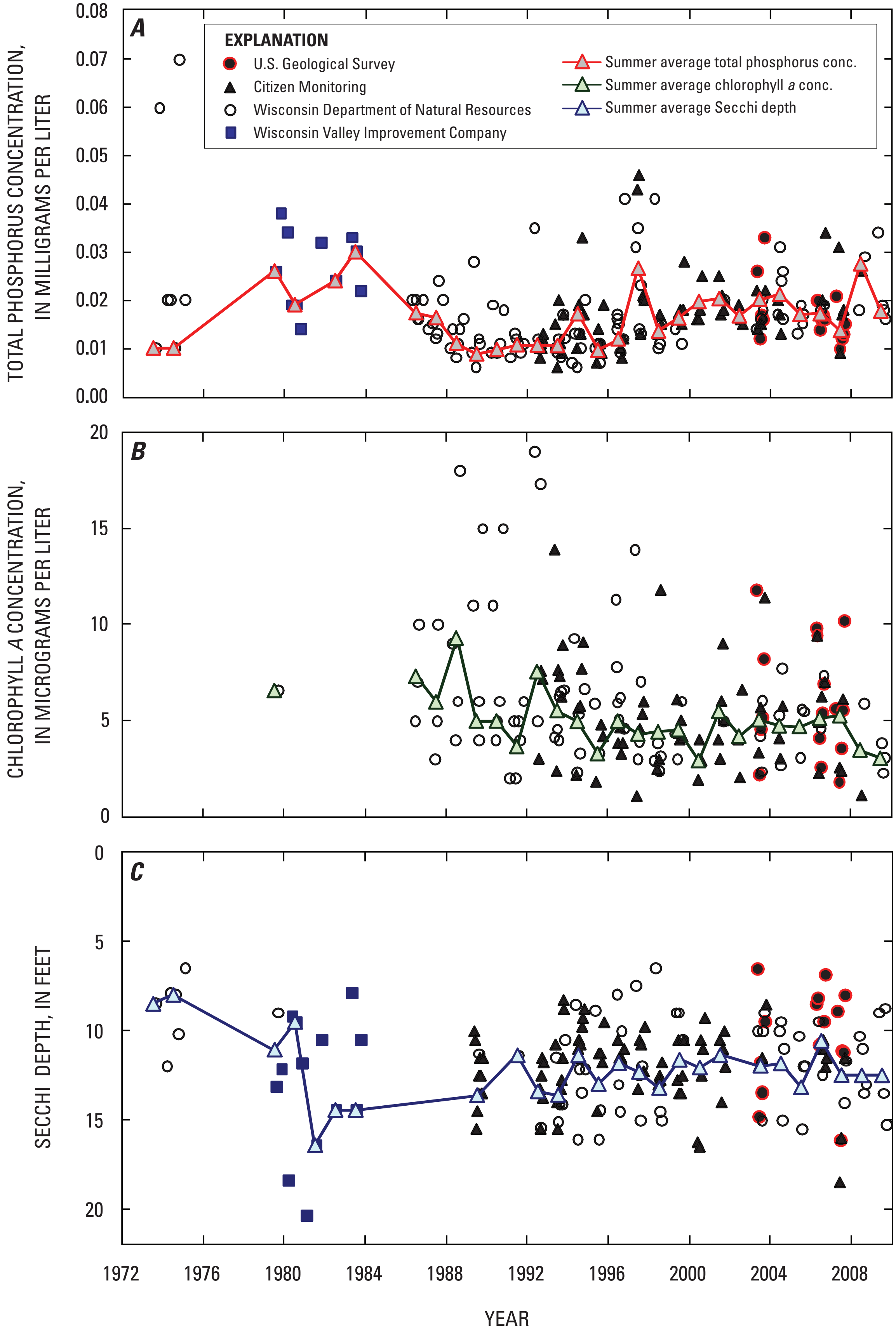


Figure 7. Near-surface (*A*) total phosphorus concentration, (*B*) chlorophyll *a* concentration, and (*C*) Secchi depths at the deep-hole site in the East Basin of Minocqua Lake, Oneida County, Wisconsin, from 1973 to 2009.

Table 3. Near-surface summer average (June through September) water-quality and trophic state index (TSI) values for Minocqua Lake, Oneida County, Wisconsin.

[**Abbreviations:** mg/L, milligrams per liter; µg/L, micrograms per liter; ft, foot; –, not measured]

Year	Total phosphorus (mg/L)	Chlorophyll *a* (µg/L)	Secchi depth (ft)	Trophic state index values		
				Phosphorus	Chlorophyll *a*	Secchi depth
East Basin (Deep-hole site)						
1973	0.010	–	8.5	37	–	46
1974	0.010	–	8.0	37	–	47
1979	0.026	6.6	11.1	51	49	43
1980	0.019	–	9.5	47	–	45
1981	0.000	–	16.4	0	–	37
1982	0.024	–	14.4	50	–	39
1983	0.030	–	14.4	53	–	39
1986	0.017	7.3	–	45	50	–
1987	0.016	6.0	–	44	47	–
1988	0.011	9.3	–	38	50	–
1989	0.009	5.0	13.6	35	46	40
1990	0.010	5.0	–	37	46	–
1991	0.011	3.7	11.4	38	43	42
1992	0.011	7.6	13.4	38	49	40
1993	0.011	5.6	13.6	37	47	40
1994	0.017	5.0	11.4	43	45	42
1995	0.010	3.3	13.0	36	42	40
1996	0.012	5.0	11.8	39	46	42
1997	0.027	4.3	12.3	50	44	41
1998	0.014	4.4	13.2	41	43	40
1999	0.016	4.6	11.6	44	45	42
2000	0.020	2.9	12.1	47	41	42
2001	0.020	5.5	11.4	47	46	42
2002	0.017	4.2	–	45	44	–
2003	0.020	5.1	12.0	47	46	42
2004	0.021	4.8	11.8	48	45	42
2005	0.017	4.7	13.2	45	45	40
2006	0.017	5.1	10.6	45	46	43
2007	0.014	5.3	12.5	41	45	41
2008	0.028	3.5	12.5	52	40	41
2009	0.018	3.1	12.5	46	41	41
Average: 1973–2009	0.016	5.1	12.2	42	45	41
Average: 2006–07	**0.015**	**5.2**	**11.5**	**43**	**46**	**42**
Northwest Basin						
1991	0.011	5.3	8.5	38	47	46
1992	–	–	12.8	–	–	40
1993	0.018	9.8	10.8	46	53	43
1994	–	–	9.6	–	–	44
1995	–	–	9.7	–	–	44
1996	–	–	14.2	–	–	39
1997	–	–	11.6	–	–	42
1998	–	–	9.4	–	–	45
1999	–	–	9.2	–	–	45
2000	–	–	8.9	–	–	46
2001	–	–	9.0	–	–	45
2003	0.022	10.4	9.5	49	54	45
2006	0.021	11.7	8.4	48	55	47
2007	0.020	9.9	10.9	47	53	43
Average: 1991–2007	0.018	9.4	10.2	46	52	44
Average: 2006–07	**0.021**	**10.8**	**9.6**	**48**	**54**	**45**

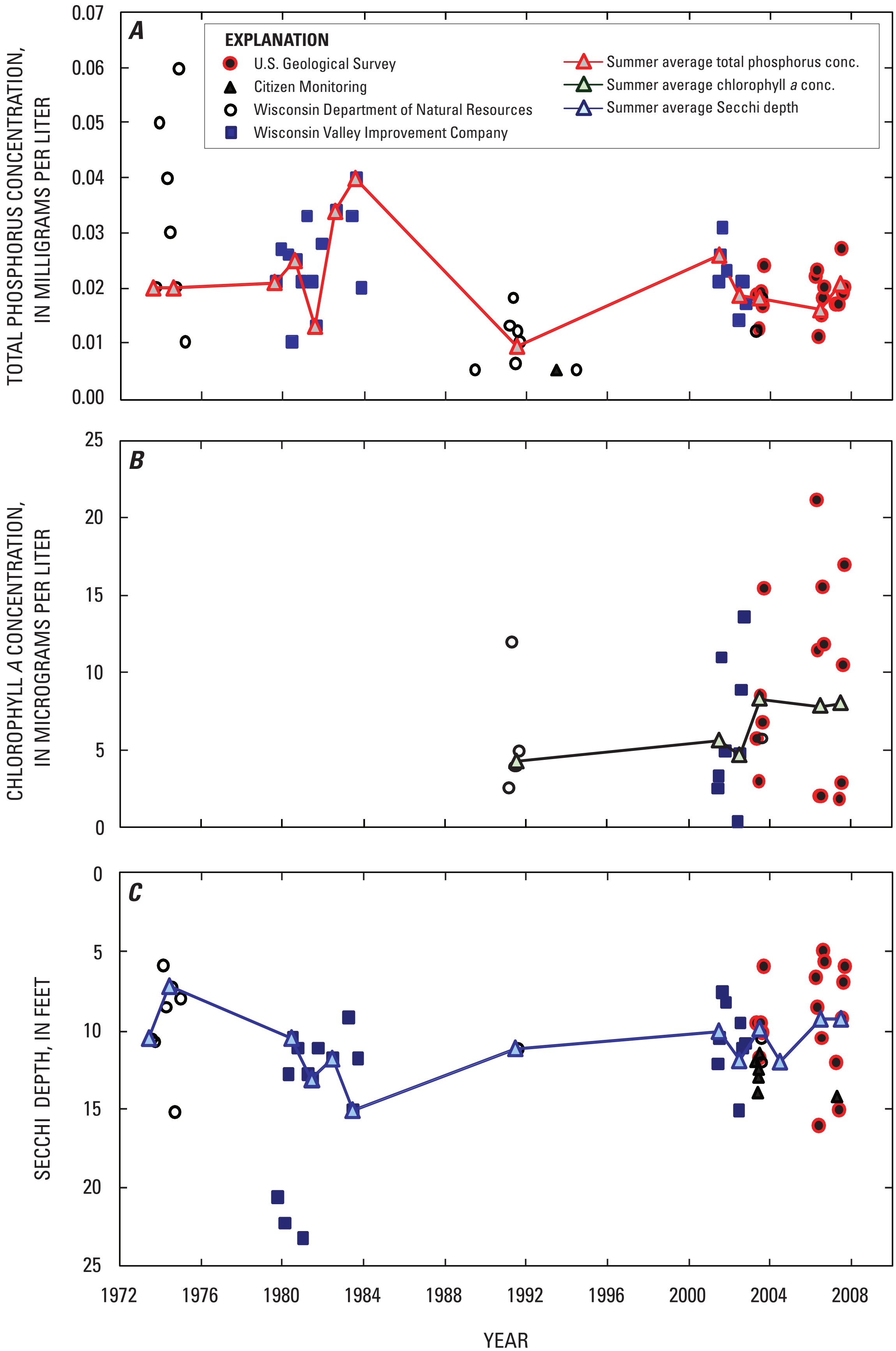


Figure 8. Near-surface (*A*) total phosphorus concentration, (*B*) chlorophyll *a* concentration, and (*C*) Secchi depths at the deep-hole site of Kawaguesaga Lake, Oneida County, Wisconsin, from 1973 to 2007.

Table 4. Near-surface summer average (June through September) water-quality and trophic state index (TSI) values for Kawaguesaga Lake, Oneida County, Wisconsin.

[**Abbreviations:** mg/L, milligrams per liter; µg/L, micrograms per liter; ft, feet; –, not measured]

Year	Total phosphorus (mg/L)	Chlorophyll *a* (µg/L)	Secchi depth (ft)	Trophic state index values		
				Phosphorus	Chlorophyll *a*	Secchi depth
1973	0.020	–	10.5	47	–	43
1974	0.020	–	7.2	47	–	49
1975	0.000	–	–	–	–	–
1979	0.021	–	–	48	–	–
1980	0.025	–	10.5	51	–	43
1981	0.013	–	13.1	41	–	40
1982	0.034	–	11.8	55	–	42
1983	0.040	–	15.1	57	–	38
1991	0.009	4.3	11.2	36	45	42
2001	0.026	5.7	10.1	51	46	44
2002	0.019	4.7	11.9	46	40	42
2003	0.018	8.3	9.9	46	50	45
2004	–	–	12.0	–	–	41
2006	0.016	7.9	9.3	44	47	47
2007	0.021	8.1	9.3	48	48	46
Average: 1973–2008	0.020	6.5	10.9	47	46	43
Average: 2006–07	**0.018**	**8.0**	**9.3**	**46**	**47**	**46**

Total phosphorus concentrations just above the bottom at the deep-hole sites ranged from less than 0.01 to 0.57 mg/L for Minocqua Lake and from less than 0.01 to 0.23 mg/L for Kawaguesaga Lake (fig. 9). In the 1970s, late-summer near-bottom concentrations measured in Minocqua Lake were as high as 0.17 mg/L; in the 1980s, bottom concentrations were as high as 0.256 mg/L; and during 2003–07 were as high as 0.273 to 0.465 mg/L after the onset of anoxic conditions (fig. 9). During 2003-07, near-bottom concentrations in the Northwest and Southwest Basins reached maximum concentrations of 0.349 and 0.359 mg/L, respectively, during anoxic conditions. In Kawaguesaga Lake, late-summer near-bottom concentrations measured in the 1970s through 1980s reached only 0.11 mg/L. During 2003–07, near-bottom concentrations in Kawaguesaga Lake reached a maximum of 0.100 to 0.231 mg/L. It appears that the bottom concentrations in both the East Basin of Minocqua Lake and Kawaguesaga Lake have increased since the 1970s; however, the apparent increase was primarily caused by a change in sampling protocols with more intense sampling in late summer (August) occurring after 1982.

Total phosphorus concentrations observed during anoxic periods are indicative of phosphorus release from the bottom sediments (referred to as “internal loading”). Because of the shallow average depth of parts of Minocqua Lake—especially in the Northwest Basin—and Kawaguesaga Lake, it is probable that mixing events during summer distribute some of the phosphorus released from the sediment throughout the water column, increasing near-surface concentrations and decreasing the buildup of phosphorus in bottom water as summer progresses.

Chlorophyll *a* is a photosynthetic pigment found in algae and other green plants. Its concentration is commonly used as a measure of the density of the algal population in a lake. Concentrations between about 2 and 7 µg/L indicate mesotrophic conditions, between 7 and 20 µg/L indicate eutrophic conditions, and greater than 20 µg/L indicate hypereutrophic conditions and are usually associated with frequent algal blooms. Few chlorophyll *a* data were available for Minocqua Lake prior to 1980; the one value available was 6.59 µg/L measured in 1979. Since 1986, near-surface chlorophyll *a* concentrations have ranged from less than 1 to 19 µg/L (fig. 7; table 3). In a number of years, highest concentrations were measured in spring. Summer average concentrations for the period of record ranged from 2.9 µg/L in 2000 to 9.33 µg/L in 1988, with an overall average of summer concentrations of 5.2 µg/L. The average summer concentration during 2006–07 was also 5.2 µg/L. Chlorophyll *a* concentrations remained relatively unchanged since the early 1990s. Therefore, summer average concentrations of chlorophyll *a* since 1986 indicate that the lake typically is mesotrophic to occasionally borderline eutrophic.

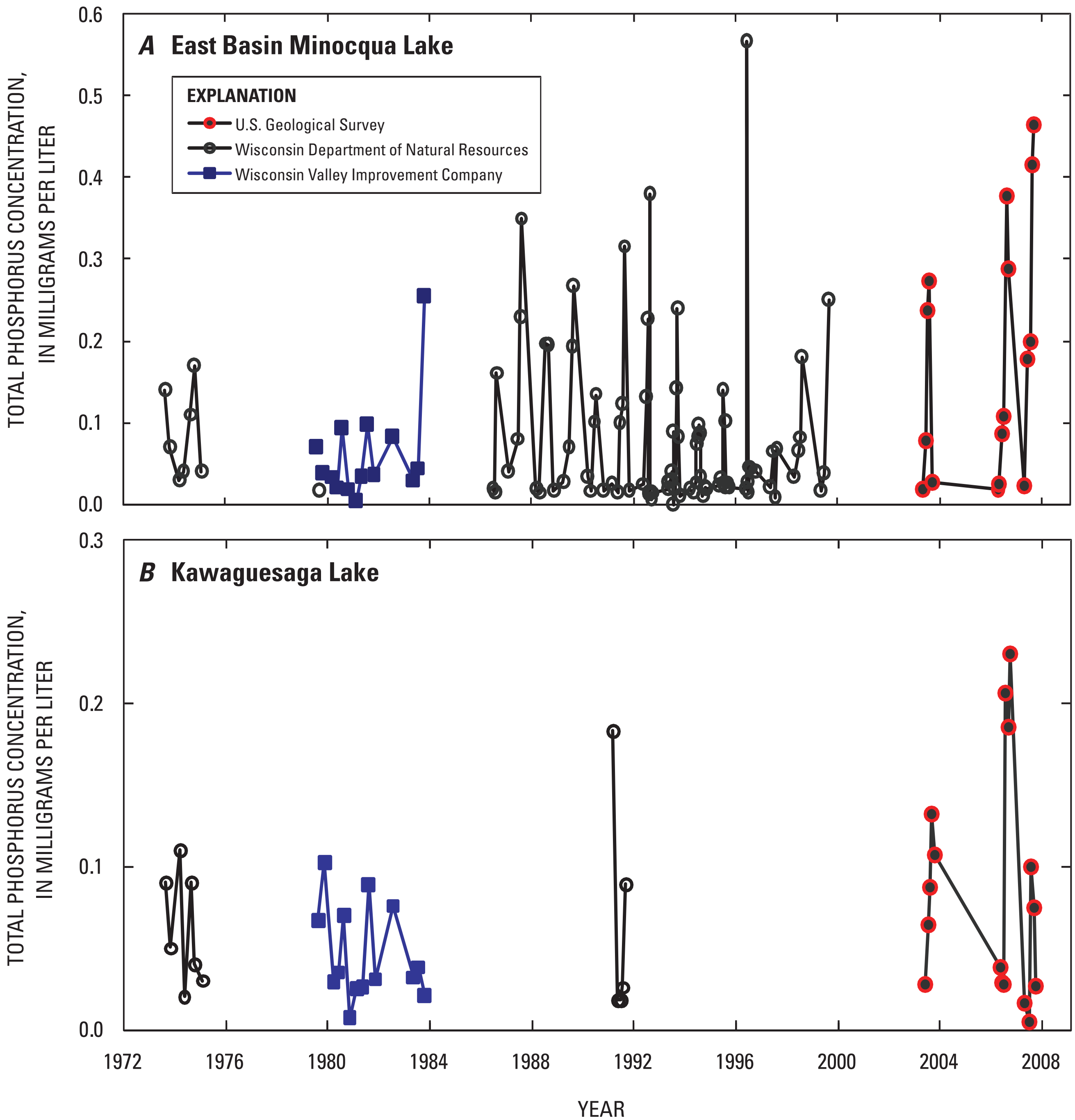


Figure 9. Near-bottom total phosphorus concentrations at the deep-hole sites in the (*A*) East Basin of Minocqua Lake, and (*B*) Kawaguesaga Lake, Oneida County, Wisconsin.

Chlorophyll *a* data were available for the Northwest Basin of Minocqua Lake for 1991, 1993 2003, and 2006–07. From 1991 to 2007, chlorophyll *a* in the Northwest Basin ranged from 1.73 to 23.2 µg/L, and summer average concentrations ranged from 5.33 µg/L in 1991 to 11.72 µg/L in 2006. During 2006–07, the average summer concentration of chlorophyll *a* was 10.8 µg/L.

Chlorophyll *a* data were available for Kawaguesaga Lake for 1991 and 2001–07 (fig 8; table 4). Concentrations of chlorophyll *a* ranged from less than 1 µg/L (2002) to 21.1 µg/L (2006). Summer average concentrations ranged from 4.33 µg/L in 1991 to 8.33 µg/L in 2003, with an overall average of summer concentrations of 6.50 µg/L. Therefore, summer average concentrations of chlorophyll *a* indicate that Kawaguesaga Lake typically is mesotrophic and occasionally is borderline eutrophic.

The average summer water clarity in the East Basin of Minocqua Lake, as measured with a Secchi disk, is 12.2 ft, but individual measurements have ranged from about 6.5 ft in several years to 20.3 ft in 1981 (fig. 7; table 3). Summer average readings from 1973 to 2009 ranged from 8.0 ft in 1974 to 16.4 ft in 1981, with no apparent trend since 1989. During 2006–07, the average summer Secchi depth was 11.5 ft. In the Northwest Basin, from 1991 to 2007, Secchi depths ranged from 4.9 ft in 1993 and 2006 to 22.7 ft in 1992; summer average readings ranged from 8.4 ft in 2006 to 14.2 ft in 1996 and averaged 10.2 ft overall. During 2006–07, the average summer Secchi depth was 9.6 ft in the Northwest Basin, which is 0.3 ft less than in the East Basin. Secchi depths less than 6 ft indicate eutrophic conditions, from 6 to 13 ft indicate mesotrophic conditions, and greater than 13 ft indicate oligotrophic conditions. Therefore, summer average Secchi depths also indicate that Minocqua Lake is typically mesotrophic.

