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Water Quality and Hydrology of Silver Lake, Barron County, Wisconsin, With Special Emphasis on Responses of a Terminal Lake to Changes in Phosphorus Loading and Water Level

Scientific Investigations Report 2009–5077

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

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KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Cover photos:
Changes in the water levels at two locations on Silver Lake from 2004 (top photos) to 2007 (bottom photos) as viewed from the county park on the south shore of the lake.

Contents

Figures

Tables

Conversion Factors and Abbreviations

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	0.004047	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
	Miscellaneous rates and yields	
inch per day (in/d)	25.4	millimeter per day (mm/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic feet per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
pound per year (lb/yr)	0.4536	kilogram per year (kg/yr)
pound per cubic ft (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)
pounds per square mile per year ($lb/mi^2/yr$)	0.1751	kilograms per square kilometer per year ($kg/km^2/yr$)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°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).

Concentrations of chemicals in soil and sediment are given in milligrams per kilogram (mg/kg).

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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Water Quality and Hydrology of Silver Lake, Barron County, Wisconsin, With Special Emphasis on Responses of a Terminal Lake to Changes in Phosphorus Loading and Water Level

By Dale M. Robertson, William J. Rose, and Faith A. Fitzpatrick

Abstract

Silver Lake is typically an oligotrophic-to-mesotrophic, soft-water, terminal lake in northwestern Wisconsin. A terminal lake is a closed-basin lake with surface-water inflows but no surface-water outflows to other water bodies. After several years with above-normal precipitation, very high water levels caused flooding of several buildings near the lake and erosion of soil around much of the shoreline, which has been associated with a degradation in water quality (increased phosphorus and chlorophyll *a* concentrations and decreased water clarity). To gain a better understanding of what caused the very high water levels and degradation in water quality and collect information to better understand the lake and protect it from future degradation, the U.S. Geological Survey did a detailed study from 2004 to 2008. This report describes results of the study; specifically, lake-water quality, historical changes in water level, water and phosphorus budgets for the two years monitored in the study, results of model simulations that demonstrate how changes in phosphorus inputs affect lake-water quality, and the relative importance of changes in hydrology and changes in the watershed to the water quality of the lake.

From 1987 to about 1996, water quality in Silver Lake was relatively stable. Since 1996, however, summer average total phosphorus concentrations increased from about 0.008 milligrams per liter (mg/L) to 0.018 mg/L in 2003, before decreasing to 0.011 mg/L in 2008. From 1996 to 2003, Secchi depths decreased from about 14 to 7.4 feet, before increasing to about 19 feet in 2008. Therefore, Silver Lake is typically classified as oligotrophic to mesotrophic; however, during 2002–4, the lake was classified as mesotrophic to eutrophic.

Because productivity in Silver Lake is limited by phosphorus, phosphorus budgets for the lake were constructed for monitoring years 2005 and 2006. The average annual input of phosphorus was 216 pounds: 78 percent from tributary and nearshore runoff and 22 percent from atmospheric deposition. Because Silver Lake is hydraulically mounded above the local groundwater system, little or no input of phosphorus to the lake is from groundwater and septic systems. Silver Lake had previously been incorrectly described as a groundwater flowthrough lake. Phosphorus budgets were constructed for a series of dry years (low water levels) and a series of wet years (high water levels). About 6 times more phosphorus was input to the lake during wet years with high water levels than during the dry years. Phosphorus from erosion represented 13–20 percent of the phosphorus input during years with very high water levels.

Results from the Canfield and Bachman eutrophication model and Carlson trophic state index equations demonstrated that water quality in Silver Lake directly responds to changes in external phosphorus input, with the percent change in chlorophyll *a* being about 80 percent of the percent change in total phosphorus input and the change in Secchi depth and total phosphorus concentrations being about 40 and 50 percent of the percent change in input, respectively. Therefore, changes in phosphorus input should impact water quality. Specific scenarios were simulated with the models to describe the effects of natural (climate-driven) and anthropogenic (human-induced) changes. Results of these scenarios demonstrated that several years of above-normal precipitation cause sustained high water levels and a degradation in water quality, part of which is due to erosion of the shoreline. Results also demonstrated that 1) changes in tributary and nearshore runoff have a dramatic effect on lake-water quality, 2) diverting water into the lake to increase the water level is expected to degrade the water quality, and 3) removal of water to decrease the water level of the lake is expected to have little effect on water quality.