Secchi-depth data for Kawaguesaga Lake were intermittent over time but exhibit a similar pattern to that for Minocqua Lake. Secchi depths in Kawaguesaga Lake have ranged from 4.9 ft in 2006 to 23.3 ft in 1981 (fig. 8). From 1973 to 2007, summer average Secchi depths ranged from 7.2 ft in 1974 to 15.1 ft in 1983, with an average of 10.9 ft. During 2006–07, the average of summer depths was 9.3 ft (fig. 8; table 4). Therefore, the summer average Secchi depths also indicate that the lake was generally mesotrophic.

Summer average concentrations of total phosphorus and chlorophyll *a* and Secchi depths of all four lake sampling sites are compared in figure 10. Kawaguesaga Lake and the Northwest Basin of Minocqua Lake usually had higher concentrations of total phosphorus and chlorophyll *a*, and lower Secchi depths, than did the East and Southwest Basins.

One method to describe the trophic status of a lake is to use Carlson's (1977) trophic state index (TSI). Figure 11 illustrates the variation in summer average trophic state indices for Minocqua and Kawaguesaga Lakes from 1973 to 2009. According to all three trophic state indices, the lakes are generally mesotrophic but can be classified from oligotrophic to eutrophic during individual years.

The index values based on total phosphorus and chlorophyll *a* concentrations, plus Secchi depths, indicate different trophic conditions in the lakes. From 1986 to 1996, there was more chlorophyll in the lakes than would have been expected given the measured phosphorus concentrations and water clarity. From 1997 to 2007, the amount of chlorophyll was similar to what would have been expected given the measured phosphorus concentrations, whereas the water was slightly clearer than expected from the other two parameters. In 2008 and 2009, the amount of chlorophyll was less and clarity was better than what would have been expected given the measured phosphorus concentrations. The reasons for the indices not being consistent are likely due to biological factors. The index values based on Secchi depths have not varied as dramatically as those based on the other two parameters.

The water quality of Minocqua and Kawaguesaga Lakes fluctuated during the period of record (1973 to 2009). The indices indicate that the trophic state of the lakes has changed very little since the 1970s; except for a period from the late 1980s to mid 1990s when there were lower phosphorus concentrations in the lakes.

Inferences about Changes in Water Quality from Lake-Sediment Cores

Analyses of sediment cores extracted from the East, Southwest, and Northwest Basins of Minocqua Lake by the WDNR in August 1991 were used to quantify historical changes in sedimentation rates and describe changes in the water quality of Minocqua Lake (P. Garrison and J. Hurley, written commun., 1992, 2003; Blake, 1996). That study found that development since about 1890 has caused an increase in rates of sediment and phosphorus accumulation, with largest increases in rates occurring after about 1960. The cores indicated that the Southwest Basin was more strongly affected by the development of the Town of Minocqua than the other basins. Analysis of the diatom communities in the cores indicated a progressive but gradual decline in the water quality (increased eutrophication) throughout the lake until about 1950 and an acceleration of that decline after 1950. The nutrient input from raw sewage until 1935 and treated effluent until 1965 into the Northwest Basin was not reflected in the sediment cores. Degradation in water quality appeared to have changed the least in the deeper East Basin of the lake.

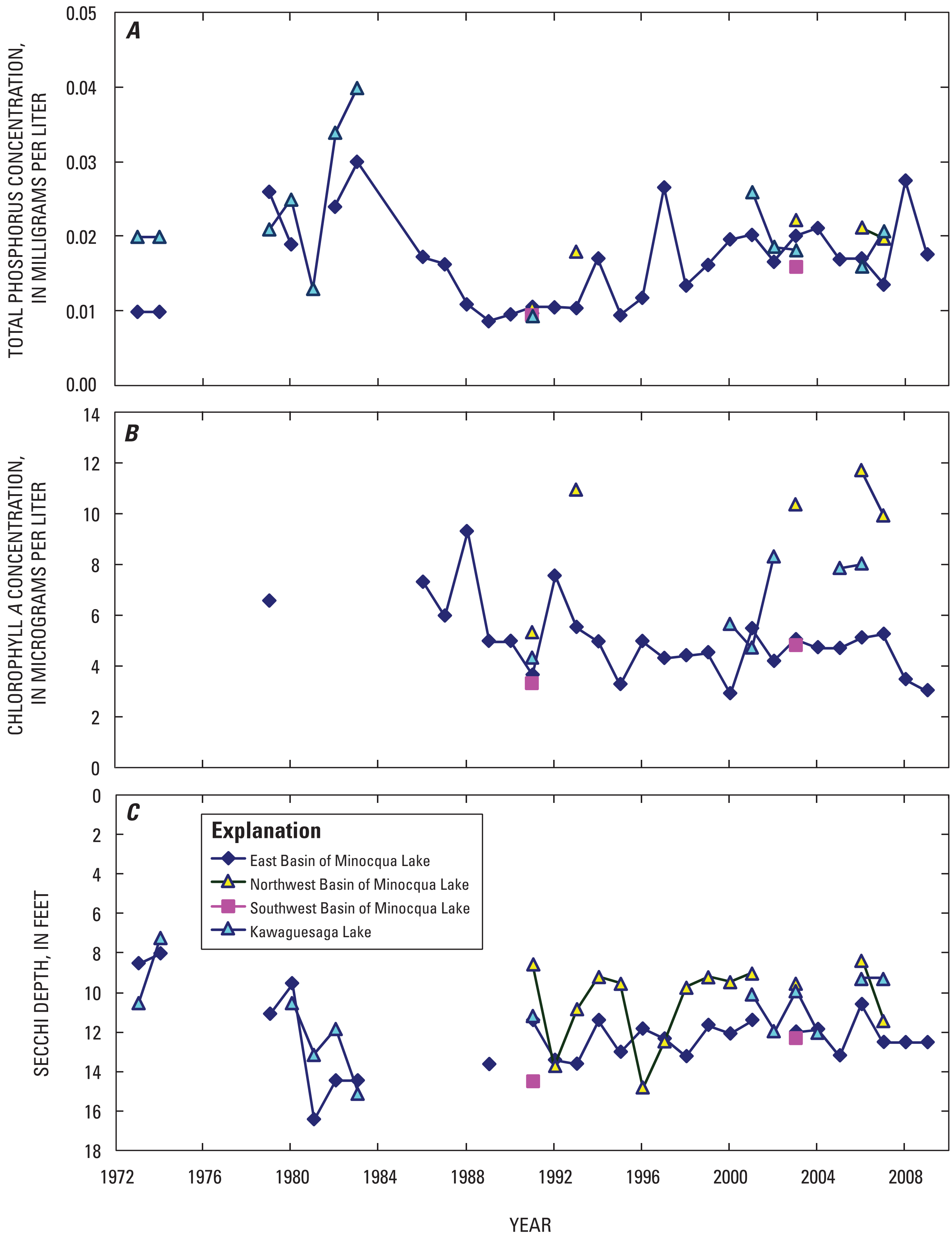


Figure 10. Summer average near-surface (*A*) total phosphorus concentrations, (*B*) chlorophyll *a* concentrations, and (*C*) Secchi depths at deep-hole sites in the basins of Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin, from 1973 to 2009.

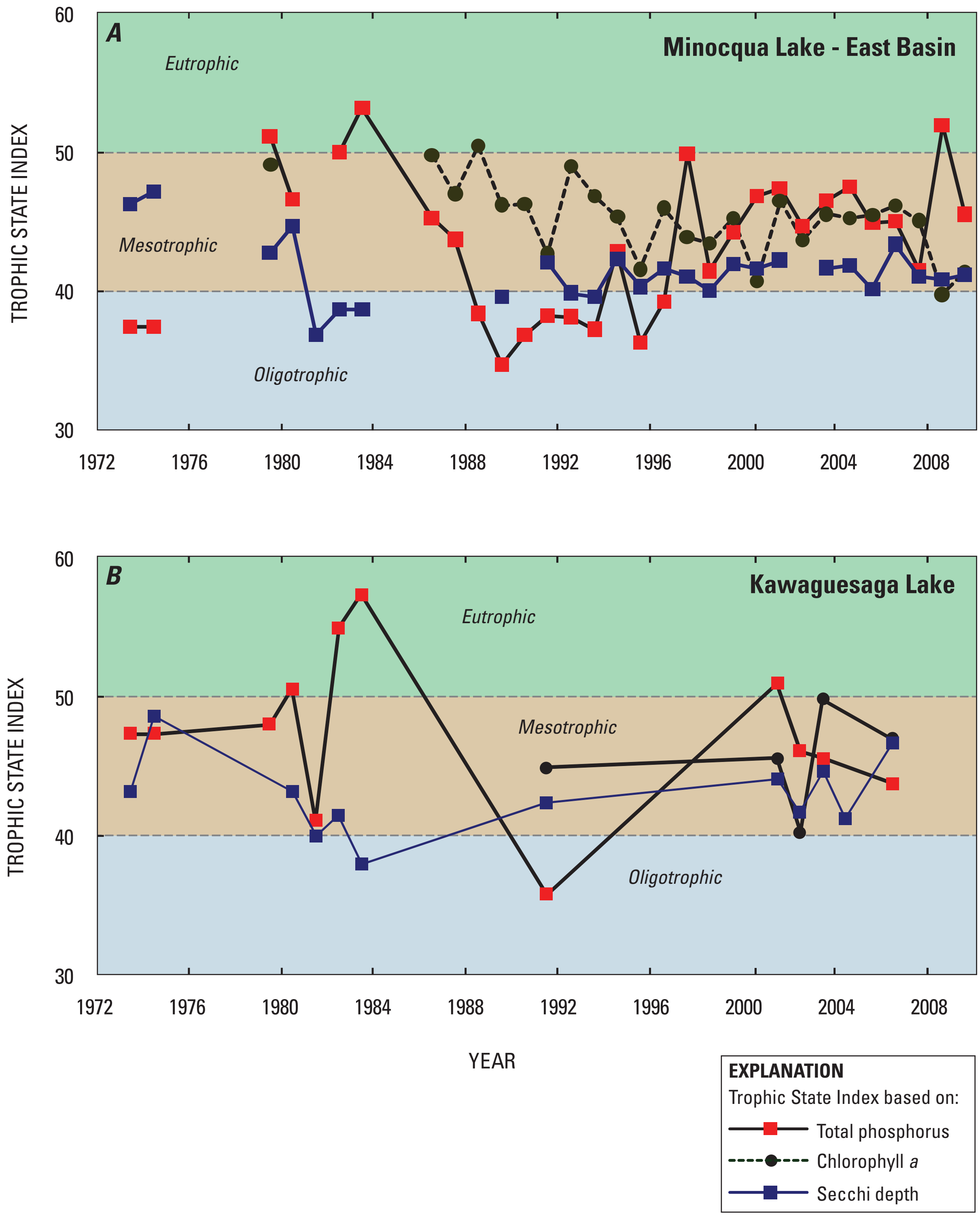


Figure 11. Trophic state index (TSI) values based on surface concentrations of total phosphorus, chlorophyll *a*, and Secchi depths at the deep-hole sites in (*A*) the East Basin of Minocqua Lake, and (*B*) Kawaguesaga Lake, Oneida County, Wisconsin, 1973 to 2009.

Hydrology and Water Budget

Because the productivity in Minocqua and Kawaguesaga Lakes is limited or colimited by phosphorus (based on N:P ratios) and because reductions in phosphorus concentrations should favor production of green algae over blue-green algae, reductions in the input of phosphorus to the lakes should reduce phosphorus concentrations in the lakes and thus improve water quality. Therefore, it is important to understand the origins of the phosphorus reaching the lake. Almost all of the phosphorus entering the lakes is transported by water inputs; therefore, to quantify phosphorus inputs, it is necessary to first quantify the water inputs. Water budgets for the lakes were quantified for each of the two monitoring years, MY 2006 (November 1, 2005, to October 31, 2006) and MY 2007 (November 1, 2006, to October 31, 2007).

The hydrology of the lakes can be described in terms of components of its water budget. The water budget for a period of interest may be represented as follows:

$$\Delta S = (P + SW_{In} + GW_{In}) - (E + SW_{Out} + GW_{Out}), \quad (4)$$

where ΔS is change in the volume of water stored in the lakes and is equal to the sum of the volumes of water entering the lakes minus the sum of the volumes leaving the lakes. Water enters the lakes as precipitation (P), surface-water inflow (SW_{In}), and groundwater inflow (GW_{In}). Water leaves the lakes through evaporation (E), surface-water outflow (SW_{Out}), and groundwater outflow (GW_{Out}). Each term of the water budget was estimated on a daily basis.

Change in Storage

Changes in the volume of the lakes were determined from water elevations measured continuously at the lake-stage gage on the northeast side of Minocqua Lake at the Minocqua Thoroughfare gaging site rather than the less frequent manual readings at the WVIC staff gage at the Minocqua Dam (fig. 5). Water is released from about mid-November to late February and stored in spring and summer. In MY 2006, water level fluctuated from 1584.39 ft (November) to 1,583.15 ft (February), and in MY 2007, water level fluctuated from 1,583.76 ft (November) to 1,584.80 ft (May) (Waschbusch and others, 2007; 2008). Because of dry conditions, no drawdown occurred in MY 2007, and the lakes gradually lost storage over the summer. To simplify computations of the change in storage, the areas of Minocqua and Kawaguesaga and Lakes were assumed to be constant (1,318 and 690 acres, respectively) during the study. For MY 2006, the net change in lake level from the beginning to end of the period was −0.45 ft, representing a loss in storage of 593 acre-ft in Minocqua Lake and 315 acre-ft in Kawaguesaga Lake. For MY 2007, there was a gain in stage of 0.75 ft, representing a gain in storage of 988 acre-ft in Minocqua Lake and 517 acre-ft in Kawaguesaga Lake.

Precipitation

During the 2-year study period, daily precipitation was measured with a recording gage at the Tomahawk Thoroughfare gaging station near the southeastern end of Minocqua Lake during nonfreezing periods and at the Minocqua Dam, reported by the National Weather Service, during freezing periods. During winter and other periods of missing record, precipitation was estimated by averaging the daily data from two other National Weather Service stations at Willow Reservoir (about 13 mi southwest of Minocqua) and at St. Germain (about 11 mi northeast of Minocqua; National Climatic Data Center, 2006, 2007). Precipitation on the lake surface during MY 2006 was 25.67 in. (2,820 acre-ft for Minocqua Lake and 1,480 acre-ft for Kawaguesaga Lake); during MY 2007, precipitation totaled 28.22 in. (3,100 acre-ft for Minocqua Lake and 1,620 acre-ft for Kawaguesaga Lake). Precipitation was 80 percent of the long-term average (1971–2000) in 2006 and 88 percent in 2007, reflecting an extended dry period in the region. Monthly precipitation during each study year is compared to the 1971–2000 average monthly precipitation in figure 12. In MY 2006, precipitation totals for November through March and for July were above or near the long-term average; all other monthly totals were much below average. In MY 2007, only December, March, May, and October totals were above or near the long-term average, and all other months were below average.

Evaporation

Evaporation from the lake surface was estimated from pan evaporation measured at Marshfield, Wis., during June–September (National Climatic Data Center, 2006, 2007) and long-term monthly estimates of pan evaporation at Green Bay, Wis., from Farnsworth and Thompson (1982). Pan evaporation at Marshfield for months without data was estimated from the ratio of Marshfield to Green Bay pan evaporation. Estimated pan data for Marshfield were then adjusted for the difference in location to Minocqua Lake. Monthly lake/pan coefficients computed from long-term pan- and lake-evaporation data for Rainbow Reservoir furnished by S. Morgan (Wisconsin Valley Improvement Company, written commun., 2008) were then used to adjust the pan-evaporation rates to obtain monthly lake evaporation for the lakes. These coefficients ranged from 0.73 in May to 1.03 in September. It was assumed that evaporation from the lakes was zero during periods of ice cover and that the lakes were ice covered from December through March. Annual evaporation was estimated to be 23.93 in. in MY 2006 (2,630 acre-ft from Minocqua Lake and 1,380 acre-ft from Kawaguesaga Lake) and 23.22 in. in MY 2007 (2,550 acre-ft from Minocqua Lake and 1,340 acre-ft from Kawaguesaga Lake; table 5).

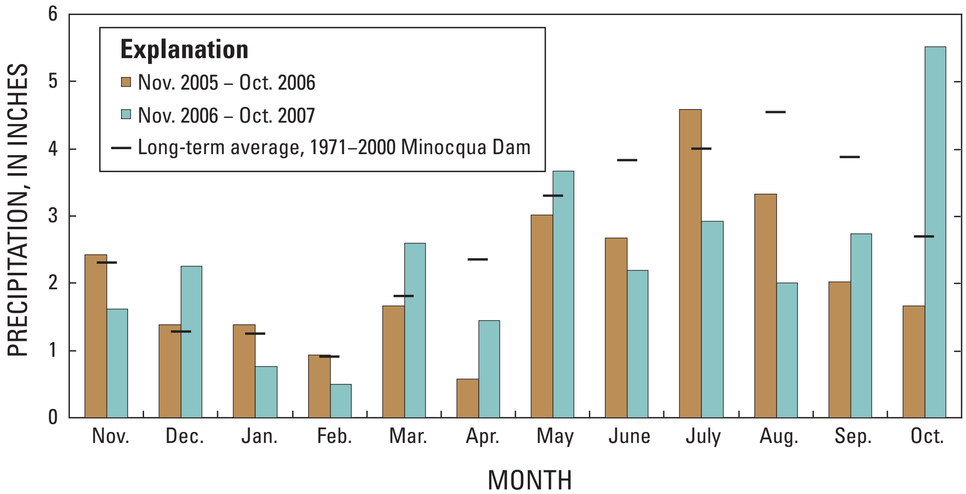


Figure 12. Precipitation at Minocqua Lake during November 2005 to October 2007 relative to long-term average precipitation, measured at Minocqua Dam, Oneida County, Wisconsin.

Surface-Water Inflow

Annual runoff for rivers in the region reflected the dry conditions in north-central Wisconsin during both monitoring years. In both 2006 and 2007, the dry summers prompted the Governor to declare counties in northern Wisconsin in a state of emergency because of drought conditions. In MY 2006, runoff at nearby long-term USGS gaging stations ranged from 60 percent of the long-term average annual runoff (1991–2006) at Bear River near Manitowish Waters, Wis., to 81 percent of the average annual runoff (1991–2006) at Trout River at Trout Lake near Boulder Junction, Wis., and 85 percent of the average annual runoff (1936–2006) at the Wisconsin River at Rainbow Lake near Lake Tomahawk, Wis. (Waschbusch and others, 2007). In MY 2007, runoff ranged from 32 percent of the average annual runoff (1991–2007) at the Bear River station to 58 percent of the average annual runoff at Trout River at Trout Lake and 62 percent of the average annual runoff at the Wisconsin River at Rainbow Lake (Waschbusch and others, 2008).

Gaged Sites

Daily inflow from Minocqua Thoroughfare (Link Creek), one of the main tributaries to the lakes, was measured at the gaging station at State Highway 47 (fig. 5). The annual average flow at this site was 16.76 ft^3/s (12,100 acre-ft) in MY 2006 and 12.76 ft^3/s (9,240 acre-ft) in MY 2007 (table 5, fig. 13*A*).

Daily inflow from Tomahawk Thoroughfare, the other main tributary that includes Tomahawk Lake, was measured at the gaging station at Thoroughfare Road (fig. 5). The annual average flow at this site was 17.5 ft^3/s (12,700 acre-ft) in MY 2006 and 5.68 ft^3/s (4,110 acre-ft) in MY 2007. This site is characterized by not only extended periods (up to several days) of negative flow caused by west winds but also changes in gate openings and water releases at the dam (fig. 13*B*). This station is not directly at the mouth to Minocqua Lake, so there is a resulting ungaged area of 598 acres (fig. 5). The flow from Mid Lake and the intervening area between the mouth of Tomahawk Thoroughfare and the gage was estimated with the following equation, which was applied on a daily time step.

$$Q_i = P - E + GW - \Delta S, \qquad (5)$$

where

Q_i is the flow from the intervening area,
P is precipitation,
E is evaporation,
GW is groundwater discharge to Mid Lake, and
ΔS is change in storage in the channel and Mid Lake from the previous day.

It was assumed that the water level in the channel and Mid Lake is the same as the water level in Minocqua Lake. The estimated flow from this additional Mid Lake drainage area was added to the measured streamflow at Thoroughfare Road. Thus, the total annual flow from Tomahawk Thoroughfare at its mouth with Minocqua Lake was an estimated 19.69 ft^3/s (14,300 acre-ft) in MY 2006 and 7.06 ft^3/s (5,110 acre-ft) in MY 2007 (table 5).

Nearshore Ungaged Area (Including Urban Areas)

Smaller subwatersheds making up the near-lake drainage area (referred to herein as “near-lake drainage”; fig. 2) also contribute runoff to the lakes, especially from the more developed urbanized areas with impervious surfaces. These were subdivided into the areas contributing runoff to each of the basins of Minocqua Lake and to Kawaguesaga Lake. Numerous noncontributing drainage areas exist within the near-lake drainage that effect surface runoff to the lakes.