Fluctuations in water levels since 1967, when records began for the lake, are representative of what has occurred since 1900; fluctuations of about 4 to 10 feet occurred about every 15 years. During periods of sustained low water levels caused by a series of dry years and low runoff, the lake probably was oligotrophic to mesotrophic, whereas during sustained high water levels caused by a series of wet years and high runoff, water quality of the lake degraded and the lake probably was mesotrophic to eutrophic. Therefore, the recent degradation in water quality is consistent with possible

past occurrences associated with high water levels. During the 1940s and 1950s, because of high phosphorus inputs from agriculture in the watershed, the lake may have been typically classified as mesotrophic to eutrophic and possibly classified as moderately eutrophic during years with high water levels, especially around 1945 and 1954 when water levels were likely to have been very high.

As of 2008, Silver Lake is typically oligotrophic to mesotrophic because of the relatively small contributions of phosphorus from its watershed, although its water quality changes dramatically because of natural changes in water and phosphorus inputs during years of high runoff. Because of the limited phosphorus that is presently input into the lake, small increases in phosphorus input could have a very large effect on lake-water quality. Therefore, management actions to minimize future phosphorus input to this lake are likely to have great effect on maintaining the quality of its water.

Introduction

Silver Lake is a deep, soft-water lake in northwestern Wisconsin. Several years with above-normal precipitation caused increased runoff and very high water levels in the lake during 2001–4. The high water levels, in turn, caused extensive erosion and flooding of homes and cottages near the lake. In addition, on the basis of data collected by the Citizen Lake Monitoring Network (Citizen Monitoring; Wisconsin Department of Natural Resources, 2008), the water quality of the lake degraded during the period with highest water levels: phosphorus and chlorophyll *a* (algae) concentrations were higher and water clarity was worse during 2002–4 than during 1988–98. Local residents were unsure whether the cause of increased water level was only above-normal precipitation and whether the cause of degraded water quality was increased runoff and high water levels or some anthropogenic (human-induced) factor(s) in the watershed. A detailed study, described in this report, was done from 2004 to 2008 by the U.S. Geological Survey (USGS) to (1) aid in understanding what caused the high water levels in the lake and degradation of its water quality and (2) find evidence as to whether such changes have occurred in the past. This study was done in cooperation with the Barron County Soil and Water Conservation Department and was partially funded through the Lake Protection Grant Program of the Wisconsin Department of Natural Resources (WDNR) and the Cooperative Water Program of the USGS.

Silver Lake and Its Watershed

Silver Lake (fig. 1)—a natural, closed-basin, terminal lake in Barron County, in northwestern Wisconsin—is about 5 mi northeast of Cumberland, Wis., and 9.5 mi northwest of Rice Lake, Wis. A closed-basin lake has no surface-water outflows, and a terminal lake is a closed-basin lake that has inflowing streams. Precipitation that falls within the watershed of a closed-basin lake does not flow out of the basin and leaves the lake only by evaporation and seepage into the underlying groundwater system. Silver Lake is typically oligotrophic to mesotrophic, meaning it does not contain an abundance of nutrients (phosphorus and nitrogen compounds); it is characterized by relatively clear, deep water and low-to-moderate primary productivity. Mesotrophic and oligotrophic lakes are extremely sensitive to increases in phosphorus input (Newton and Jarrell, 1999).

The area and volume of Silver Lake were given on the 1967 Wisconsin Conservation Department lake survey map as 336.7 acres and 12,793 acre-ft, respectively. In this study, the morphometry of the lake was reevaluated on the basis of an aerial image obtained in 2005 from the National Agricultural Imagery Program (U.S. Department of Agriculture, 2006). In 2005, the lake was near full volume, similar to when the original map was constructed in 1967. The resulting surface area of the lake was determined to be 355 acres and the volume to be 12,654 acre-ft (table 1). These values are slightly different from the original 1967 estimates. All the calculations in this study are based on the recently estimated morphometry. Given that the water level of the lake fluctuates widely, the morphometric information for the lake was also computed for elevations 3 ft greater and 5 ft less than in 2005 (table 1).