Table 5. Summary of water-budget components for Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin, during monitoring years 2006–07, during average hydrologic conditions, and with future development in the watershed.

[**Abbreviations:** MY, monitoring year November–October; NA, not applicable]

Budget component	MY 2006	MY 2007	2-year average	Percent of 2-year total	Average hydrology	2030 buildout	
						MY 2006–07 hydrology	Average hydrology
Change in storage (acre-feet)	-908	1,500	592	NA	0	0	0
Inputs to lake (acre-feet)							
Precipitation							
Minocqua Lake	2,820	3,100	2,960	10.5	3,520	2,960	3,520
Kawaguesaga Lake	1,480	1,620	1,550	5.5	1,850	1,550	1,850
Tributaries							
Minocqua Thoroughfare (inlet)	12,100	9,240	10,700	37.8	14,300	10,700	14,300
Tomahawk Thoroughfare (inlet)	14,300	5,110	9,680	34.3	16,400	9,680	16,400
Near-lake drainage (including urbanized areas)							
Minocqua Lake							
East Basin	108	133	121	0.4	140	191	223
Northwest Basin	84	104	94	0.3	98	127	170
Southwest Basin	32	41	36.5	0.1	45	60	63
Kawaguesaga Lake	19	23	21	0.1	23	38	42
Groundwater							
Minocqua Lake	2,880	2,200	2,540	9.0	3,000	2,540	3,000
Kawaguesaga Lake	638	486	562	2.0	650	562	650
TOTAL INPUT	34,400	22,100	28,300	100	40,000	28,400	40,200
Outputs from lake (acre-feet)							
Evaporation							
Minocqua Lake	2,630	2,550	2,590	9.4			
Kawaguesaga Lake	1,380	1,340	1,360	4.9			
Groundwater							
Minocqua Lake	0	0	0	0.0			
Kawaguesaga Lake	667	667	667	2.4			
Tomahawk River (outlet)	30,300	15,600	22,900	83.3			
TOTAL OUTPUT	35,000	20,100	27,600	100			

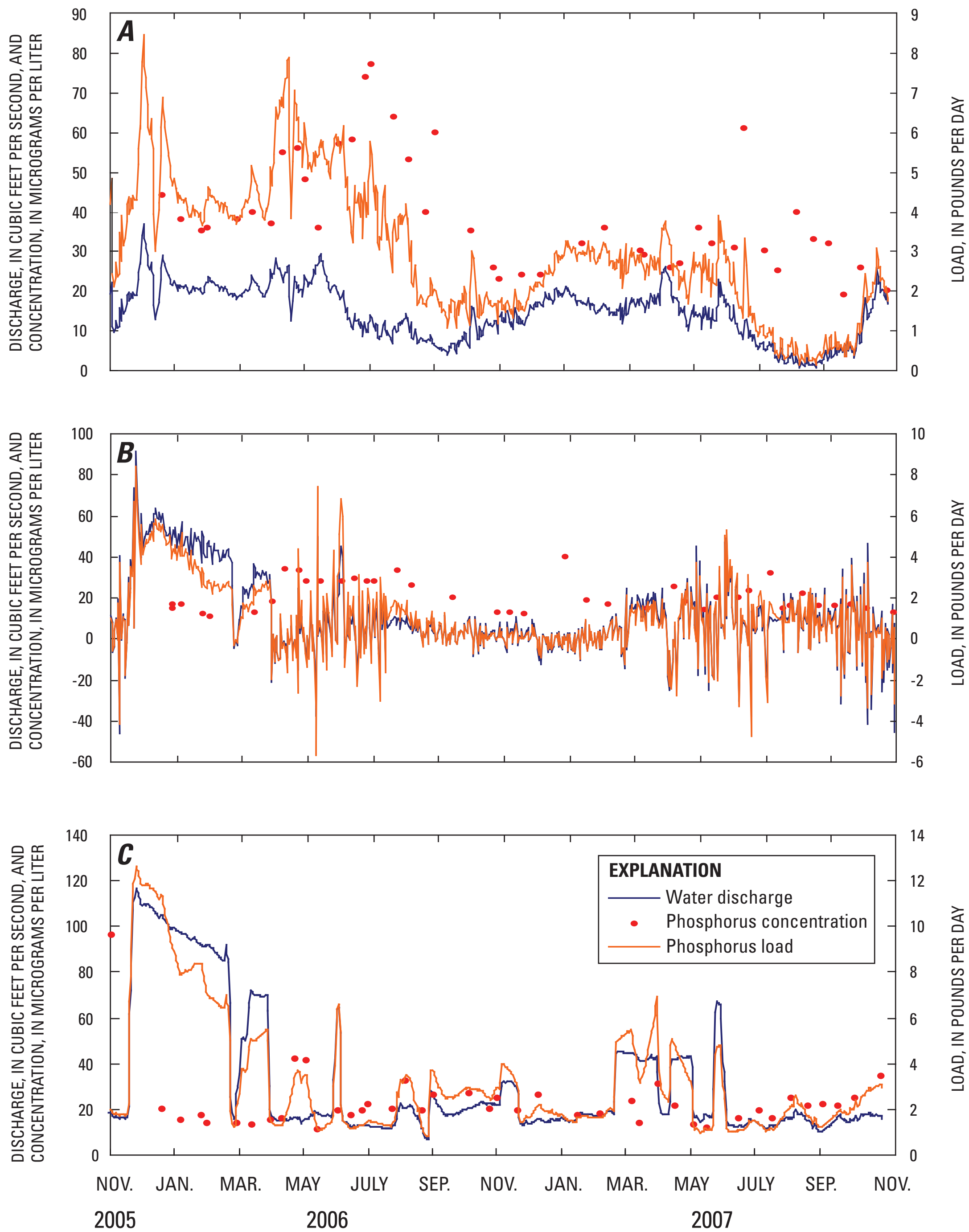


Figure 13. Daily discharge, phosphorus concentrations, and phosphorus loads at (*A*) Link Creek near Woodruff (Minocqua Thoroughfare), (*B*) Tomahawk River at Thoroughfare Road near Minocqua (Tomahawk Thoroughfare), and (*C*) Tomahawk River at Minocqua Dam near Minocqua, Wisconsin, November 2005 through October 2007.

Runoff from the ungaged area was estimated by using the Windows Source Loading and Management Model (WinSLAMM), which is commonly used to generate runoff volumes and loads from urban areas (Pitt and Voorhees, 1993). The latest standard parameter files and coefficients (May 2009) were used in WinSLAMM to estimate runoff (available on the USGS Web page http://wi.water.usgs.gov/slamm/index.html). Runoff coefficients for forest on sandy soils were from those estimated by Graczyk and others (2003) for northern Wisconsin. Runoff was estimated on the basis of actual precipitation measured in MY 2006 and MY 2007 (less than average rainfall); urban land uses (commercial/industrial and high-density residential) were assumed to have streets with curb-and-gutter drainage, whereas low-density rural residential uses were assumed to have roads drained by shallow roadside swales. Total runoff estimated for the ungaged contributing areas was 243 acre-ft in MY 2006 and 301 acre-ft in MY 2007. Runoff to the East Basin was 108 acre-ft in MY 2006 and 133 acre-ft in MY 2007, to the Southwest Basin was 32 acre-ft in MY 2006 and 41 acre-ft in MY 2007, and to the Northwest Basin was 84 acre-ft in MY 2006 and 104 acre-ft in MY 2007. The remaining ungaged area surrounding Kawaguesaga Lake has a contributing area of about 1,581 acres and contributed only about 19 acre-ft in MY 2006 and 23 acre-ft in MY 2007.

Surface-Water Outflow

Daily outflow from the lakes was measured at the gaging station at the Tomahawk River at State Highway 70 (about 0.5 mi downstream from Minocqua Dam; fig. 5). The measured outflow was adjusted for the estimated groundwater discharge between the dam and the gaging station (0.7 ft^3/s) to determine the outflow at Minocqua Dam. Outflow at the dam ranged from 6 to 116 ft^3/s (fig. 13*C*). The total annual surface-water outflow was 30,300 acre-ft in MY 2006 and 15,600 acre-ft in MY 2007 (table 5).

Groundwater Inflow and Outflow

The two-dimensional, analytic-element, steady-state, groundwater-flow model GFLOW (Haitjema, 1995) was used to define groundwater-source areas around Minocqua and Kawaguesaga Lakes and to allocate groundwater discharge to shoreline segments represented by the installed piezometers around the lakes. A complete description of analytic-element modeling is beyond the scope of this report; however, a brief description is given below. A thorough discussion of the methods for applying the model can be found in Strack (1989) and Haitjema (1995).

An infinite aquifer is assumed in analytic-element modeling. In GFLOW, the study area (domain) does not require a grid or involve interpolation between cells. To construct an analytic-element model, features that affect groundwater flow (such as surface-water bodies, aquifer characteristics, and recharge) are entered as mathematical elements or strings of elements. The amount of detail specified for the features depends on the distance from the area of interest. Each element is represented by an analytic solution. The effects of these individual solutions are added together to arrive at a solution for the groundwater-flow system. Because the solution is not confined to a grid, groundwater levels (heads) and flows can be computed anywhere in the study area without averaging values at specific locations in the model (nodal averaging). In the GFLOW model, the analytic elements are two dimensional and are used to simulate only steady-state conditions. Groundwater-flow systems are three dimensional; however, two-dimensional models can provide reasonable approximations of groundwater flowlines when the lengths of the flowlines are long compared to the aquifer thickness (Haitjema, 1995, p. 23). In the study area, most groundwater was assumed to move through unconsolidated deposits that have a maximum saturated thickness of 250 ft or less. The lengths of flowlines from recharge areas to discharge areas are typically several thousand feet or more.

The GFLOW model for the study area covers an area extending approximately 10 to 15 mi around Minocqua and Kawaguesaga Lakes (fig. 14). The geometry of the single-layer model includes a bottom elevation set at 1,450 ft and an average aquifer thickness of 250 ft, which were based on well logs for the study area and additional information from Patterson (1989). Recharge was applied uniformly across the entire simulated area. Surface-water features were simulated by using several types of linesink elements. The model includes “farfield” and “nearfield” sources and sinks of water (collectively referred to as linesinks). The farfield area surrounds the nearfield area of interest. In the farfield, streams and lakes are simulated as coarse linesinks having little or no resistance between the surface-water feature and the groundwater-flow system. The purpose of simulating the farfield is to have the model explicitly define the regional groundwater-flow field near the area of interest. The nearfield represents the area of interest and includes Minocqua and Kawaguesaga Lakes, all upstream lakes and streams, plus most adjacent lakes and streams.

Nearfield lakes and streams, which are in good connection with the groundwater-flow system, were included as linesinks with resistance. In analytic-element modeling, resistance is computed by dividing the bed-sediment thickness by the vertical hydraulic conductivity. Nearfield streams were simulated by using head-specified linesinks with resistance of 0.3 day and widths ranging from 5 to 100 ft. Nearfield lakes were simulated as head-specified or lake linesinks, both with a resistance of 0.5 day. Lake widths and depths were determined from USGS topographic maps, and lake stages were measured with a GPS-RTK survey instrument. Resistance values used in this model are similar to values used in other GFLOW models for areas nearby (Hunt and others, 1998; Graczyk and others, 2003, Robertson and others, 2005). Minocqua,

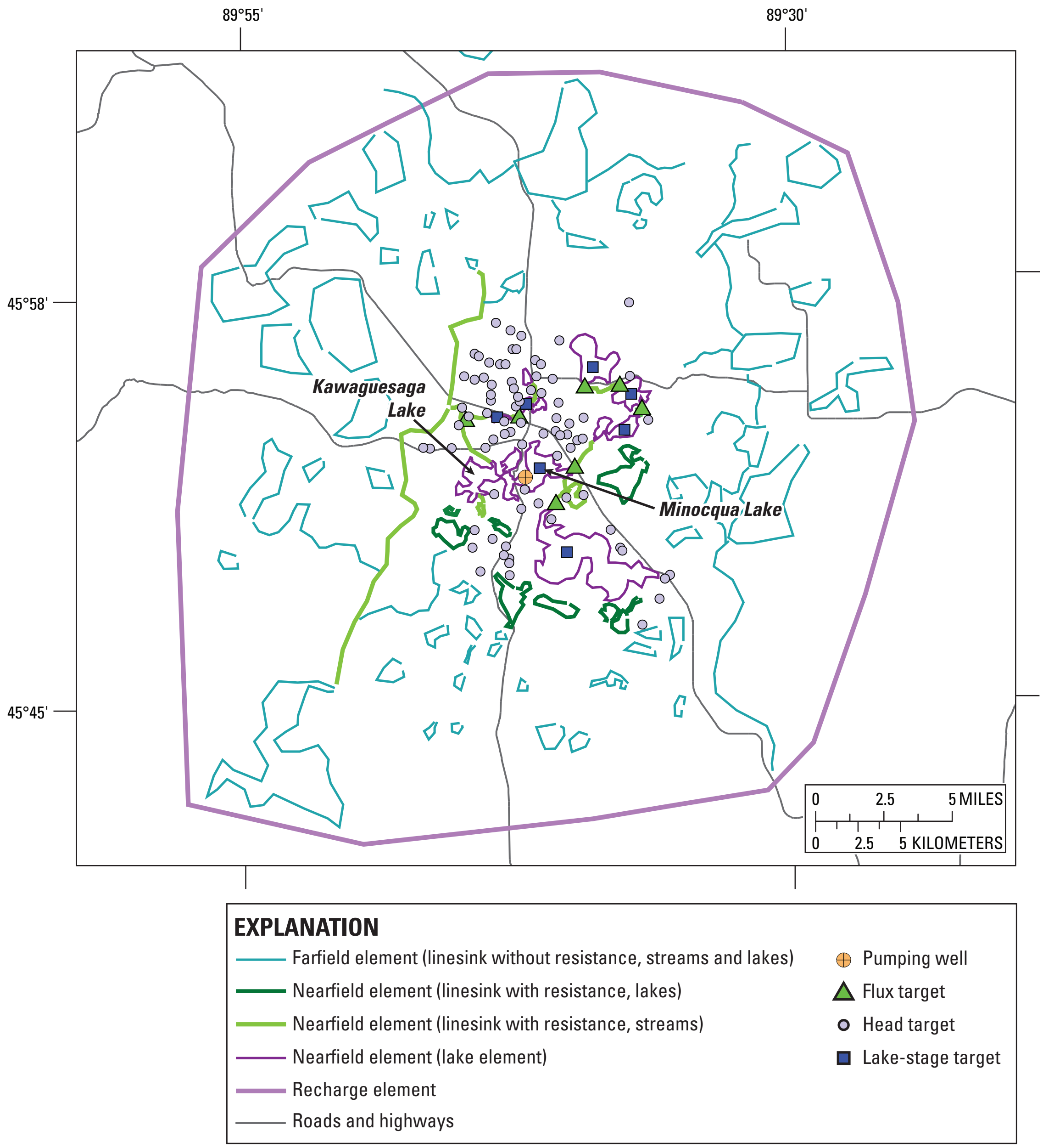


Figure 14. Hydrologic features simulated with GFLOW analytic elements near Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin.

Kawaguesaga, Tomahawk, Carrol/Madeline, Little Arbor Vitae, Big Arbor Vitae, Little Musky, Arrowhead, Brandy, and Johnson Lakes were simulated as lake linesinks, in accordance with the methodology described by Hunt and others (2003). The lake linesink solves for lake stage on the basis of simulated surface–water inflows and estimated surface-water outflows from the lake. Use of the lake linesink requires an estimate of the lake stage/outflow and lake stage/surface-area relationships. Surface outflows from six lakes were estimated from nearby, downstream streamflow measurements, made under base-flow conditions during October 19–20, 2006. Where applicable, lake stage was measured concurrently with streamflow (lake outflow) measurements. The model includes one pumping well that represents average daily pumping in 2006 (0.71 ft^3/s) from Minocqua municipal wells 3 and 4. Domestic pumping wells were not included in the model because the withdrawals from these wells are widely distributed and the withdrawals are relatively small (especially where balanced by return flow from septic systems).

The GFLOW model was calibrated by using the parameter estimation code PEST (Doherty, 2004). Measured streamflows and lake stages were used as flux and head targets during model calibration. Water-level elevations estimated from 81 driller's well logs (by using measured depth to water and corresponding topographic quadrangle map elevations) also were used as head targets. Recharge and horizontal hydraulic conductivity were automatically varied during model calibration until differences between measured and simulated water levels, lake stages, and streamflows were minimized. Measured lake stages and streamflows were given relatively similar weight during model calibration. To do this, weights for lake stages were set to 10; weights for streamflows ranged from 0.00001 to 0.0004 (because model streamflow units were in cubic feet per day). Because groundwater levels were measured over a period of years and estimated from topographic maps, these targets were given less weight (set to 1) during calibration than those for lake stages and streamflows. Groundwater gradients from the shoreline piezometers were not included in the PEST calibration, but were manually compared with the simulated gaining and losing shoreline segments.

The calibrated model has a recharge rate of 8.4 in/yr and hydraulic conductivity of 41.8 ft/d. These are similar to values used in previous models near the study area (Hunt and others, 1998; Graczyk and others, 2003; Robertson and others, 2005). Simulated heads and streamflows were reasonably close to measured values. The mean and absolute mean difference between simulated and measured groundwater levels were −0.5 and 4.4 ft, respectively (fig. 15). The mean and absolute mean differences were 0.09 and 0.54 ft^3/s, respectively, for streamflow. For lake stages, mean and absolute mean differences were 0 and 0.3 ft, respectively. Simulated gaining and losing shoreline segments were reasonably similar to those indicated by gradients measured in shoreline piezometers.

On the basis of similarity between measured and simulated groundwater levels, lakes stages, and streamflows, the model appears to accurately simulate the groundwater flow near Minocqua and Kawaguesaga Lakes during October 2006. The model represents one set of steady-state, base-flow conditions; however, in reality, there are seasonal variations in groundwater levels, lake stage, and streamflow. It was assumed that seasonal variations in groundwater levels and natural lake stages would be relatively uniform throughout the model area, thus having minimal effect on the extent of the groundwater-source areas and on the net gains and losses to the groundwater-flow system immediately adjacent to nearfield lakes. Additionally, it was assumed that human-induced seasonal changes in lake stages (dams) would cause only short-term effects on gains and losses and that those effects would be nearly zero on an annual basis. Given these assumptions, the model can be used to define groundwater-source areas around Minocqua and Kawaguesaga Lakes and to allocate groundwater gains and losses on an annual basis to shoreline segments represented by the piezometers installed around the lakes.

The groundwater contributing area for the lakes was delineated by using particle-tracking techniques in GFLOW. The groundwater contributing area covers about 59 mi^2 and represents an area that is slightly different than the surface-water contributing area (fig. 16). Based on measured and simulated information, groundwater discharges to most of the shoreline surrounding Kawaguesaga and Minocqua Lakes, except for the northern shore of Kawaguesaga Lake near the dam, which loses water, and the western shore near piezometers 10 and 11, which seasonally may gain or lose water. Net groundwater flow to the lakes via direct shoreline segments is 3.46 ft^3/s (2,510 acre-ft per year). The area of greatest groundwater discharge to Minocqua Lake is along the east and northeast shorelines (fig. 17). Although much of the Kawaguesaga shoreline has groundwater discharge to the lake, the net discharge is negative due to losses from the lake to the groundwater system near the dam and the outlet stream.

In order to match groundwater inflows and outflows from the steady-state model with the monitoring period during which data were collected to compute nutrient loading, the simulated groundwater to the lakes needed to be adjusted. This adjustment was necessary because the 2-year study was done during a period of continuing below-normal precipitation and below-normal groundwater recharge. It is reasonable to assume that groundwater discharge was declining through the 2-year study period. The steady-state model was calibrated on the basis of conditions near the end of the first year of the study. Simulated groundwater discharges to the lakes were adjusted proportionately to the declining flow at the Minocqua Thoroughfare gage from MY 2006 to MY 2007. The average flow at the Minocqua Thoroughfare gaging station during MY 2007 was 76 percent of that in MY 2006. The key assumption is that groundwater discharge to Minocqua and Kawaguesaga Lakes is proportional to flow in Link Creek at the Minocqua Thoroughfare gaging station and is based on the likelihood that most of the flow in Link Creek originates as groundwater discharge. The adjustment factor for the midpoint of the second year was assumed to be 0.76 of that for MY 2006. Adjusted groundwater discharges to Kawaguesaga and Minocqua Lakes are given in table 5.

Although this model was considered reasonably calibrated and was sufficient for estimates of groundwater inflow to and outflow from Minocqua and Kawaguesaga Lake, local heterogeneities that were not simulated with the model may locally alter the contributing area to a small degree. The accuracy of simulated groundwater level, lake stage, and streamflow is only as good as the accuracy of the measured data used for calibration. Groundwater levels based on driller's logs have an accuracy of ±5 feet (one half of the topographic quadrangle map contour interval). Lake stages measured using RTK-GPS have an accuracy of ±0.1 ft. Measured streamflows were generally rated as fair to good with an accuracy of ±5 to 8 percent. Use of the model for evaluations beyond the stated purpose (to estimate groundwater-contributing areas to the lakes and groundwater exchanges with the lakes) or accuracy may require reevaluation of the model and may require recalibration of the model to match new or existing data that correspond to the new purpose.