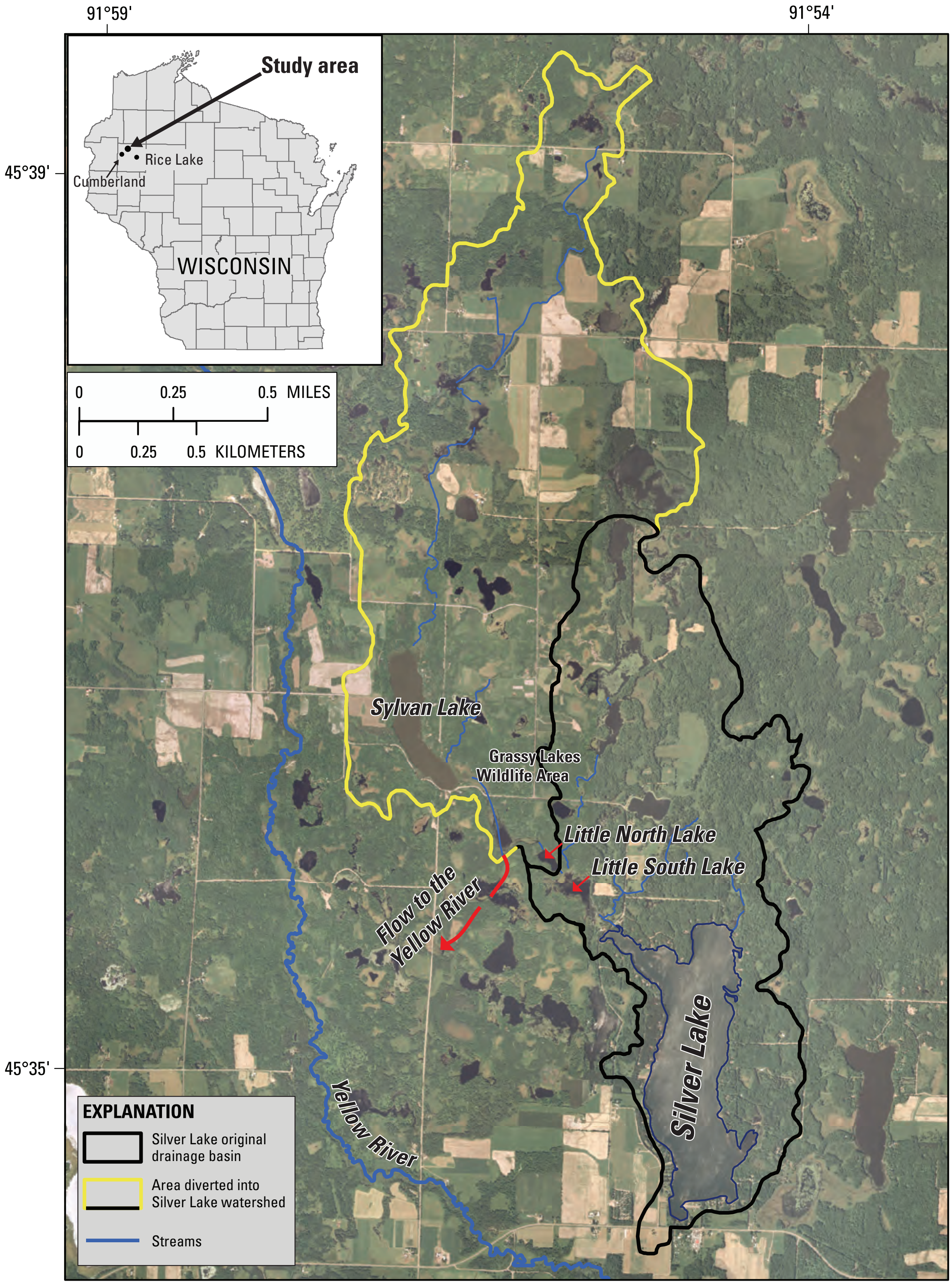
The natural drainage area of Silver Lake is 1,800 acres (fig. 1). During several periods after 1934, however, part or all the water from the Sylvan Lake watershed (just north of the Silver Lake watershed in fig. 1) was diverted into Silver Lake (discussed in detail below). If the Sylvan Lake watershed is included, the total area draining to Silver Lake increases to 4,490 acres. The land cover of the natural watershed (based on data from Homer and others, 2007) is primarily a mixture of forest (76 percent), wetlands (7 percent), and pasture/grassland/agriculture (9 percent). The Sylvan Lake watershed contains more pasture/grassland/agriculture (31 percent) than does the natural Silver Lake watershed. The soil in the Silver Lake watershed consists primarily of a hilly, moderately permeable, Milaca-Cloquet peat complex (from midlake northward);

Table 1. Morphometric characteristics of Silver Lake, Barron County, Wis., at three elevations.

[Altitude of the local datum is 1165.31 feet above the National Geodetic Vertical Datum of 1929]

Elevation (feet above a local datum)	Area (acres)	Length (miles)	Width (miles)	Maximum depth (feet)	Mean depth (feet)	Volume (acre-feet)
90.18	371	1.57	0.37	94	37.4	13,845
87.18[1]	**355**	**1.57**	**.37**	**91**	**35.6**	**12,654**
82.18	317	1.54	.37	86	34.6	10,974

[1] Elevation of lake for morphometric map in Figure 2.



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

Figure 1. Aerial photograph of Silver Lake, Barron County, Wis., with its watershed delineated. The area from which surface water has been diverted into the Silver Lake watershed also is delineated with a yellow line.

however, the extreme southern part of the watershed is a relatively flat, with moderate to very permeable mixture of Campia silt loam and Chetak sandy loam soils (from midlake southward; U.S. Department of Agriculture, 1958). Although the surficial soils are moderately permeable, well logs indicate a poorly permeable layer of till below these soils just north of the lake.

Before 1900, the land cover around Silver Lake was primarily pristine forests and wetlands; however, beginning in the early 1900s, agriculture began to spread throughout most of the flatter parts of the region, including the southern part of the Silver Lake watershed (table 2). By the early 1950s, agriculture in the watershed peaked, with more than half of the area immediately adjacent to the lake being used for farming (based on the 1951 aerial photograph), including at least three small herds of cattle (Edward Jacobson, local resident, oral commun., 2008). One dairy farm was on the southwest shore of the lake, and each day about 25 cows were moved along the shore to a nearby pasture. In addition, about 20 head of cattle were pastured on the southeast shoreline, and 20–25 head of cattle were pastured just north of the lake. The cattle on the southeast shoreline had direct access to the lake. In the early 1960s, most of the agriculture in the watershed was discontinued. In the 1960s, weedbeds were more prevalent in the lake than in 2008, and the bay on the extreme southeast part of the lake was dredged (Edward Jacobson, local resident, oral commun., 2008). A Wisconsin Conservation Department lake survey map shows 86 cottages and permanent homes near the lake in 1967. The number of cottages and permanent homes has been relatively stable since the 1970s, increasing to just over 100 in 2008 (Robert Wenzel, local resident, written commun., 2008). Several residents, however, have replaced small seasonal structures with large, year-round structures.

Large fluctuations in water level have been documented in Silver Lake since the 1930s. Residents around the lake have tried to modify the extremes in water levels, especially the low water levels. Before 1934, the magnitude of fluctuations in water level was driven primarily by climatic variations. During the drought in the early 1930s (Dust Bowl years), water levels were very low, which resulted in cottages being built near the lake, including a small cottage on a small island in the northwest end of the lake. To try to increase the very low water levels, a ditch was dug sometime around 1934 between the Grassy Lakes Wildlife Area and Little North Lake and between Little North Lake and Little South Lake to divert water that normally flows from Sylvan Lake to the Yellow River into Silver Lake (R.R. Read, local resident, written commun., 1943). To increase the flow through this channel, a berm was built between the Grassy Lakes Wildlife Area and the natural flow path to the Yellow River. A history of the use of this diversion is summarized in table 2. The ditch has intermittently increased the drainage area and input of water (and nutrients) to Silver Lake. In the 1950s, two small dams with boarded openings were constructed to control the flow through these channels (D. Hanson, Barron County Soil and Water Conservation Department, written commun., 1996). The specific periods when this diversion was used were not able to be determined; however, the diversion was documented to have been used between the late 1930s and early 1940s, and between the late 1990s and September 16, 2003, when the ditch was permanently filled with stone and gravel (Silver Lake Association, 2003).