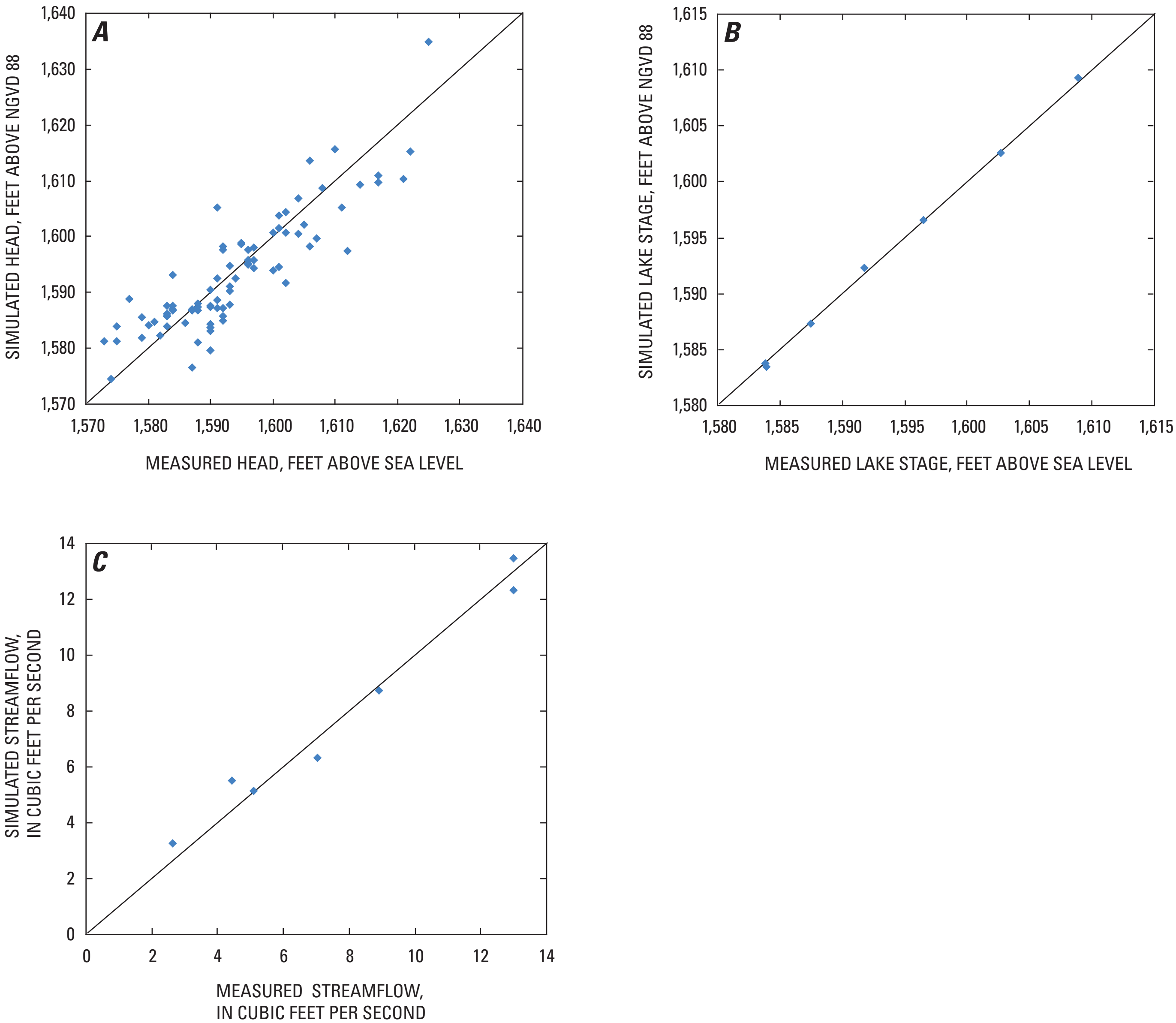


Figure 15. Measured and simulated (*A*) head (groundwater levels), (*B*) lake stage, and (*C*) streamflow for the calibrated GFLOW model.

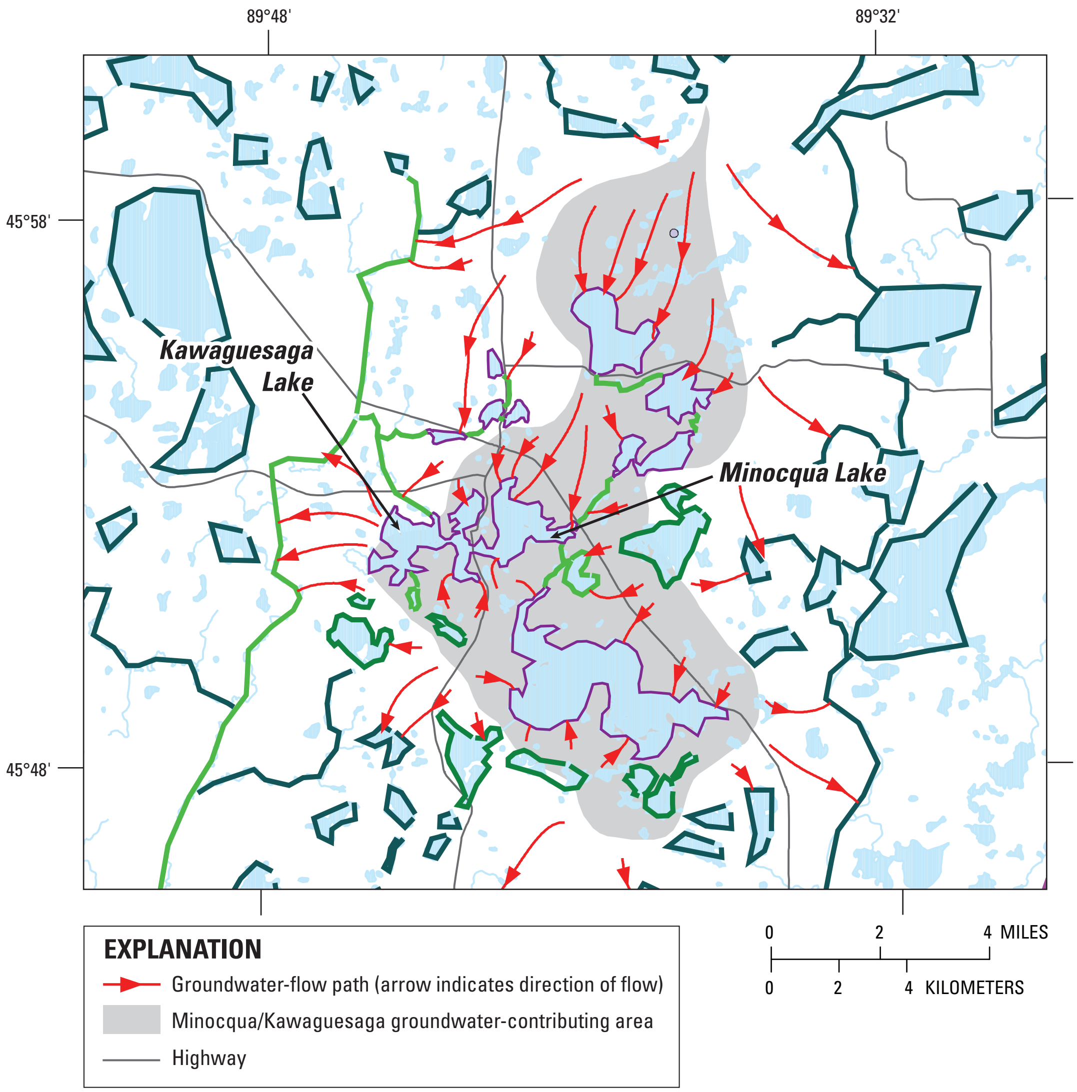


Figure 16. Simulated groundwater contributing area and flow direction for Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin.

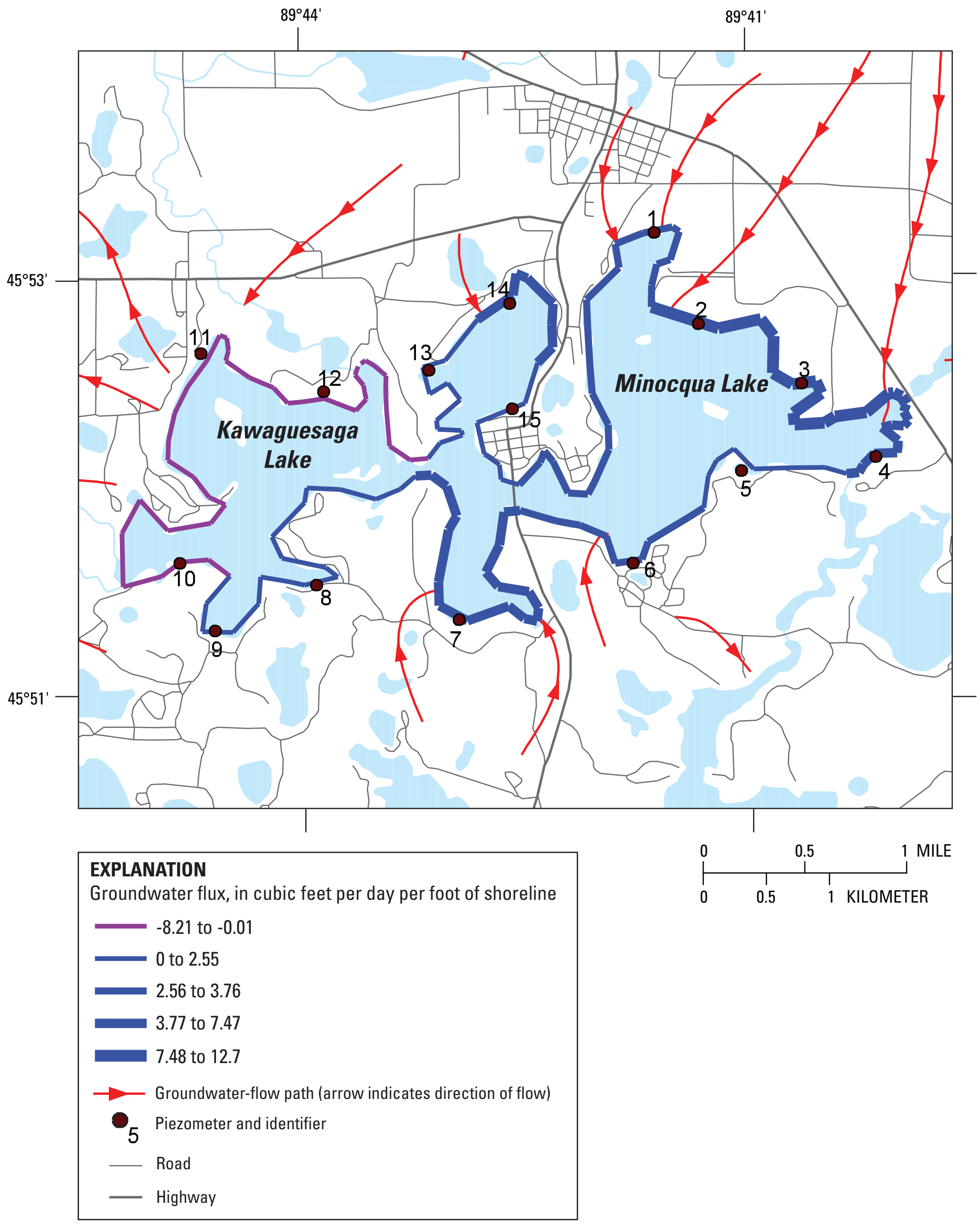


Figure 17. Simulated groundwater-flow direction and flux (flow) rates for shoreline segments of Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin.

Water-Budget Summary

Minocqua and Tomahawk Thoroughfares are the largest sources of water to the lakes, supplying about 38 and 34 percent, respectively, of the total input during the 2-year study period (table 5; fig. 18). Other sources were precipitation (16 percent), groundwater (11 percent), and the ungaged near-lake drainage that includes the urbanized area (less than 1 percent). The total input of water in MY 2006 (34,400 acre-ft) was more than in MY 2007 (22,100 acre-ft) because of the prolonged dry period and below-normal precipitation, even though precipitation was somewhat greater in MY 2007. The residence time—that is, the length of time required for water entering the lakes to completely replace the volume of water in the lakes—was 1.2 and 2.1 years, respectively, or 1.5 years on the basis of the average inflow for the 2 years.

The total annual output of water from the lakes was more than the total input in MY 2006, resulting in a decrease in lake stage of 0.45 ft or a decrease of 908 acre-ft in storage from the beginning to the end of the study year. Annual output of water was less than the total input in MY 2007, resulting in an increase in lake stage of 0.75 ft or an increase of 1,500 acre-ft in storage for the year. This amounted to an overall increase in lake stage of 0.30 ft in the lakes during the 2-year study period. On average, 83 percent of the total water leaving the lakes left through the Tomahawk River outlet at the Minocqua Dam, evaporation accounted for 14 percent, and outflow to groundwater accounted for the remaining 2 percent (table 5; fig. 18).

The quality or accuracy of the water budget was evaluated by comparing the monthly sum of all inputs with the sum of all outputs plus the change in storage for the lakes (fig. 19). The differences between the calculated inputs and outputs reflect the cumulative errors in the estimates of all of the components in the water budget. The largest monthly differences in 2006 were in June and July, which when expressed as percentages of the total measured output plus change in storage were 13.4 and 12.8 percent, respectively. In 2007, the largest monthly differences were in April and September, which when expressed as percentages were about 22 and 30 percent. On an annual basis, the percentage error was about 1 percent for MY 2006 and about 2 percent for MY 2007.

The hydrology documented in MY 2006–07 represents conditions occurring during a series of dry years. To determine how the hydrologic loading to the lakes would change under more typical hydrologic conditions, flows were calculated for each of the budget components (table 5) during long-term average hydrologic conditions. During MY 2006–07, precipitation was 84 percent of average; runoff volumes at the Minocqua Thoroughfare and Tomahawk Thoroughfare gaging stations were assumed to be 75 percent and 59 percent of average, respectively, on the basis of record from nearby gaging stations; groundwater discharge was assumed to be about 85 percent of average. Runoff volumes for the near-lake drainage areas were computed with WinSLAMM by using 1975 precipitation values at Duluth, which represented average conditions. Allocation of the hydrologic inputs during average hydrologic conditions is given in table 5.

Total hydrologic inputs to the lakes were also estimated for the two 2030 buildout scenarios: 2030 buildout with 2006–07 hydrology and 2030 buildout with average hydrology. All of the hydrologic inputs except nearshore runoff were assumed to remain unchanged from average MY 2006–07 and average hydrologic conditions. However, runoff from the ungaged area was estimated by using WinSLAMM with precipitation from MY 2006–07 and 1975 (table 5).

Sources of Phosphorus

To help define where the phosphorus in Minocqua and Kawaguesaga Lakes originates and how much may be controllable, a detailed phosphorus budget was computed for each monitoring year. External sources of phosphorus to the lakes include precipitation, surface-water and groundwater inflow, and contributions from septic systems. In addition to these external sources, phosphorus can be released from the bottom sediments of the lakes, which is considered an internal source of phosphorus (internal loading). Phosphorus is removed from the lakes through surface-water outflow and deposition to the lake sediments.

Precipitation

Atmospheric deposition of phosphorus on Minocqua and Kawaguesaga Lakes was determined from phosphorus concentrations measured in wetfall (rain and snow) and phosphorus-deposition rates measured in dryfall at a weather station operated at Whitefish Lake in Douglas County, Wis. (Robertson and others, 2009). Total monthly wetfall deposition was computed by multiplying the average estimated phosphorus concentration of 0.016 mg/L by the monthly precipitation on the lakes. Phosphorus in dryfall was estimated from monthly deposition rates measured at Whitefish Lake, which were adjusted for lakes with few conifers in the surrounding area (approximately 26 lb/mi^2/yr and applied equally over May through October). Total phosphorus inputs to the lakes from precipitation were 269 lb in MY 2006 and 288 lb in MY 2007 (table 6).

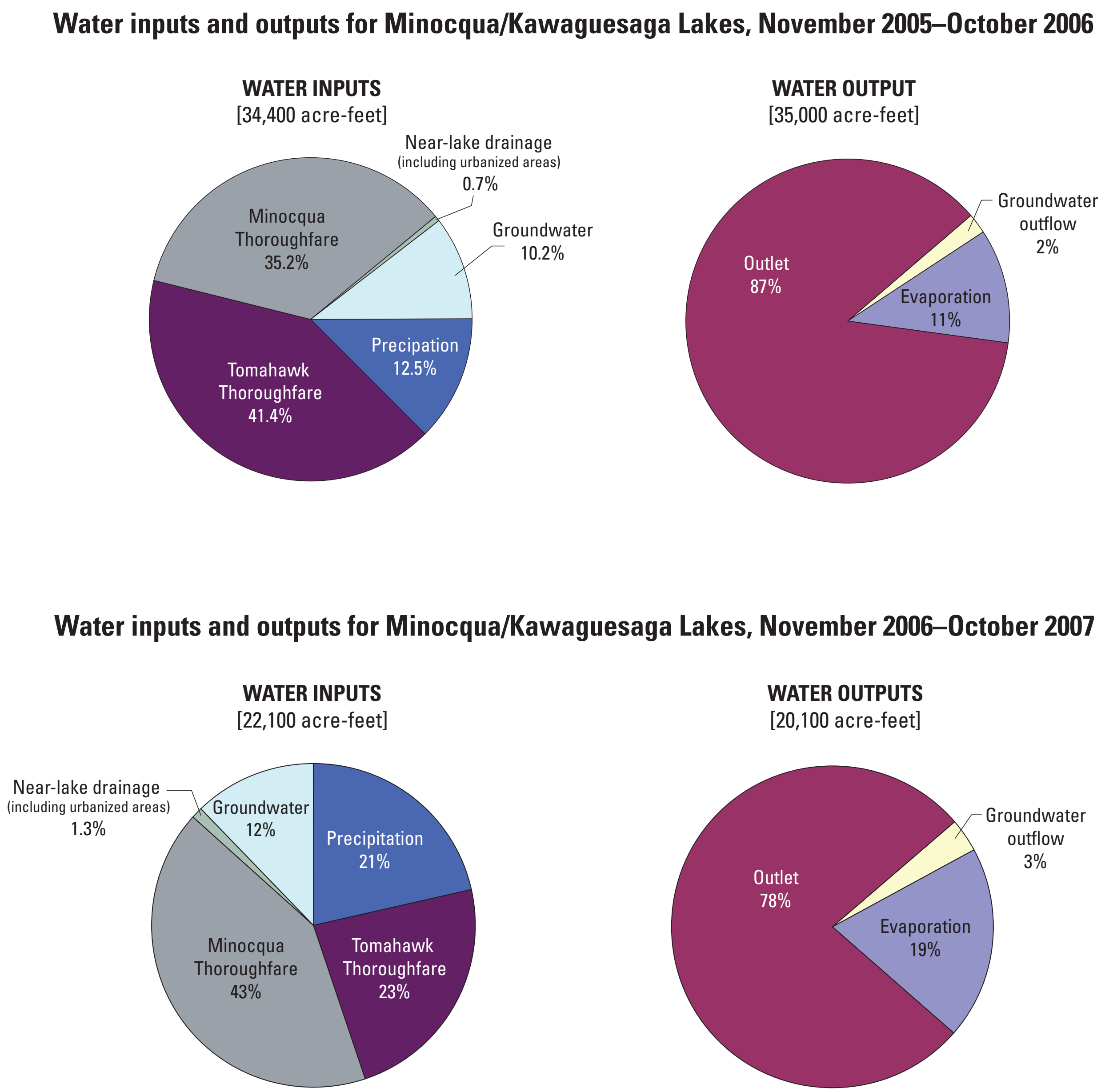


Figure 18. Charts showing water budgets for Minocqua and Kawaguesaga Lakes, Wisconsin, for monitoring years 2006 and 2007. (%, percent).