In the interest of managing the water level of Silver Lake and protecting its water quality, the Silver Lake Association was formed in the mid 1990s. The purpose of the Association is to promote a sense of community, to address various environmental and/or public-nature issues, to promote safety in lake use, and to help educate its members and nonmembers on lake preservation. During 2001–4, high water levels in Silver Lake caused flooding of many homes and cottages and erosion of shoreline around parts of the lake. In addition, the high runoff and high water levels apparently caused deterioration in the water quality of the lake. It was believed that water being diverted from Sylvan Lake was part of the reason for the high water and that nutrients (phosphorus) in the diverted water helped degrade the water quality of Silver Lake (D. Hanson, Barron County Soil and Water Conservation Department, written commun., 1996). The Silver Lake Association and the Barron County Soil and Water Conservation Department worked together to permanently fill the upstream diversion ditch (work completed in September 2003) and to find funds for a study to describe the factors affecting the water quality of Silver Lake. The main goals of the study were to (1) determine whether the wide fluctuations in water level were natural phenomena or caused primarily by increased input through the diversion ditch and (2) to determine whether the deterioration in lake-water quality during 2002–4 was caused by the high water levels or by changes in human activity in the watershed.

Effects of Changes in Nutrient Loading, Water Level, and Climate on Water Quality

Degradation in water quality (trophic conditions) of many lakes is caused by an increase in nutrient inputs from their watersheds. The effects of nutrient loading (input of nutrients over a specified period of time) are sufficiently understood that empirical eutrophication models can be used to predict in-lake phosphorus and chlorophyll *a* concentrations and water clarity (Secchi depth) from external phosphorus loading (Reckhow and Chapra, 1983; Cooke and others, 1993; Panuska and Kreider, 2003). Most of these models were derived from analyses of many lakes with widely differing loading rates and hydrologic conditions (for example, Vollenweider, 1975; Canfield and Bachmann, 1981); however, Lathrop and others (1998; 1999) also developed response models based on changes in nutrient loading to a specific lake—Lake Mendota, Wisconsin.

Changes in nutrient inputs to lakes are usually associated with changes in anthropogenic factors in the watershed, such as changes in land use or inputs from point sources (for example, pipe discharge from a factory or wastewater-treatment plant); however, changes in nutrient inputs also occur naturally as a function of hydrologic changes. For example,

Table 2. History of known[1] land-use changes near Silver Lake, Barron County, Wis., and water diversions into the Silver Lake watershed.

Year(s)	Action	Expected upstream flow	Expected change in phosphorus loading
	Land use and land-use changes		
Prior to 1900	Natural forest.	Background	Background
About 1900	Agriculture begins in watershed.	Slight increase	Slight increase
1940s–1950s	Agriculture peaks in watershed.	Slight increase	Large increase
Mid 1960s	Agriculture mostly ending in watershed and homes and cottages built near lake.	Slight decrease	Moderate decrease
2000s	Minimal pastureland (north of lake) and homes and cottages surround lake.	Slight decrease	Slight decrease
	Water diversions into the watershed		
Prior to about 1934	Natural flow to the Yellow River as evidenced by many large old trees near lake.	No Sylvan Lake water	Background
About 1934 – about 1940	Dams built stopping flow to the Yellow River and ditches dug to Silver Lake.	All Sylvan Lake water	Large increase
1942	Some water going into the Yellow River.	Most of Sylvan Lake water (about 75 percent)	Moderate increase
1943	Temporary ditches dammed. All natural flow diverted to the Yellow River.	No Sylvan Lake water	Background
1950s	Two small dams built in the ditches. Dam in wetland washed out. All natural flow diverted to the Yellow River.	No Sylvan Lake water	Background
1997	Channels to Silver Lake opened. Most of the natural flow diverted to Silver Lake.	Most Sylvan Lake water	Large increase
2003	Diversion completely filled with gravel in late summer.	No Sylvan Lake water	Background

[1] Additional undocumented land-use changes and diversions may have occurred.

more nutrients are typically delivered to a lake during wet years than during dry years. In addition, Lathrop and others (1998) demonstrated that water quality in Lake Mendota, Wis., had a larger response following a series of wet or dry years than during a single unusual year. Therefore, a few years may pass before a lake comes into equilibrium with inputs from its watershed. After a series of wet years, additional sources of nutrients can develop, such as shoreline erosion caused by increased water level, increased runoff from wetlands around a lake, or increased nutrient release from nutrient-rich soils or old septic systems near the lake when groundwater levels increase or nearshore areas are flooded (Leira and Cantonati, 2008). Therefore, persistent extremes in precipitation and runoff can result in changes in water level that can affect the water quality of lakes.