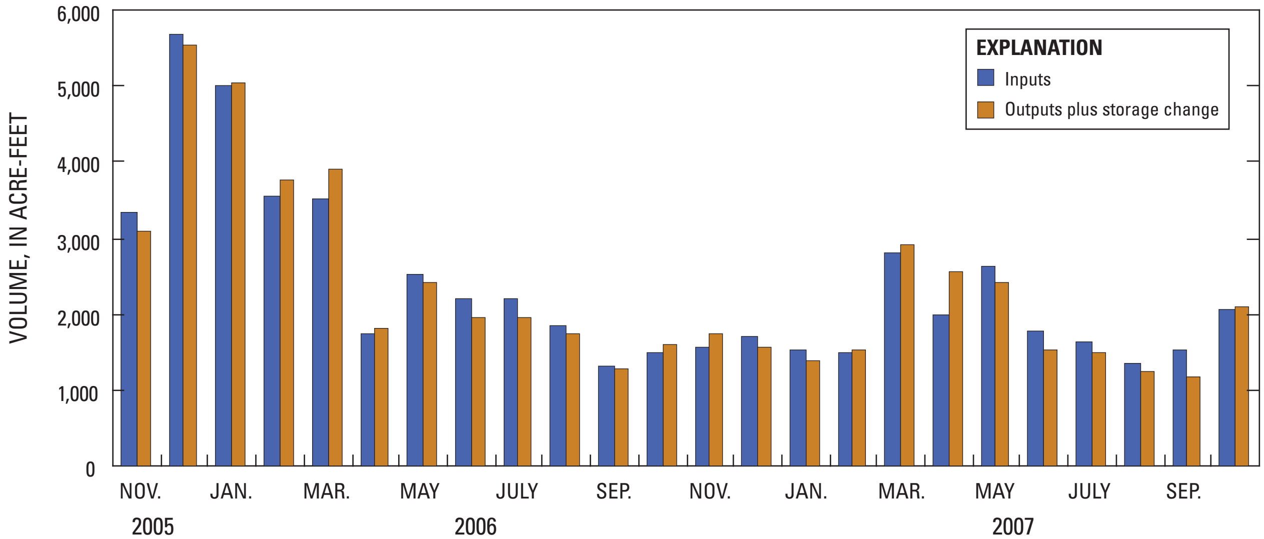


Figure 19. Monthly accuracy of the water budget based on comparison of total water inputs and outputs plus storage change for Minocqua and Kawaguesaga Lakes, Wisconsin, November 2005 to October 2007.

Table 6. Summary of phosphorus-budget components for Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin, for monitoring years 2006–07, during average hydrologic conditions, and with future development in the watershed.

[Abbreviations: MY, monitoring year November–October]

Budget component	MY 2006	MY 2007	2-year average	Percent of 2-year total	Average hydrology	2030 buildout	
						MY 2006–07 hydrology	Average hydrology
Inputs to lake (pounds)							
Precipitation							
Minocqua Lake	177	189	183	6.5	218	183	218
Kawaguesaga Lake	92	99	96	3.4	114	96	114
Tributaries							
Minocqua Thoroughfare (inlet)	1,460	720	1,090	38.7	1,460	1,090	1,460
Tomahawk Thoroughfare (inlet)	995	442	719	25.5	1,220	719	1,220
Near-lake drainage (including urbanized areas)							
Minocqua Lake							
East Basin	132	155	144	5.1	160	227	232
Northwest Basin	88	106	97	3.4	110	130	156
Southwest Basin	41	51	46	1.6	55	61	61
Kawaguesaga Lake	33	46	40	1.4	45	64	67
Groundwater							
Minocqua Lake	108	82	95	3.4	106	95	106
Kawaguesaga Lake	17	13	15	0.5	18	15	18
Septic systems							
Minocqua Lake	183	183	183	6.5	183	183	183
Kawaguesaga Lake	113	113	113	4.0	113	186	186
TOTAL INPUT	3,440	2,200	2,820	100.0	3,800	3,050	4,010
Outputs from lake and storage (pounds)							
Retained in lake *	1,910	1,320	1,610	57.2			
Tomahawk River (outlet)	1,530	878	1,210	42.7			
TOTAL OUTPUT AND STORAGE	3,440	2,200	2,820	100.0			

* Assumed that groundwater output was negligible from lake and was included with storage.

Surface-Water Inflow

Phosphorus loads were computed for the continuously monitored sites at the Minocqua Thoroughfare inlet and the Tomahawk Thoroughfare inlet to Minocqua Lake, and at the Kawaguesaga Lake outlet to the Tomahawk River. Phosphorus loads were estimated for the ungaged near-lake drainage areas for each basin in Minocqua and Kawaguesaga Lakes.

Gaged Inlets

Phosphorus in Minocqua Thoroughfare inlet at State Highway 47 (fig. 5) originates from the upper watershed, including four upstream lakes. Total phosphorus concentrations for 42 samples collected during the 2-year study ranged from 0.019 to 0.077 mg/L (fig. 13). The median and flow-weighted-average concentrations were 0.036 and 0.038 mg/L, respectively. On average, about 50 percent of the phosphorus was in the dissolved form, based on seven samples. The total quantity of phosphorus delivered from Minocqua Thoroughfare was 1,460 lb in MY 2006 and 720 lb in MY 2007 (table 6). Yields from the Minocqua Thoroughfare watershed were 52.2 lb/mi^2 in MY 2006 and 25.7 lb/mi^2 in MY 2007. These yields are among the lowest of rural watersheds that were monitored in Wisconsin and similar to that measured for the Bear River near Manitowish Waters in the Northern Lakes and Forests ecoregion (Corsi and others, 1997). The yields are likely lower than long-term average yields because the two study years were characterized by below-average precipitation and runoff. Yields are also expected to be low from this watershed because of the trapping effect of upstream lakes.

The WDNR fish hatchery was not an important point source of phosphorus. Most of the effluent is pumped into a settling pond and then into an infiltration pond before the overflow is discharged into the Minocqua Thoroughfare. Discharge from the hatchery ranged from about 0.1 to 2.0 ft^3/s, and phosphorus concentrations ranged from 0.027 to 0.068 mg/L (S. Ohm, Wisconsin Department of Natural Resources, written commun., 2007). With few exceptions, phosphorus concentrations of the hatchery discharge were near or less than the stream concentrations measured at the gaging station at State Highway 47; therefore, the hatchery is no longer an important source of phosphorus loading to the lakes. Any loading from the hatchery would be included in the total quantity of phosphorus delivered from Minocqua Thoroughfare measured at the gaging station.

Phosphorus in Tomahawk Thoroughfare at the gaging station originates from the upstream watershed that includes 3,400-acre Tomahawk Lake. Total phosphorus concentrations for 40 samples collected during the 2-year study ranged from 0.011 to 0.040 mg/L (fig. 13). The median and flow-weighted-average concentrations of total phosphorus were 0.018 and 0.017 mg/L, respectively. On average, about 40 percent of the phosphorus was in the dissolved form, based on seven samples. The total quantity of phosphorus measured at Tomahawk Thoroughfare at Thoroughfare Road was 570 lb in MY 2006 and 200 lb in MY 2007.

Estimated phosphorus loading from the additional Mid Lake drainage area was added to the measured load at Thoroughfare Road. Phosphorus input from Mid Lake and the intervening area between the mouth of Tomahawk Thoroughfare and the gaging station at Thoroughfare Road was estimated by multiplying the estimated flow by the estimated average phosphorus concentration from the intervening area. The average phosphorus concentration from the intervening area was determined on the basis of nine samples collected at the mouth, which had a higher average concentration of 0.029 mg/L, compared with an average of 0.017 mg/L measured at the gaging station. In order to increase the average concentration by 0.012 mg/L and only increase the water volume by 13 to 25 percent requires the average phosphorus concentration for the water added in this area to be 0.109 mg/L. The total quantity of phosphorus added in this intervening area was 425 lb in MY 2006 and 242 lb in MY 2007. The intervening channel area and Mid Lake were important sources of phosphorus.

The total quantity of phosphorus delivered from Tomahawk Thoroughfare at the inlet to Minocqua Lake was 995 lb in MY 2006 and 442 lb in MY 2007 (table 6); on average, about 50 percent of this total load was contributed by the Mid Lake intervening area. The flow-weighted-average concentration of total phosphorus at the mouth was 0.027 mg/L. Yields from the Tomahawk Thoroughfare watershed were 32.2 lb/mi^2 in MY 2006 and 14.3 lb/mi^2 in MY 2007; these are very low yields, reflecting the nature of the watershed (size of Tomahawk Lake and low watershed/lake area ratio) and the dry period during the study.

Urban and Other Ungaged Near-Lake Drainage Areas

Phosphorus loading to the lakes from the near-lake drainage was divided into contributions to the East, Northwest, and Southwest Basins, which contain the urbanized and residential land-use areas, and that for Kawaguesaga Lake.

During the 2-year study, 16 water samples were obtained from stormwater outfalls in the urban area of the Island. Total phosphorus concentrations in these samples ranged from 0.031 to 0.281 mg/L, with an average concentration of 0.113 mg/L. The WDNR had collected stormwater grab samples at five sites in 1991 that ranged from 0.1 to 1.6 mg/L, averaging 0.49 mg/L (Blake, 1996). Water and phosphorus loads from the near-lake drainage areas were simulated with WinSLAMM. WinSLAMM was applied with all of the standard phosphorus concentrations except those for forested areas: which were obtained from Graczyk and others (2003). Average flow-weighted concentrations of total phosphorus for each basin resulting from the modeling were 0.44 mg/L (East Basin), 0.38 mg/L (Northwest Basin), 0.46 mg/L (Southwest Basin), and 0.70 mg/L (Kawaguesaga contributing area).

On the basis of the WinSLAMM model that included the drainage controls that exist in the watershed, the estimated load of phosphorus from the near-lake drainage area of the East Basin was 132 lb in MY 2006 and 155 lb in MY 2007; from the near-lake drainage area of the Northwest Basin was 88 lb in MY 2006 and 106 lb in MY 2007; and the near-lake drainage area of the Southwest Basin was 41 lb in MY 2006 and 51 lb in MY 2007 (table 6). The average annual yields and flow-weighted average total phosphorus concentration were highest from the more urbanized areas in watersheds of the Northwest and Southwest Basins (30 and 20 percent urban land use, respectively): about 165 lb/mi^2 and 0.40 mg/L, respectively. The median yield from monitored urban watersheds reported by Corsi and others (1997) was 318 lb/mi^2, with a range from 133 to 1,210 lb/mi^2. The load estimated by WinSLAMM was near the lower end of this range but considered reasonable. The estimated load of phosphorus by WinSLAMM from the contributing areas of the near-lake drainage area of Kawaguesaga Lake was 33 to 46 lb/yr, a low yield resulting from the small amount of runoff produced by the sandy soils from the 2.5-mi^2 contributing area during the 2 years of below-average rainfall. The contributing area to Kawaguesaga Lake also has a high percentage of wetlands, which is not included in loading estimates by WinSLAMM. For comparison, if unit-area loads similar to those measured at the Bear River and Tomahawk Thoroughfare gaging stations were applied (about 20 lb/mi^2 phosphorus in MY 2006 and 15 lb/mi^2 in MY 2007), the resulting estimated load from the Kawaguesaga Lake contributing area would be about 49 lb in MY 2006 and 37 lb in MY 2007. The total estimated phosphorus load from the contributing areas of the entire near-lake drainage was 294 lb in MY 2006 and 358 lb in MY 2007, for an average annual yield of about 71 lb/mi^2.

Groundwater

Estimates of loading from natural background groundwater inflow and contributions from septic systems into the groundwater were made separately. To determine the natural groundwater contributions, piezometers were installed around the lakeshore and sampled to determine the concentrations of dissolved phosphorus in groundwater entering the lakes. Average dissolved phosphorus concentrations in piezometers ranged from less than 0.007 to 0.098 mg/L (table 7). Phosphorus concentrations in some piezometers appeared elevated above background levels and likely affected by septic-tank effluent and urban or wetland sources. Phosphorus concentrations in 3 out of the 14 piezometers (piezometers 6, 7, and 13) were much greater than concentrations in the other piezometers. Hence, it was assumed that these piezometers may have been influenced by a local factor, such as septic-system effluent, and they were not used to estimate background concentrations. Concentrations from the remaining piezometers, 0.008 to 0.027 mg/L, were used for different shoreline segments to estimate the phosphorus load from natural groundwater inflow for the areas where gradients were into the lake (fig. 17). The annual phosphorus load contributed by groundwater was estimated to be 108 lb in MY 2006 and 82 lb in MY 2007 for Minocqua Lake and 17 lb in MY 2006 and 13 lb in MY 2007 for Kawaguesaga Lake (table 6).

Septic Systems

Lakeshore septic systems may represent an important source of phosphorus to some lakes. Phosphorus loading from nearshore septic systems to Minocqua and Kawaguesaga Lakes was estimated separately from background groundwater inflow by applying per capita export coefficients from households to onsite septic systems. Input from septic systems was only determined for areas where groundwater enters the lakes. These areas were determined from the nearshore piezometers with positive groundwater gradients to the lake and the groundwater model. The latest population and occupancy information, site-specific soil information, and septic-system characteristics were evaluated and used in calculations to estimate the quantity of phosphorus from near-lake systems.

The input of phosphorus from septic systems (M) was estimated by use of equation 6 (Reckhow and others, 1980):

$$M = E_s * (\text{number of capita years}) * (1 - S_R), \qquad (6)$$

where M is a function of a phosphorus export coefficient, E_s, a soil retention coefficient, S_R, and the number of people using the septic systems annually (number of capita years). In applying equation 6, it was assumed that the most likely value for E_s was 1.5 lb of phosphorus per capita per year. Typical export coefficients range from about 1 lb per capita per year (Reckhow and others, 1980; Panuska and Kreider, 2002) to more than 2 lb per capita per year (Garn and others, 1996). This approach is described in more detail by Garn and others (1996).

Population and occupancy information were obtained from 2000 census data and local sources. About 40 percent of the total number of housing units around Minocqua and Kawaguesaga Lakes were assumed to be year-round residences according to the 2002 Town of Minocqua Land Use Plan (Lindemann and others, 1997; A. Faust, North Central Wisconsin Regional Planning Commission, written commun., 2007). Of the remaining seasonal residences, 60 percent were assumed to have occupancy during the summer and weekends (0.5 year) and 40 percent to be occupied during summer only for 0.3 year (J. Beckwith, Minocqua /Kawaguesaga Lakes Protection Association, written commun., 2007). The average number of persons per household for Minocqua was assumed to be 2.4 on the basis of 2000 Oneida County census data (ePodunk, Inc., 2007).

Table 7. Concentrations of dissolved phosphorus in groundwater from piezometers around Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin.

[All concentrations are given in milligrams per liter (mg/L). **Symbols:** <, less than; –, not available]

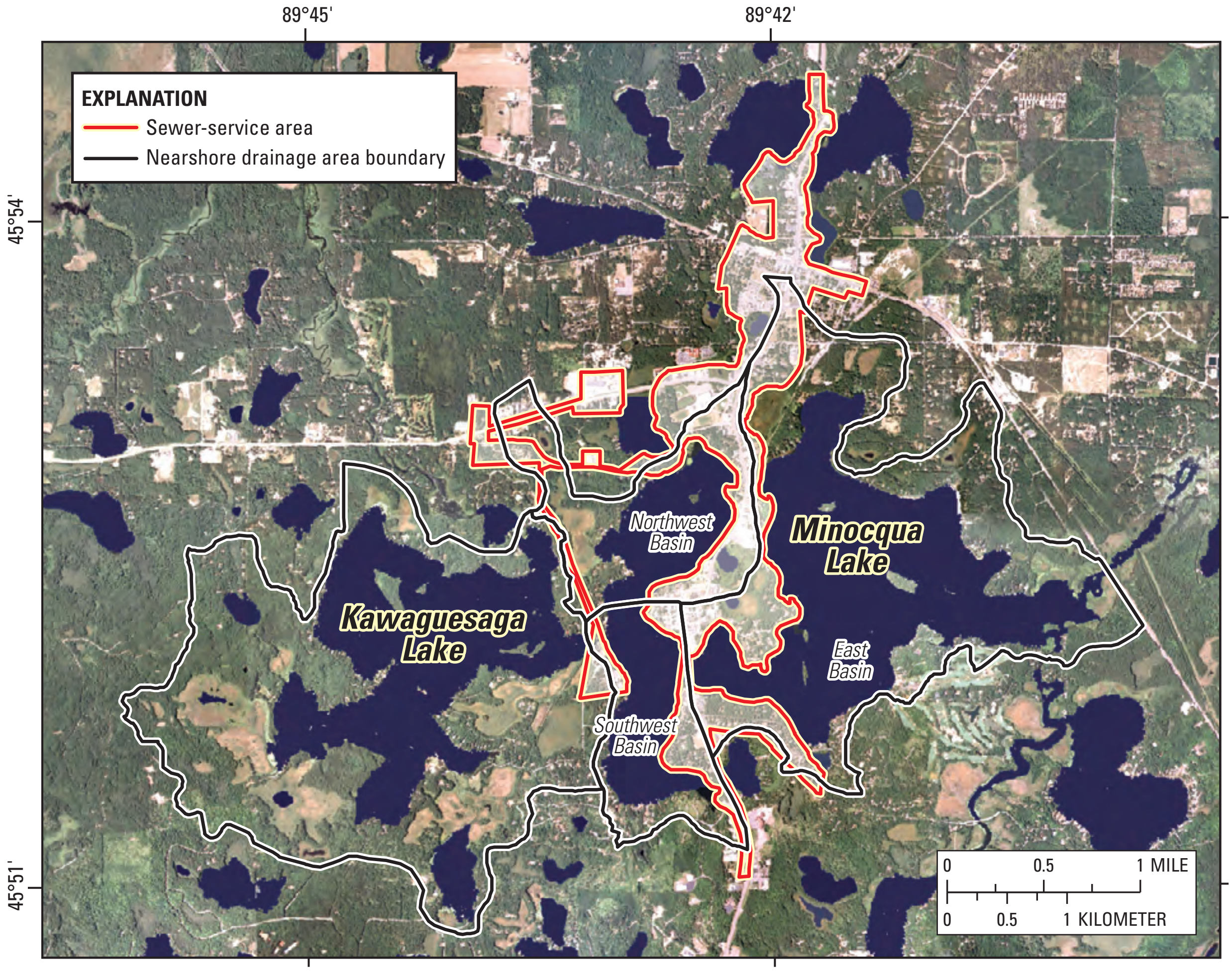
Piezometer number	Date of measurement						Average concentration
	2006			2007			
	09-07	07-18	10-19	06-04	07-25	09-19	
1	0.022	0.006	0.009	0.005	<0.005	<0.005	<0.009
2	0.009	0.008	0.012	<0.005	<0.005	<0.005	<0.007
3	0.016	0.006	0.014	0.005	<0.005	<0.005	<0.009
4	0.030	0.018	0.019	0.010	0.012	0.012	0.017
5	0.018	0.017	0.013	0.009	0.010	0.020	0.015
6	0.038	0.025	0.025	0.019	0.023	0.021	0.025
7	0.119	0.123	0.072	0.066	0.141	0.068	0.098
8	0.012	0.009	0.018	<0.005	<0.005	<0.005	< 0.009
9	–	0.017	0.020	0.012	0.013	0.014	0.015
10*	0.013	0.017	0.018	0.009	0.006	0.013	0.013
11*	0.014	0.014	0.016	0.010	0.012	0.011	0.013
12*	0.032	0.028	0.015	–	–	0.03	0.026
13	–	0.033	0.020	0.026	0.029	0.027	0.027
14	–	–	0.015	0.011	0.013	0.015	0.014
15	0.019	0.020	0.028	0.013	0.014	0.015	0.018

* Piezometers were in areas with neutral flow or groundwater outflow.

All households and facilities around the lakes are not likely to affect the lakes because part of the area and shoreline, including the Island, is served by sanitary sewer (fig. 20), and part of the shoreline of Kawaguesaga Lake has groundwater gradients that are away from the lake (fig. 17). In this study, the number of residences potentially affecting the lakes was determined for the area within 250 ft of the unsewered portion of the lakeshore and having groundwater gradients into the lakes. Residences with septic drain fields greater than 250 ft from the shoreline were assumed to have no effect on the lakes. The number of parcels of land with houses within this 250-ft zone was determined from aerial photos and land records available from Oneida County Department of Planning and Zoning (2007). The total number of residences in this 250-ft zone was 235 (145 seasonal) for Minocqua Lake and 169 (101 seasonal) for Kawaguesaga Lake. Heavy seasonal visitor use at the Minocqua Country Club on Minocqua Lake and at Camp Kawaga on Kawaguesaga Lake was also included. Number of capita-years was then calculated by multiplying the number of residences by number of persons per household by fraction of the year occupied. The Northwest and Southwest Basins of Minocqua Lake have few residences with onsite septic systems because much of that shoreline is served by sewer. The west shoreline of Kawaguesaga Lake that is in a neutral or transition area having groundwater outflow part of the time was assumed to contribute septic input 50 percent of the time.

A soil has a finite phosphorus adsorption capacity, which may be reduced by drain-field effluent over time; hence, new systems provide more soil retention than old systems do. The septic survey by Lindemann and others (1997) found that about 58 percent of the systems around Minocqua Lake were installed during the 1970s or earlier (42 percent in the 1980s or more recent)—an age near or exceeding the normal life expectancy of the system. About 15 percent of the systems were found to be failing. In addition to age, maintenance of septic systems also influences the effectiveness of the system. If scum and sludge are allowed to build up in the tank to a point where solids are carried out into the drain field, soil spaces may become plugged and result in system failure. Septic-system failures and water contamination are most likely to occur in shallow soils with high or perched water tables, in shallow soils over bedrock, on steep slopes that allow effluent to surface, and in very coarse textured soils low in organic matter that have high permeability rates and low phosphorus-retention capacity.

Soils of the nearshore area consist predominantly of Vilas loamy sand, Croswell sand and loamy sand, Sayner loamy sand, and Keweenaw-Vilas or Keweenaw-Sayner Complex (Natural Resources Conservation Service, 2006). These soils that are underlain by sand and gravel are excessively drained, have high subsoil permeabilities, and are classified as a poor filter and very limited application for septic-tank absorption fields. A S_R coefficient of 0.5 was used for these soils, plus an



Aerial image from U.S. Department of Agriculture, 2006

Figure 20. Area served by sanitary sewer within the Lakeland Sanitary District No. 1, Minocqua, Wisconsin.

S_R of 0.25 for the fraction of the phosphorus that is removed by storage of solids in the septic tank. For septic systems that were determined to be failing within the 250-ft zone, $S_R = 0.20$ was used. Therefore, as with the selection of an E_s value, a most likely S_R value of 0.75 (75 percent retention) was used in the calculations for that case, and a low value of 0.60 and high value of 0.85 were also evaluated for best-case and worst-case estimates.

On the basis of the above assumptions, the annual estimated "most likely" input of phosphorus from near-lake septic systems was 183 lb to Minocqua Lake and 113 lb to Kawaguesaga Lake (table 6). Because inputs from septic systems were not directly measured, low and high estimates for septic inputs were obtained by applying high and low estimates for E_s and S_R in equation 6. The low and high estimates for phosphorus inputs from septic systems were 77 to 345 lb into Minocqua and 45 to 220 lb into Kawaguesaga Lake, respectively. Oneida County has a septic-system inspection (repeated at 3-year intervals), pumping, and corrective-action program; but this program applies only to those systems constructed after July 1, 1980, to identify those systems in need of replacement or repairs (K. Jennrich, Oneida County Planning and Zoning Department, oral commun., 2009).

Surface-Water Outflow

Phosphorus is discharged from Kawaguesaga Lake into the Tomahawk River through the Minocqua Dam. Total phosphorus concentrations in the 40 samples collected at the outlet during the 2-year study period ranged from 0.012 to 0.034 mg/L, and the flow-weighted-average concentration was 0.019 mg/L. The total phosphorus output from the lakes to the Tomahawk River was 1,530 lb in MY 2006 and 878 lb in MY 2007 (table 6).

Phosphorus-Budget Summary

The average annual load of phosphorus to Minocqua and Kawaguesaga Lakes during MY 2006 and 2007 was 2,820 lb, of which 1,610 lb (57 percent) was retained within the lake system (table 6). The total load was 3,440 lb in MY 2006 and 2,200 lb in MY 2007. The largest external source of phosphorus entering the lakes was from Minocqua Thoroughfare, which delivered about 39 percent of the total load (fig. 21) compared with about 38 percent of the water input (fig. 18). The next largest contribution was from Tomahawk Thoroughfare, which delivered about 26 percent of the total phosphorus load (34 percent of the water input). The ungaged near-lake area containing the town and rural residential areas contributed 11.5 percent of the total load, compared with only about 1 percent of the water input. Septic systems accounted for 10.5 percent of the total load. Contributions from precipitation and groundwater accounted for 9.9 and 3.9 percent of the total load, respectively. If the high estimates for phosphorus contributions from septic systems (345 lb to Minocqua Lake and 220 lb to Kawaguesaga Lake) were used in the budget, septic systems would increase to about 18 percent of the total external phosphorus load. Phosphorus loading in MY 2006 was about 1.6 times that in MY 2007 because the continuing drought during 2007 reduced stream and groundwater inputs, even though precipitation was greater in 2007.

The average annual surface-water discharge of phosphorus to the Tomahawk River from the lakes was 1,210 lb: 1,530 lb in MY 2006 and 878 lb in MY 2007. Therefore, on average, about 43 percent of the total phosphorus load to the lakes is lost through the Minocqua Dam. More than 50 percent of the external phosphorus entering the lakes is retained in the lake sediments, part of which may be potentially released to the water column in the future. Lakes normally accumulate phosphorus in their bottom sediment; therefore, phosphorus inputs exceed phosphorus losses in most lakes (Graneli, 1999). A prolonged period with phosphorus exports exceeding inputs would indicate that there has been a reduction in phosphorus inputs from the watershed and that phosphorus concentrations in the lakes should be decreasing.

The phosphorus loading documented in MY 2006–07 represents what occurs during a series of dry years. To determine how the phosphorus loading to the lakes would change under more typical or average hydrologic conditions, loads were calculated for each component of the phosphorus budget (tables 5 and 6) on the basis of long-term average precipitation and flow values (described earlier) and with the same phosphorus concentrations as estimated for MY 2006–07. Loads for the near-lake drainage areas were computed with WinSLAMM, with flows estimated by use of average precipitation. No adjustments were made to septic-system inputs. Thus, for average hydrologic conditions, the total annual phosphorus load to the lakes is estimated to increase to about 3,800 lb (table 6).

The total load of phosphorus to the lakes in MY 2006 and MY 2007 and that estimated for more typical hydrologic conditions is probably less than it was prior to 1965, when sewage effluent was discharged into Minocqua Lake. After 1965, however, the loading to the lakes may have gradually increased because of development in the watershed. The WDNR estimated that the total external load of phosphorus to Minocqua Lake during 1991 was about 4,500 lb, with 1,480 lb (33 percent) contributed by the two inlets, 1,050 lb (23 percent) by precipitation, 760 lb (17 percent) by urban and residential development from the Town of Minocqua, 700 lb (15 percent) by groundwater, and 335 lb (7 percent) from septic systems (Blake, 1996). This total estimate is more than 1.5 times that in MY 2006–07 and about 1.2 times estimated for typical or average hydrologic conditions. The 1991 loading estimates for individual sources to Minocqua Lake differ greatly from those estimated in this study: precipitation, 1,050 lb in 1991 compared to 183 lb in MY 2006–07 and 218 lb with average hydrology; groundwater, 700 lb in 1991 compared to 95 lb in MY 2006–07 and average hydrology; and urban development, 760 lb in 1991 compared to 287 lb in MY 2006–07 and 325 lb with average hydrology. It is believed that the values found in this study are more accurate than those estimated for 1991 (Blake, 1996) because of additional atmospheric deposition studies (Robertson and others, 2009), and the additional groundwater measurements and modeling (groundwater and urban) done as part of this study. Input from precipitation, groundwater, and urban areas should not have changed significantly over the past 20 years; they may have possibly even increased. Loading from urban and residential development may have increased over the past recent years, although inputs from septic systems may have decreased by expansion of the sewered area. Therefore, the phosphorus loading to the lakes should not have decreased since 1991. The refined budget from this study provides a different interpretation of the relative importance of human-related sources of phosphorus than would be inferred from the 1991 estimates (Blake, 1996).

According to information in the Towns of Minocqua and Woodruff Zoning Maps and Land Use Plan developed by the North Central Wisconsin Regional Planning Commission, much of the watershed around the lakes may be further developed in the near future. Future residential and urban/commercial development throughout the watershed may affect the phosphorus loading and potentially the water quality of the lakes. Therefore, the loading for this future condition was estimated. In the absence of estimated acreages for specific land uses in the future, it was assumed that by 2030 (referred to as “2030 buildout”) there would be an additional 506 acres of residential and urban development (a growth of 60 percent in each land-use category was assumed). Of the 506 acres, 134 acres would be in the Kawaguesaga Lake contributing watershed area, and 372 acres would be in the Minocqua Lake contributing area. For the Kawaguesaga Lake watershed, forested acres would be converted to an additional 124 acres of low-density and 10 acres of high-density residential land.

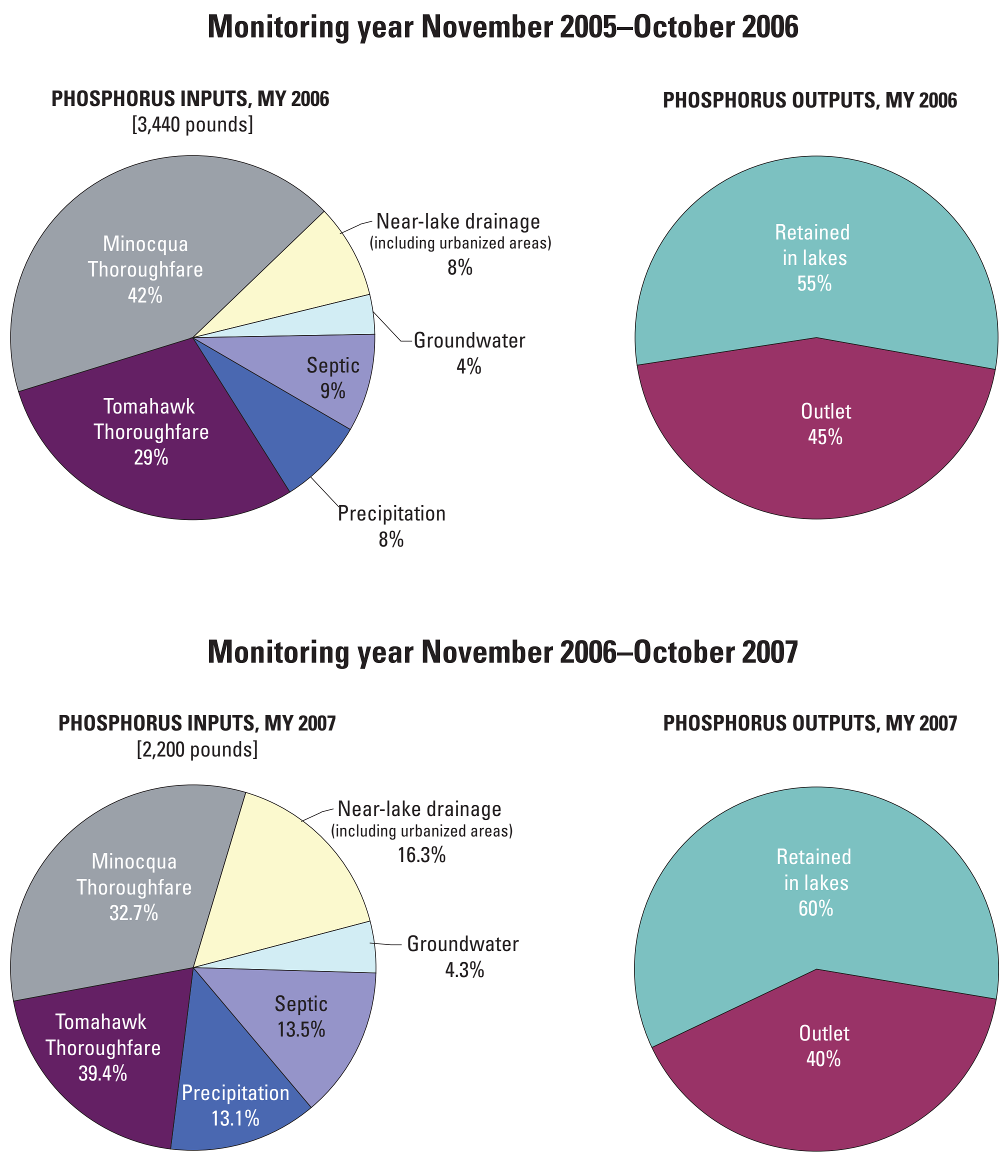


Figure 21. Phosphorus budgets for Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin, combined, for monitoring years 2006 and 2007. (%, percent).

This development was assumed to take place on lakeshore properties and increase septic-system inputs to 186 lb (table 6). For the Minocqua Lake watershed, forested acres would be converted to an additional 234 acres of low-density residential (151 acres in the area around the East Basin, 41 acres in the area around the Northwest Basin, and 42 acres in the area around Southwest Basin) and 138 acres of urban/commercial land (51 acres in the area around East Basin, 57 acres in the area around Northwest Basin, and 30 acres in the area around Southwest Basin). These developments on Minocqua Lake were assumed to be in sewered areas or away from the lake and not to affect septic-system inputs.

With changes in land use for the 2030 buildout without additional stormwater controls and hydrology similar to MY 2006–07, the total annual phosphorus load from the nearshore areas of the lakes was estimated with WinSLAMM to increase by about 160 lb (or an overall increase in loading of about 5 percent). The total loading to the lakes would increase from 2,820 lb to 3,050 lb (table 6). If average hydrology is used, the total loading to the lakes would increase by 150 lb (from 3,800 to 4,010 lb) or an overall increase in loading of about 4 percent. Another possible future condition that was examined assumed the changes in phosphorus loading associated with 2030 buildout occurred, but with stormwater and nonpoint controls added in subwatersheds to achieve a 50-percent reduction in loading from these areas. With these changes, the annual phosphorus loading is estimated to slightly decrease to about 2,810 lb for hydrology similar to MY 2006–07 and decrease to about 3,760 lb with average hydrology (slightly less than current conditions).

Simulated Changes in Water Quality in Response to Changes in Phosphorus Loading

Empirical models that relate phosphorus loading to measured water-quality characteristics can be used to determine how changes in phosphorus loading to Minocqua and Kawaguesaga Lakes, including that from urban sources, could either improve or degrade the water quality of the lakes. These models were developed on the basis of comparisons of hydrologic and phosphorus loading estimates determined for many different lake systems with specific measures describing lake water quality, such as near-surface phosphorus and chlorophyll *a* concentrations and Secchi depth. Some of these empirical models are contained within the BATHTUB model (Walker, 1996). The BATHTUB model includes hydrologic transport algorithms and is, therefore, capable of simulating changes in water quality in complex lakes (multibasin lakes or lakes connected by short channels). To predict changes in the water quality of Minocqua and Kawaguesaga Lakes that should occur with changes in phosphorus loading, the BATHTUB model was applied to the three basins of Minocqua Lake and the main basin of Kawaguesaga Lake.

Modeling Approach

To estimate the expected changes in water quality in Minocqua and Kawaguesaga Lakes in response to changes in phosphorus loading, 19 scenarios were simulated with the BATHTUB model (table 8). Scenario 1 simulated the average conditions for MY 2006–07 and was used to calibrate the BATHTUB model and establish a base case to which other simulations can be compared. Three basinwide scenarios (2–4) simulated decreases in controllable external phosphorus loading by 75, 50, and 25 percent, and six scenarios (5–10) simulated increases in controllable external phosphorus loading by 25, 50, 75, 100, 150, and 200 percent. Controllable external loading includes phosphorus from all of the tributaries and nearshore areas around the lakes and input from septic systems. Scenarios 11–14 simulate possible anthropogenic changes in the near-lake watershed with hydrology similar to that of MY 2006–07:

- scenario 11, projected development in the near-lake watershed (2030 buildout);
- scenario 12, projected 2030 buildout with controls;
- scenario 13, removing septic effluent from around both lakes; and
- scenario 14, removing septic effluent from just around Minocqua Lake.

Because MY 2006–07 were dry years, scenarios 15–19 are similar to scenarios 1 and 11–14, respectively, but simulated how the anthropogenic modeling results would change if the simulations were performed with long-term average hydrologic conditions. Scenario 1 (MY 2006-07 hydrology) and scenario 15 (average hydrology) establish base cases to compare the other simulations under two different hydrologic regimes.

Data Requirements

Four types of data are required as input into BATHTUB: morphometric data (table 1), water-quality data (tables 3 and 4), hydrologic data (table 5), and nutrient-loading data (table 6). In addition to total phosphorus concentrations (computed by dividing the input of phosphorus by the input of water for each source), dissolved orthophosphorus concentrations are needed. Dissolved orthophosphorus concentrations were obtained by assuming that the dissolved form represented 35 percent of the total phosphorus in Minocqua and Tomahawk Thoroughfares, 50 percent of the phosphorus in nearshore runoff, and 100 percent of the phosphorus in septic and groundwater inputs. The time period for the hydrologic and nutrient loading used in the BATHTUB model is dependent on the phosphorus-turnover ratio (number of times the phosphorus mass in the lakes is replaced in a specific time period). The model should be run for a period that results in a phosphorus-turnover ratio of 2 or larger.

Table 8. Predicted near-surface, summer average total phosphorus and chlorophyll *a* concentrations and Secchi depths in Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin, for various scenarios based on simulations with the BATHTUB model.

Scenario number	Scenario description	Total annual external phosphorus loading (pounds)	Simulated total phosphorus (milligrams per liter)				Simulated chlorophyll *a* (micrograms per liter)				Simulated Secchi depth (feet)			
			East Basin	South-west Basin	North-west Basin	Kawaguesaga	East Basin	South-west Basin	North-west Basin	Kawaguesaga	East Basin	South-west Basin	North-west Basin	Kawaguesaga
	General response scenarios													
1	**Average of MY 2006–07 (base scenario)**	**2,820**	**0.015**	**0.016**	**0.021**	**0.017**	**5.6**	**6.0**	**8.6**	**7.0**	**10.8**	**10.5**	**8.9**	**9.8**
	Change in controllable phosphorus loading:													
2	75-percent decrease	997	0.009	0.009	0.014	0.011	2.9	3.3	5.7	4.0	14.1	13.5	10.8	12.5
3	50-percent decrease	1,610	0.011	0.012	0.017	0.013	4.0	4.3	6.8	5.2	12.8	12.1	9.8	11.5
4	25-percent decrease	2,210	0.013	0.014	0.019	0.015	4.8	5.2	7.7	6.2	11.8	11.5	9.2	10.5
5	25-percent increase	3,420	0.017	0.017	0.023	0.019	6.2	6.7	9.3	7.8	10.5	10.2	8.2	9.2
6	50-percent increase	4,040	0.018	0.019	0.025	0.021	6.8	7.3	10.0	8.5	9.8	9.5	7.9	8.9
7	75-percent increase	4,640	0.020	0.020	0.026	0.022	7.4	7.8	10.6	9.2	9.5	9.2	7.9	8.5
8	100-percent increase	5,250	0.021	0.022	0.028	0.024	7.9	8.4	11.2	9.7	9.2	8.9	7.5	8.2
9	150-percent increase	6,470	0.024	0.024	0.030	0.026	8.7	9.3	12.2	10.8	8.5	8.5	7.2	7.5
10	200-percent increase	7,680	0.026	0.027	0.033	0.029	9.5	10.1	13.0	11.7	8.2	7.9	6.9	7.2
	Specific scenarios													
	MY 2006–07 hydrology:													
11	Proposed 2030 buildout	3,050	0.016	0.016	0.022	0.019	5.8	6.2	9.1	7.8	10.8	10.5	8.5	9.2
12	Proposed 2030 buildout with controls	2,810	0.015	0.016	0.020	0.018	5.5	5.9	8.1	7.4	11.2	10.5	9.2	9.5
13	Septic effluent removed around both lakes	2,520	0.014	0.014	0.019	0.015	5.0	5.3	7.8	5.8	11.5	11.2	9.2	10.8
14	Septic effluent removed from around Minocqua Lake	2,640	0.014	0.015	0.019	0.017	5.1	5.5	7.9	6.7	11.5	11.2	9.2	10.2
	Average hydrology:													
15	Base scenario	3,800	0.015	0.015	0.020	0.016	5.5	5.8	8.1	6.6	11.2	10.8	9.2	10.2
16	Proposed 2030 buildout	4,010	0.015	0.016	0.021	0.017	5.6	6.0	8.7	7.1	10.8	10.5	8.5	9.8
17	Proposed 2030 buildout with controls	3,760	0.015	0.015	0.019	0.017	5.4	5.7	7.6	6.8	11.2	10.8	9.2	9.8
18	Septic effluent removed from around both lakes	3,500	0.014	0.014	0.019	0.014	5.1	5.3	7.5	5.7	11.5	11.2	9.5	10.8
19	Septic effluent removed from around Minocqua Lake	3,610	0.014	0.014	0.019	0.016	5.1	5.4	7.5	6.3	11.5	11.2	9.5	10.5

Annual simulations resulted in a phosphorus turnover ratio of 2 for the lakes as a whole; therefore, the average annual loadings in tables 5 and 6 were used in the model. Even though loading data are summarized for the entire year, the model simulates water quality only for the growing season (May through September).

Phosphorus from internal loading (sediment release) is not typically included as a phosphorus source for BATHTUB, because most empirical models already incorporate this source. Additional internal loading, therefore, should be added only when a lake/reservoir has abnormally high internal loading (Walker, 1996). It was believed that Northwest Basin, being shallower than the other basins and probably polymictic (that is, mixing multiple times throughout the summer), has abnormally high internal loading; therefore, an additional internal loading of 0.075 $mg/m^2/d$ was applied in BATHTUB simulations, which equates to about 50 pounds per year. It was assumed that internal phosphorus loading to the Northwest Basin remained constant in all simulations.

Algorithms and Calibration

When applying BATHTUB, dispersion coefficients between each pair of basins (exchange of water with adjacent upstream basins/lakes) and the specific algorithms used to simulate each water-quality characteristic must be defined. A dispersion coefficient of 1.0 represents very little constriction between adjacent basins, and a value near 0.0 represents almost no mixing with the upstream adjacent basin. Because of the constrictions between the Northwest and Southwest Basins and between the Southwest Basin and Kawaguesaga Lake, a dispersion coefficient of 0.5 was applied between these basins. The dispersion coefficient between the other adjacent basins was set to the default value of 1.0. The algorithms chosen to simulate total phosphorus and chlorophyll *a* concentrations are listed in table 9; all are the default algorithms and have been shown to usually be the best models for most lakes and reservoirs (Walker, 1996). Nonalgal turbidity factors (or the reduction in clarity caused by factors other than algae) were computed within BATHTUB.

With the average annual loading data from MY 2006–07, BATHTUB was used to simulate the summer average water quality (May through September) in each basin. The capability of the model to simulate changes in the water quality of the lakes was evaluated by inputting the morphometry of the lakes and the hydrologic and phosphorus loadings into the model and simulating near-surface total phosphorus and chlorophyll *a* concentrations and Secchi depth. The simulated concentrations and Secchi depth were close to those measured in the lakes. This similarity confirms that the model is expected to accurately simulate changes in the lakes in response to changes in phosphorus loading. Calibration coefficients for each water-quality constituent may be applied for each lake/basin to improve the accuracy of the model. The only calibration coefficients applied in the simulations were those for phosphorus in the East Basin (3.0) and in Kawaguesaga Lake (0.4). No other calibrations were required. The simulated (before and after calibration) and measured values for MY 2006–07 are compared in figure 22. The coefficient of variation for each measured value was computed on the basis of average summer data from 2001 to 2008 to provide an estimate of the certainty of the measured data (plus and minus 1 standard error around the average value). After model calibration, BATHTUB accurately simulated total phosphorus, chlorophyll *a*, and Secchi depth.

Table 9. Algorithms used within BATHTUB to simulate water quality in the basins in Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin.

[**Abbreviations:** –, not simulated]

Process	Model Number	Algorithm description
Total phosphorus	1	Second order, available phosphorus
Nitrogen balance	–	None
Chlorophyll *a* concentration	2	Phosphorus, light, and residence time
Secchi depth	1	Chlorophyll *a* and turbidity
Dispersion	1	Fisher numeric
Phosphorus calibration	1	Decay rates
Nitrogen calibration	–	None

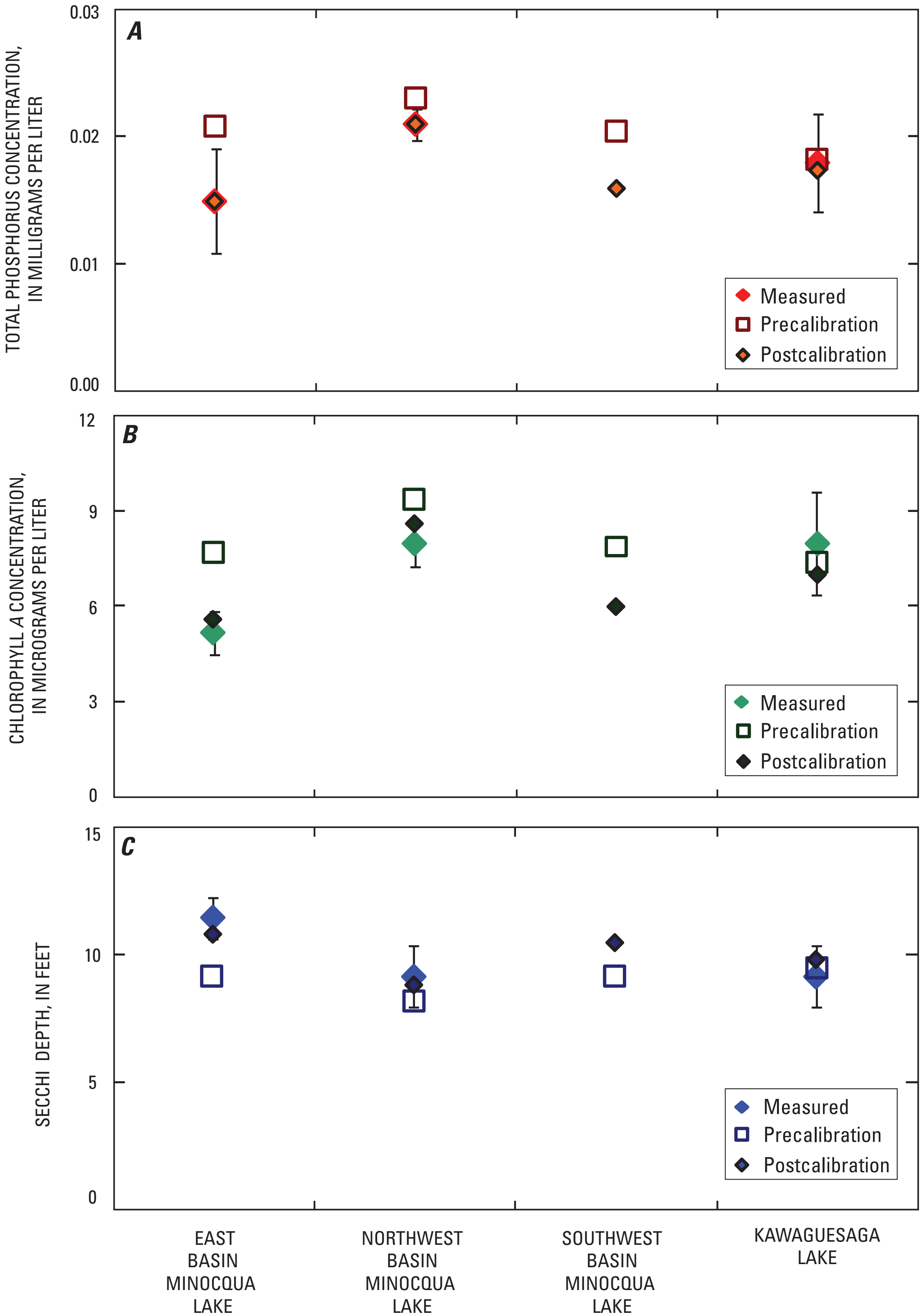


Figure 22. Measured and simulated (before and after calibration with the BATHTUB model) average summer (May through September) near-surface (*A*) total phosphorus concentrations, (*B*) chlorophyll *a* concentrations, and (*C*) Secchi depths in the basins of Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin.

Response in Water Quality to General Changes in Phosphorus Loading

To predict the expected response in water quality in Minocqua and Kawaguesaga Lakes to watershed-wide changes in external phosphorus loading, nine scenarios (2–10) were simulated with the BATHTUB model. The volume-weighted-average total and dissolved orthophosphorus concentrations (total nutrient load divided by total water load) for each of the sources were decreased by 75, 50, and 25 percent and increased by 25, 50, 75, 100, 150 and 200 percent. Nitrogen concentrations were not altered in the various scenarios. Because the lakes were often phosphorus limited, altering nitrogen concentrations was expected and shown to have little effect on the simulated results.

Changes in Phosphorus Concentrations

On the basis of BATHTUB model simulations, phosphorus concentrations in each basin should have a relatively linear response to a linear change in controllable external phosphorus loading (fig. 23*A* and table 8). The changes in in-lake phosphorus concentrations, on a percentage basis, are smaller than the changes in external phosphorus loadings. Changes in in-lake phosphorus concentrations are only about 40–50 percent of the changes in phosphorus loading. For example, a 50-percent reduction in controllable external phosphorus loading causes about a 26-percent decrease in in-lake phosphorus concentrations (a decrease from 0.015 mg/L to 0.011 mg/L in the Minocqua East Basin); a 50-percent increase in external loading causes a 20-percent increase in concentrations (from 0.015 to 0.018 mg/L; table 8). The estimated percent changes in in-lake phosphorus concentrations, being smaller than the percent reductions in controllable external phosphorus loadings, are partly the result of not simulating reductions in the contributions from groundwater and precipitation, which represent about 15 percent of the total phosphorus input to the lake.

Changes in Chlorophyll *a* Concentrations

Simulated average summer chlorophyll *a* concentrations have a nonlinear response to a linear change in controllable external phosphorus loading (fig. 23*B* and table 8). The response in chlorophyll *a* concentrations is larger (on a percentage basis) for decreases in loading than for similar increases in loading. A 50-percent reduction in controllable external phosphorus loading in the East Basin results in a 29-percent reduction in chlorophyll *a* concentrations (from 5.6 to 4.0 µg/L), whereas a 50-percent increase in loading results in an increase by only 21 percent, and a 200-percent increase in loading results in an increase by only 70 percent. The estimated percent changes in chlorophyll *a* concentrations, being smaller than the reductions in controllable external phosphorus loadings, are again partly the result of not simulating reductions in the phosphorus input from groundwater and precipitation.

Changes in Secchi Depths (Water Clarity)

Simulated Secchi depths are more responsive to decreases in controllable external phosphorus loading than to increases in loading (fig. 23*C* and table 8). When external phosphorus loading to the East Basin is decreased by 50 percent, Secchi depths increase by 2 ft (18 percent); however, when loading is increased by 50 percent, Secchi depths decrease by only about 1ft (10 percent). With a 200-percent increase in external phosphorus loading, Secchi depths are estimated to decrease by 2.6 ft (24 percent).

Changes in Trophic Status

TSI values indicate that Minocqua and Kawaguesaga Lakes are typically mesotrophic (TSI values between 40 and 50; fig. 7 and tables 3 and 4). On the basis of the simulations with the BATHTUB model, if controllable external phosphorus loading could be reduced by 50 percent from that measured in MY 2006–07, all of the basins in the lakes, except the Northwest Basin, would become oligotrophic with respect to phosphorus concentration (less than 0.012 mg/L); however, all basins would remain mesotrophic with respect to chlorophyll *a* concentration and Secchi depth (fig. 23). If, however, controllable external phosphorus loading increased by 150 percent from that measured in MY 2006–07, all areas of both lakes would become eutrophic with respect to total phosphorus and chlorophyll *a* concentrations.

Importance of Internal Phosphorus Loading

When deep water of productive lakes becomes anaerobic, the rate of phosphorus release from the deep sediments is often greatly accelerated. Typically, in deep dimictic lakes (lakes that remain stratified throughout summer, such as the East Basin), phosphorus from internal loading is trapped in the hypolimnion during most of the summer and released into the shallow water primarily at fall overturn. But in polymictic lakes, such as the Northwest Basin, phosphorus released from the sediments is not trapped in the bottom of the lake but is intermittently released to the shallow water throughout summer. These mixing events resulted in near-surface phosphorus concentrations in the Northwest Basin increasing as summer progressed, and they further resulted in a higher overall near-surface, summer average phosphorus concentration than that of the rest of the lake. This is the primary reason why the additional internal phosphorus load had to be added to Northwest Basin in the BATHTUB model for accurate simulations. It was estimated that internal loading added about 50 lb of phosphorus during summer, or about 23 percent of the annual phosphorus loading to the Northwest Basin.

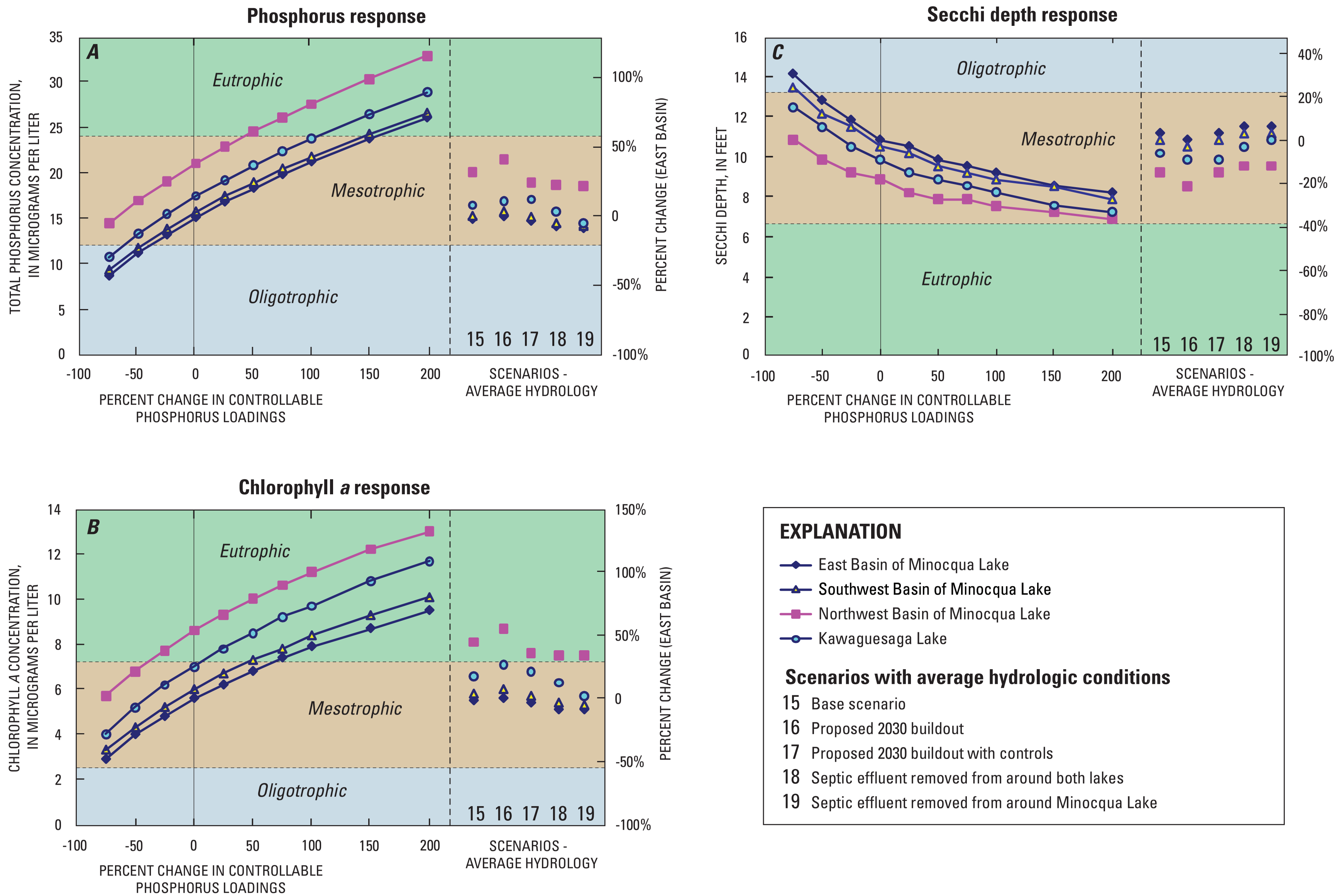


Figure 23. Simulated changes in near-surface (*A*) total phosphorus concentrations, (*B*) chlorophyll *a* concentrations, and (*C*) Secchi depths in the basins of Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin, in response to various phosphorus-loading scenarios. Controlled external loading includes phosphorus from all of the tributaries and nearshore areas around the lakes and input from septic systems. Specific scenarios are described in table 9.

If external phosphorus loading to the Northwest Basin is reduced in the future, the results from the BATHTUB model (with internal loading included) should accurately predict the short-term changes in water quality that would occur in this basin. However, if the reduction in external load were to persist for many years, the internal phosphorus release rate should gradually decrease and come to equilibrium with the new external loading. This should ultimately result in a slightly greater improvement in water quality than predicted in figure 23.

Response in Water Quality to Specific Urbanization/Residential Development Scenarios

Responses in water quality to anthropogenic changes in the near-lake drainage area were simulated with hydrology similar to that for average MY 2006–07 conditions, as well as for long-term average hydrologic conditions.

Response Under Average 2006–07 Conditions

Future development of the near-lake drainage area around the lakes was estimated and described previously for the 2030 buildout condition. To estimate how these changes would affect water quality, scenario 11 was used to simulate the effects of future changes in phosphorus loading from residential and urban/commercial development throughout the watershed. With these changes in land use, but without new or additional stormwater controls, the total annual phosphorus load to the lakes would increase by about 230 lb (or an overall increase in loading of about 8.2 percent), from about 2,820 lb to about 3,050 lb (tables 6 and 8). Scenario 12 represents the changes in phosphorus loading associated with 2030 buildout but with stormwater and nonpoint controls added (implementation of best management practices) in subwatersheds to achieve a 50-percent reduction in loading from these areas. With these changes, the annual phosphorus loading is estimated to decrease to about 2,810 lb (an overall decrease in loading of 0.4 percent).

Future 2030 buildout in the watershed without controls (scenario 11) resulted in a slight degradation in water quality: phosphorus concentrations increased by about 0.001 mg/L, chlorophyll *a* concentrations increased by about 0.2 to 0.8 µg/L, and Secchi depths decreased slightly (table 8). The largest degradation in water quality was estimated to occur in Kawaguesaga Lake, where chlorophyll *a* concentrations were estimated to increase by 0.8 µg/L and Secchi depth was estimated to decrease by 0.6 ft. If, however, the buildout occurs with additional stormwater and nonpoint controls (installation of various best management practices) for a 50-percent reduction in loading from these near-lake areas (scenario 12), it is possible that water quality will change very little. In 2009, statewide legislation was passed to include additional point and nonpoint controls such as banning the use of phosphorus in lawn fertilizer and household dishwasher detergents to control phosphorus inputs from these sources (Wisconsin Association of Lakes, written commun., 2009). Buildout with controls (scenario 12) resulted in a slight improvement in water quality in the Northwest Basin because of decreases in near-lake loading and slight degradation in Kawaguesaga Lake because of increases in loading from new septic systems. In the Northwest Basin, phosphorus concentrations decreased by about 0.001 mg/L, chlorophyll *a* concentrations decreased by 0.5 µg/L, and Secchi depths increased by 0.3 ft. In Kawaguesaga Lake, phosphorus concentrations increased by about 0.001 mg/L , chlorophyll *a* concentrations increased by 0.4 µg/L, and Secchi depths decreased by 0.3 ft.

If it were possible to completely remove the phosphorus loading from septic systems around both lakes (scenario 13), the total phosphorus loading to the lakes would decrease from 2,820 lb to 2,520 lb: a reduction of about 300 lb or a reduction of total loading of 10 percent. This reduction in phosphorus loading is expected to improve water quality: phosphorus concentrations decreased by about 0.001–0.002 mg/L, chlorophyll *a* concentrations decreased by 0.6–1.2 µg/L, and Secchi depths increased by 0.7 to 1.0 ft (table 8). The largest improvements in water quality are expected to occur in Kawaguesaga and the Northwest and Southwest Basins of Minocqua Lake. If it were only possible to remove phosphorus loading from septic systems around Minocqua Lake (scenario 14), the total phosphorus loading to the lakes would decrease from 2,820 lb to 2,640 lb: a reduction of about 180 lb or a reduction in total loading of about 6 percent. This reduction in phosphorus loading is expected to improve the water quality in Minocqua Lake. Phosphorus concentrations would decrease by about 0.001 mg/L, chlorophyll *a* concentrations would decrease by 0.5–0.7 µg/L, and Secchi depths would increase by 0.3 to 0.7 ft (table 8). A slight improvement in water quality is also expected to occur in Kawaguesaga Lake because of the movement of water from Minocqua Lake into Kawaguesaga Lake.

Response Under Average Hydrologic Conditions

Because MY 2006–07 were dry years, scenarios 15–19 simulated how the modeling results would change if the simulations were performed for years with average hydrologic conditions. Scenario 15 was used to determine what the water quality in the lakes would have been if average hydrological conditions had occurred during the study period. During average hydrological conditions, the total loading to the lakes is estimated to increase from 2,820 lb to about 3,800 lb (tables 6 and 8: an increase of about 1,000 lb or about 35 percent). This increase in loading is expected to occur with an increase in water input by about 42 percent (table 5).

Results from scenario 15 indicate that the increased loading of water and phosphorus should result in a slight improvement in water quality in most basins. Total phosphorus concentrations would decrease by less than 0.001 mg/L, chlorophyll *a* concentrations would decrease by 0.1–0.5 µg/L, and Secchi depths would increase by 0.3–0.4 ft in comparison to the MY 2006–07 hydrologic conditions (table 8 and fig. 23). The largest improvement in water quality occurs in the Northwest Basin, where the relative importance of internal loading decreased. It is expected that the general response curves for each basin in figure 23 would remain relatively similar but be offset by these small changes; therefore, the general response curves would still be applicable.

Scenarios 16–19 simulated the effects of each of the anthropogenic modifications to the watershed during average hydrologic conditions (only the results for scenarios 15–19 for the average, more typical, hydrologic conditions are shown in fig. 23). The changes in water quality from the base scenario with MY 2006–07 hydrology (scenario 1) to the base scenario with average hydrologic conditions (scenario 15) were found to be the same for each of the other anthropogenic modifications (scenarios 16–19). Therefore, each anthropogenic modification (2030 buildout or septic removal) has similar impacts on water quality as described in the previous section whether the hydrology from MY 2006–07 or average hydrologic conditions is considered.

Response in Water Quality to a Combination of Changes in the Watershed

In the previous section, BATHTUB was used to simulate the effects of specific scenarios; however, in reality multiple changes can take place in the watershed. Once the additive effects of these potential actions are quantified, either with the approaches used in this study or with other numerical models, the results in figure 23 can be used to evaluate how the lakes should respond. For example, if septic effluent from the entire near-lake drainages were removed and 2030 buildout occurred with additional stormwater and nonpoint controls, then the total loading to the lakes should be reduced by approximately 310 to 340 lbs. This represents a total reduction of about 10 percent. The general response curves on the left side of each graph in figure 23 can then be used to determine how these changes affect water quality.

Other changes in the watershed could have much more dramatic effects than the scenarios evaluated in table 8 and figure 23. For example, if the large internally drained areas in figure 2 were modified to drain to the lakes, especially those on the Island or in Woodruff, then the effects of urbanization would be much larger than previously described. Presently, the urban areas represent only about 1 percent of the water added to the lakes, but represent about 10–12 percent of the phosphorus loading to the lakes. If the internally drained areas are removed, additional urbanization could occur and then the runoff and the associated phosphorus would drain to the lakes. Additional modeling would be needed to determine how this would affect the phosphorus loading.

Presently internal loading of phosphorus from the sediments appears to have only a small effect on the water quality of the lakes during summer, except for the Northwest Basin. However, if phosphorus loading to the lakes increased and remained higher than presently measured, then the internal phosphorus loading from the sediments would also increase. This should ultimately result in larger degradations in water quality than predicted in figure 23.

Summary and Conclusions

Minocqua and Kawaguesaga Lakes (1,318 and 690 acres, respectively) are the lowermost lakes of a chain in the lakes region of north-central Wisconsin. Minocqua Lake receives inflows from two major tributaries: Minocqua Thoroughfare and Tomahawk Thoroughfare. Minocqua Lake is interconnected with and flows directly into Kawaguesaga Lake. Water levels of both lakes are controlled by the Minocqua Dam, whose outlet discharges to the Tomahawk River.

Like many northern lake settlements, the two local towns, Minocqua and Woodruff, have experienced a boom in population and land development. Stormwater runoff from the residential/commercial developments and impervious surfaces on the Island, as well as septic systems in the heavily developed shoreline area of the lakes, are a concern as a source of increased nutrient loading to the lakes. The long-term management and protection of these lakes in the face of increased development and urbanization is a major concern to local and state governments.

To provide a better understanding of the factors that affect the water quality of Minocqua and Kawaguesaga Lakes, a detailed study of the lakes and their watersheds was done in 2006–07 by the USGS in cooperation with the Minocqua/Kawaguesaga Lakes Protection Association through the Town of Minocqua. The purposes of the study were to describe the hydrology and water quality of the lakes; quantify the sources of phosphorus loading to the lakes, including those associated with urban development; and evaluate the effects of future changes in phosphorus inputs on the water quality of the lakes. Water-quality data were collected in the lakes during 2003 and 2006–07 and compared with historical data. Major water and phosphorus sources were measured directly, and minor sources were estimated to construct detailed water and phosphorus budgets for the lakes during monitoring years (MY) 2006 and 2007. The lake water quality model BATHTUB was then used to simulate how the water quality of the lakes currently responds to nutrient loading and would respond to future changes. Results from model simulations will aid in decisionmaking for future lake management by predicting how the lakes should respond to specific land-development and watershed-management scenarios.

The water quality of Minocqua and Kawaguesaga Lakes appears to have improved since 1963, when a new sewage-treatment plant was constructed and its discharge was bypassed around the lakes, resulting in decreased loading of phosphorus to the lakes compared to former times. Since the mid-1980s, the water quality of the lakes has changed very little. Phosphorus concentrations from 1988 through 1996, however, were lower than the long-term average, possibly the result of an extended drought that occurred in the late 1980s. From 1986 to 2007, summer average concentrations of near-surface total phosphorus in the Minocqua main East Basin fluctuated from 0.009 mg/L to 0.027 mg/L but generally remained less than 0.022 mg/L (mesotrophic); the average summer concentration was 0.016 mg/L. Total phosphorus concentrations in the Southwest Basin generally were similar to those of the East Basin, but those of the Northwest Basin were generally greater. From 1991 to 2007, near-surface total phosphorus in the Northwest Basin ranged from 0.007 to a maximum of 0.043 mg/L; the average summer concentration was 0.018 mg/L. Nutrient concentrations in Kawaguesaga Lake exhibits a similar pattern to that of Minocqua Lake. From 1991 to 2007, summer average concentrations of near-surface total phosphorus have ranged from 0.009 mg/L to 0.026 mg/L; the overall average for summer was 0.018 µg/L. Since 1986, summer average chlorophyll *a* concentrations and Secchi depths indicate that both lakes generally are mesotrophic but occasionally borderline eutrophic, with no long-term trends.

During the 2-year detailed monitoring period, the Minocqua Thoroughfare contributed about 38 percent of the water inflow, Tomahawk Thoroughfare contributed 34 percent, and near-lake surface inflow, precipitation, and groundwater contributed about 1, 16, and 11 percent of the total inflow, respectively. The average residence time of water in the lakes was 1.5 years. Water leaves the lakes primarily through the Tomahawk River outlet (83 percent) or by evaporation (14 percent), with minor outflow to groundwater.

Total input of phosphorus to both lakes was 3,440 pounds in MY 2006 and 2,200 pounds in MY 2007. The largest sources of phosphorus entering the lakes were the Minocqua and Tomahawk Thoroughfares, which delivered about 39 and 26 percent of the total phosphorus input, respectively. A large fraction of the input from Tomahawk Thoroughfare originates from Mid Lake and the adjacent wetlands from Thoroughfare Road to the mouth. The next largest contribution came from the near-lake drainage area containing the adjacent urban and residential developments, which disproportionately accounted for about 12 percent of the total phosphorus input but only about 1 percent of the total water input. Septic systems and precipitation contributed about 11 and 10 percent of the total phosphorus input, whereas groundwater delivered about 4 percent of the total phosphorus.

To predict the changes in water quality of Minocqua and Kawaguesaga Lakes that should occur with changes in phosphorus loading, the BATHTUB model was applied to the three basins of Minocqua Lake and the main basin of Kawaguesaga Lake. A relatively linear response was found between phosphorus concentrations and external phosphorus loading. The changes in in-lake phosphorus concentrations, on a percentage basis, were smaller than the changes in external phosphorus loadings—representing only about 40–50 percent of the changes in phosphorus loading. Simulated average summer chlorophyll *a* concentrations and Secchi depths (water clarity) showed a nonlinear response to a linear change in controllable external phosphorus loading (inputs from the tributaries and nearshore areas around the lakes and input from septic systems). The response of chlorophyll *a* concentrations is larger (on a percentage basis) for decreases in loading than for similar increases in loading. Simulated chlorophyll *a* concentrations and Secchi depths were more responsive to decreases in controllable external phosphorus loading than to increases in loading. If controllable external phosphorus loading were reduced by 50 percent from that measured in MY 2006–07, all of the basins in the lakes except the Northwest Basin should become oligotrophic with respect to phosphorus concentration; however, all basins would still remain mesotrophic with respect to chlorophyll *a* concentration and Secchi depth.

Responses in water quality of the lakes to anthropogenic changes in the near-lake watershed were simulated for several scenarios, including the effects of changes in phosphorus loading from residential and urban development—referred to as “2030 buildout”—and removal of septic-system inputs. The 2030 buildout scenario with existing stormwater controls resulted in a slight degradation in water quality: phosphorus concentrations increased by about 0.001 mg/L, chlorophyll *a* concentrations increased by 0.2 to 0.8 µg/L, and Secchi depths decreased slightly. The largest degradation in water quality was estimated to occur in Kawaguesaga Lake. If 2030 buildout occurred with additional stormwater and nonpoint controls added in near-lake subwatersheds to achieve a 50-percent reduction in loading from these areas, it is possible that water quality may change very little. Buildout with controls resulted in a slight improvement in water quality in the Northwest Basin because of decreases in nearshore loading and a slight degradation in Kawaguesaga Lake because of increases in loading from new septic systems. The removal of phosphorus loading from septic systems around Minocqua Lake is expected to improve the water quality in Minocqua Lake. Simulated phosphorus concentrations decreased by about 0.001 mg/L, chlorophyll *a* concentrations decreased by 0.5–0.7 µg/L, and Secchi depths increased by 0.3 to 0.7 ft. If it were possible to remove septic-system inputs from around both Minocqua and Kawaguesaga Lakes, even greater improvements would be likely: simulated phosphorus concentrations decreased by about 0.001–0.002 mg/L, chlorophyll *a* concentrations decreased by 0.6–1.2 µg/L, and Secchi depths increased by 0.7 to 1.0 ft for that scenario. The largest improvements in water quality were expected to occur in Kawaguesaga Lake and the Northwest and Southwest basins of Minocqua Lake.

Future development in the Minocqua/Kawaguesaga watersheds with existing stormwater controls was shown to have a detrimental effect on the water quality of the lakes; therefore, management actions to minimize future phosphorus input into these lakes are important for maintaining the water quality of the lakes. Preservation of environmental corridors and open areas will also contribute to protecting the lakes' natural drainage systems and their water quality by reducing nonpoint-source pollution and by providing buffers for filtration and infiltration. In addition to protecting natural drainage systems in urban areas, environmental corridors can protect and preserve sensitive natural areas such as wetlands, flood plains, steep slopes, and other areas that would impair surface or groundwater quality if disturbed or developed. Numerous noncontributing (internally drained) areas within the watershed, such as the large noncontributing area on the Island, are of key importance in minimizing surface runoff and nutrient loading to Minocqua and Kawaguesaga Lakes. Development scenarios assumed that these noncontributing areas were maintained. Future development of these areas that included extending or connecting drainage from these areas into the lakes would increase the contributing watershed area and greatly increase loading to the lakes. Phosphorus loading from upstream tributary sources is presently (2007) at very low levels; therefore, reductions in loading and improvements in water quality may be most likely achieved by decreasing inputs from the developed near-lake drainage areas and from septic systems around the lakes.

References

Blake, Tom, 1996, Minocqua-Woodruff priority lakes project plan: Wisconsin Department of Natural Resources Publication WT–477–96, 88 p.

Booth, D.B., and Jackson, C.R., 1997, Urbanization of aquatic systems—Degradation thresholds, stormwater detection, and the limits of mitigation: Journal of the American Water Resources Association, v. 33, no. 5, p. 1077–1090.

Boyle, K.J., Lawson, S.R., Michael, H.J., and Bouchard, Roy, 1998, Lakefront property owners' economic demand for water clarity in Maine lakes: University of Maine, Maine Agricultural and Forest Experiment Station, Miscellaneous Report 410, 20 p.

Carlson, R.E., 1977, A trophic state index for lakes: Limnology and Oceanography, v. 22, p. 361–369.

Correll, D.L., 1998, The role of phosphorus in the eutrophication of receiving waters—A review: Journal of Environmental Quality, v. 27, no. 2, p. 261–266.

Corsi, S.R., Graczyk, D.J., Owens, D.W., and Bannerman, R.T., 1997, Unit-area loads of suspended sediment, suspended solids and total phosphorus from small watersheds in Wisconsin: U.S. Geological Survey Fact Sheet 195–97, 4 p.

Dodds, W.K., and Bouska, W.W., Eitzmann, J.L., Pilger, T.J., Pitts, K.L., Riley, A.J., Schloesser, J.T., and Thornbrugh, D.J., 2009, Eutrophication of U.S. freshwaters—Analysis of potential economic damages: Environmental Science & Technology, v. 43, no. 1, p. 12–19.

Doherty, John, 2004, PEST—Model-Independent Parameter Estimation, user manual (5th ed.): Brisbane, Australia, Watermark Numerical Computing, 336 p.

Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C2, 89 p.

Eiswerth, Mark, Kashian, Russ, and Skidmore, Mark, 2005, What is the value of a clean and healthy lake to a local community?: University of Wisconsin-Whitewater, unnumbered report, 80 p.

ePodunk, Inc, 2007, Oneida County, WI, profile—Population overview, accessed June 24, 2010, at http://www.epodunk.com/cgi-bin/popInfo.php?locIndex=23146.

Farnsworth, R.K., and Thompson, E.S., 1982, Mean monthly, seasonal, and annual pan evaporation for the United States: National Oceanic and Atmospheric Administration Technical Report NWS 34, 82 p.

Garn, H.S., Olson, D.L., Seidel, T.L., and Rose, W.J., 1996, Hydrology and water quality of Lauderdale Lakes, Walworth County, Wisconsin, 1993–94: U.S. Geological Survey Water-Resources Investigations Report 96–4235, 29 p.

Garn, H.S., Robertson, D.M., Rose, W.J., Goddard, G.L., and Horwatich, J.A., 2006, Water quality, hydrology, and response to changes in phosphorus loading of Nagawicka Lake, a calcareous lake in Waukesha County, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2006–5273, 41 p.

Graczyk, D.J., Hunt, R.J., Greb, S.R., Buchwald, C.A., and Krohelski, J.T., 2003, Hydrology, nutrient concentrations, and nutrient yields in nearshore areas of four lakes in northern Wisconsin, 1999–2001: U.S. Geological Survey Water-Resources Investigations Report 03–4144, 64 p.

Graneli, Wilhelm, 1999, Internal phosphorus loading in Lake Ringsjon: Hydrobiologia, v. 404, p. 19–26.

Haitjema, H.M., 1995, Analytic element modeling of groundwater flow: San Diego, Calif., Academic Press, 394 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural waters (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 264 p.

Hole, F.D., Beatty, M.T., Milfred, C.J., Lee, G.B., and Klingelhoets, A.J., 1968, Soils of Wisconsin: University of Wisconsin-Extension, Geological and Natural History Survey, scale 1:710,000, 1 sheet.

Hunt, R.J., Anderson, M.P., and Kelson, V.A., 1998, Improving a complex finite-difference ground water flow model through the use of an analytic element screening model: Ground Water, v. 36, no. 6. p. 1011–1017.

Hunt, R.J., Haitjema, H.M., Krohelski, J.T., and Feinstein, D.T., 2003, Simulating lake-ground water interactions—Approaches and insights: Ground Water, v. 41, no. 2, p. 227–237.

Lillie, R.A., and Mason, J.W., 1983, Limnological characteristics of Wisconsin lakes: Wisconsin Department of Natural Resources, Technical Bulletin 138, 116 p.

Lindemann, J., Shaw, B., and McKinney, B., 1997, An evaluation of the impacts septic systems have on groundwater and surface-water quality of Minocqua Lake, Wisconsin: University of Wisconsin-Stevens Point, College of Natural Resources, 34 p.

Michael, H.J., Boyle, K.J., and Bouchard, Roy, 1996, Water quality affects property prices—A case study of selected Maine lakes: University of Maine, Maine Agricultural and Forest Experiment Station, Miscellaneous Report 398, 18 p.

Minocqua/Kawaguesaga Lakes Protection Association, 2003, State of the lakes 2003 and member user manual: Minocqua/Kawaguesaga Lakes Protection Association, 39 p.

Mudrey, M.G., Jr., Brown, B.A., and Greenberg, J.K., 1982, Bedrock geologic map of Wisconsin: University of Wisconsin-Extension, Geological and Natural History Survey, scale 1:1,000,000, 1 sheet.

Multi-Resolution Land Characteristics Consortium, 2001, 2001 National Land Cover Data (NCLD 2001): U.S Environmental Protection Agency, accessed June 24, 2010, at http://www.epa.gov/mrlc/nlcd-2001.html.

Natural Resources Conservation Service, 2006, Web soil survey: U.S. Department of Agriculture, accessed June 24, 2009, at http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx.

National Climatic Data Center, 2006–07, Climatological data: Asheville, N.C., National Oceanic and Atmospheric Administration (published monthly).

Oakes, E.L., and Cotter, R.D. 1975, Water resources of Wisconsin—Upper Wisconsin River Basin: U.S. Geological Survey Hydrologic Investigations Atlas HA–536, 3 sheets, scale 1:1,000,000.

Omernik, J.M., Chapman, S.S., Lillie, R.A., and Dumke, R.T., 2000, Ecoregions of Wisconsin: Transactions of the Wisconsin Academy of Sciences, Arts, and Letters, v. 88, p. 77–103.

Oneida County Department of Planning and Zoning, 2007, GIS Land Record System: Accessed June 24, 2010, at http://www.co.oneida.wi.gov/section.asp?linkid=1802&locid=135.

Panuska, J.C., and Kreider, J.C., 2003, Wisconsin lake modeling suite program documentation and user's manual, Version 3.3 for Windows: Wisconsin Department of Natural Resources PUBL–WR–363–94, 32 p., accessed June 24, 2010, at http://www.dnr.state.wi.us/lakes/model/.

Patterson, G.L., 1989, Water resources of Vilas County, Wisconsin: Wisconsin Geological and Natural History Survey Miscellaneous Paper 89–1, 46 p.

Pitt, R., and Voorhees, J., 1993, Source loading and management model (SLAMM) seminar publication, *in* Seminar publication, Nation Conference on Urban Runoff Management—Enhancing urban watershed management at the local, county, and state levels, March 30–April 2, 1993: Cincinnati, Ohio, U.S. Environmental Protection Agency Center for Environmental Research Information, EPA/625/R–95/003, p. 225–243.

Pennington, S.R., Kaplowitz, M.D., and Witter, S.G., 2003, Reexamining best management practices for improving water quality in urban watersheds: Journal of the American Water Resources Association, v. 39, no. 5, p. 1027–1041.

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water Resources Investigations, book 3, chap. C3, 66 p.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow—Volume 1, measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 284 p.

Reckhow, K.H., Beaulac, M.N., and Simpson, J.T., 1980, Modeling phosphorus loading in lake response under uncertainty—A manual and compilation of export coefficients: U.S. Environmental Protection Agency EPA–440/5–80–011.

Robertson, D.M., Rose, W.J., and Juckem, P.F., 2009, Water quality and hydrology of Whitefish (Bardon) Lake, Douglas County, Wisconsin, with special emphasis on responses of an oligotrophic seepage lake to changes in phosphorus loading and water level: U.S. Geological Survey Scientific Investigations Report 2009–5089, 41 p.

Robertson, D.M., Rose, W.J., and Saad, D.A., 2005, Water quality, hydrology, and phosphorus loading to Little St. Germain Lake, Wisconsin, with special emphasis on the effects of winter aeration and ground-water inputs: U.S. Geological Survey Scientific Investigations Report 2005–5071, 36 p.

Sauer, V.B., 2002, Standards for the analysis and processing of surface-water data and information using electronic methods: U.S. Geological Survey Water-Resources Investigations Report 01–4044, 91 p.

Strack, O.D.L., 1989, Groundwater mechanics: Englewood Cliffs, N.J., Prentice Hall, 732 p.

Tang, Zhenxu; Engel, B.A.; Lim, K.J., Pijanowski, B.C.; and Harbor, Jon, 2005, Minimizing the impact of urbanization on long term runoff: Journal of the American Water Resources Association, v. 41, no. 6, p. 1347–1359.

U.S. Census Bureau, 2003, Census of population and housing, Wisconsin: U.S. Census Bureau database, accessed June 24, 2010, at http://www.census.gov/prod/www/abs/decennial/index.htm.

U.S. Department of Agriculture, 2006, National Agricultural Imagery Program (NAIP) digital orthorectified images (DOQ), Wisconsin: Accessed June 24, 2010, at http://datagateway.nrcs.usda.gov/.

U.S. Environmental Protection Agency, 1988, Ambient water-quality criteria for chloride—1988: U.S. Environmental Protection Agency, Office of Water, EPA 440/5–88–001, 39 p.

U.S. Environmental Protection Agency, 2009, International stormwater BMP database, 2009, accessed June 24, 2010, at http://www.epa.gov/npdes/urbanbmptool/.

U.S. Geological Survey, Wisconsin Water Science Center Lake-Studies Team, 2004 and 2007–8, Water quality and lake-stage data for Wisconsin lakes, water years 2004; 2006; 2007: U.S. Geological Survey Open-File Reports 2004–1087, 2007–1173, and 2008–1182 (published annually).

Walker, W.W., Jr., 1996. Simplified procedures for eutrophication assessment and prediction: U.S Army Corps of Engineers, Instruction Report W–96–2 [variously paginated].

Waschbusch, R.J., Olson, D.L., Manteufel, S.B., and Smith, J.J., 2007–8, Water resources data, Wisconsin, water years 2006–7: U.S. Geological Survey Water-Data Reports WI–06–1 and WI–07–1 (published annually).

Wisconsin Department of Natural Resources, 1992, Wisconsin water quality assessment—Report to Congress, 1992: Publ–WR254–92–REV, 220 p.

Wisconsin Department of Natural Resources, 2001, Wisconsin lakes: Wisconsin Department of Natural Resources, Pub–FH–800, 180 p.

Wisconsin Department of Natural Resources, 2008, Wisconsin Citizen Lake Monitoring Network: Accessed June 24, 2010, at http://dnr.wi.gov/lakes/CLMN/.

Wisconsin State Journal, 2005, State's lakes threatened, so DNR acts: [Madison, Wis.] August 1, 2005.

Wisconsin State Laboratory of Hygiene, Environmental Sciences Section, 1993, Manual of analytical methods, inorganic chemistry unit: Madison, Wisconsin State Laboratory of Hygiene, revised November 1993 [variously paginated].

Wisconsin Valley Improvement Company, 2007, Wisconsin River reservoir system data: Accessed June 24, 2010, at http://www.wvic.com/.

Young, Robert, 1994, Minocqua-Woodruff priority lake project water resources appraisal: Wisconsin Department of Natural Resources, North Central District, 18 p.

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