Changes in water levels are natural phenomena for most lakes; however, global climate change may have lake-level implications and may have already affected the extent of water-level fluctuations in lakes (Wantzen and others, 2008). Many scientists believe, based on results from General Circulation Models, that climate change will either cause systematic decreases or increases in the hydrologic budgets and water levels of lakes or cause water levels to fluctuate more widely than they have previously, in response to larger fluctuations in precipitation and runoff (Mulholland and Sale, 1998; Bates and others, 2008). Predicting the effects of climate change on a particular lake from large global and regional circulation models is difficult because a lake's hydrological cycle involves many interrelated components, including precipitation patterns, water temperatures, evaporation rates, groundwater inputs and outputs, and surface-water flow rates (Wittman, 2008). Scientists believe, however, that closed-basin lakes, such as Silver Lake, are most vulnerable to changes in climate because of their sensitivity to changes in the balance of inflows and evaporation (Bates and others, 2008). Results from some circulation models indicate that seasonal precipitation patterns will change, resulting in more precipitation in winter and less in summer, which could cause groundwater levels to increase and cause a rise in the water levels of lakes that have large groundwater inputs. Increased air temperatures, however, may cause an increase in evapotranspiration and cause water levels to drop (Wittman, 2008).

In addition to affecting a lake's hydrology and water level, climate change may also affect lake-water quality in other ways because of warming air temperatures (Bates and others, 2008). Increased air temperatures will increase water temperatures which, in turn, may stimulate algal blooms. Increased air temperatures will also decrease the duration of ice cover and increase the length of the growing season; which in turn, may result in a longer growth period for macrophytes (rooted aquatic plants). The longer growing season, however, may result in the available nutrients being depleted and fewer algal blooms later in the year. Only a few studies have examined how changes in water level affect the water quality of lakes (Leira and Cantonati, 2008), and these studies mainly examined changes in primary ions and alkalinity (for example, Webster and others, 1996; White and others, 2008).

The recent degradation in water quality of Silver Lake that occurred in conjunction with high water levels has led to several questions: Were the recent changes in water quality caused by changes in the watershed, or were they caused by changes in precipitation leading to more runoff and higher water level? Were the recent extremes in water level caused by global climate change or were they caused by the diversion of water from Sylvan Lake? And, are the recent changes in water level and water quality indicative of what may occur in the future? Determining whether climate change caused the changes in water levels of Silver Lake or exactly what type of climatic changes may occur in the future may be difficult; therefore, examining how conditions leading to lower and higher water levels affect the water quality of Silver Lake is important.

Several approaches can be used to predict how the water quality of a specific lake may respond to hydrologic changes and future climate change. One approach is to examine how the lake has responded to conditions leading to past changes in water level, if data are sufficient for such an analysis. Another approach is to use numerical models to simulate how the lake should respond to specific climate scenarios. A third approach is to try to determine how water quality of the lake responds to a range of conditions, such as those leading to low and high water levels.

Purpose and Scope

The primary purpose of this report is to provide an interpretation of what may have caused the degradation in water quality of Silver Lake (as detected by the ongoing monitoring program) and, therefore, furnish information that can be used by managers to protect this lake in the face of increased developmental pressure and possible climatic changes. This report (1) describes the water quality of Silver Lake, (2) describes changes in its water level since 1900, (3) quantifies water and phosphorus budgets for the lake on the basis of data collected from November 2004 through October 2006 and also includes an estimate of erosion occurring during the high water levels of 2001–3, (4) presents the results of model simulations that demonstrate the potential effects of changes in phosphorus inputs on lake-water quality, and (5) examines how climatic changes (hydrologic changes in the watershed and changes in water level) and potential strategies in managing water levels may affect the water quality of the lake.

The water-quality data and water and phosphorus budgets described in this report improve the understanding of the hydrologic system of Silver Lake and aid in the understanding of how changes in the water levels and nutrient loading affect the water quality of closed-basin terminal lakes. Results of the study should be useful to local managers in the preparation of a comprehensive lake-management plan. In addition, results of the study add to the database of lakes for which detailed hydrologic, phosphorus-loading, and lake-water-quality information are available to compare with other lakes in the region.

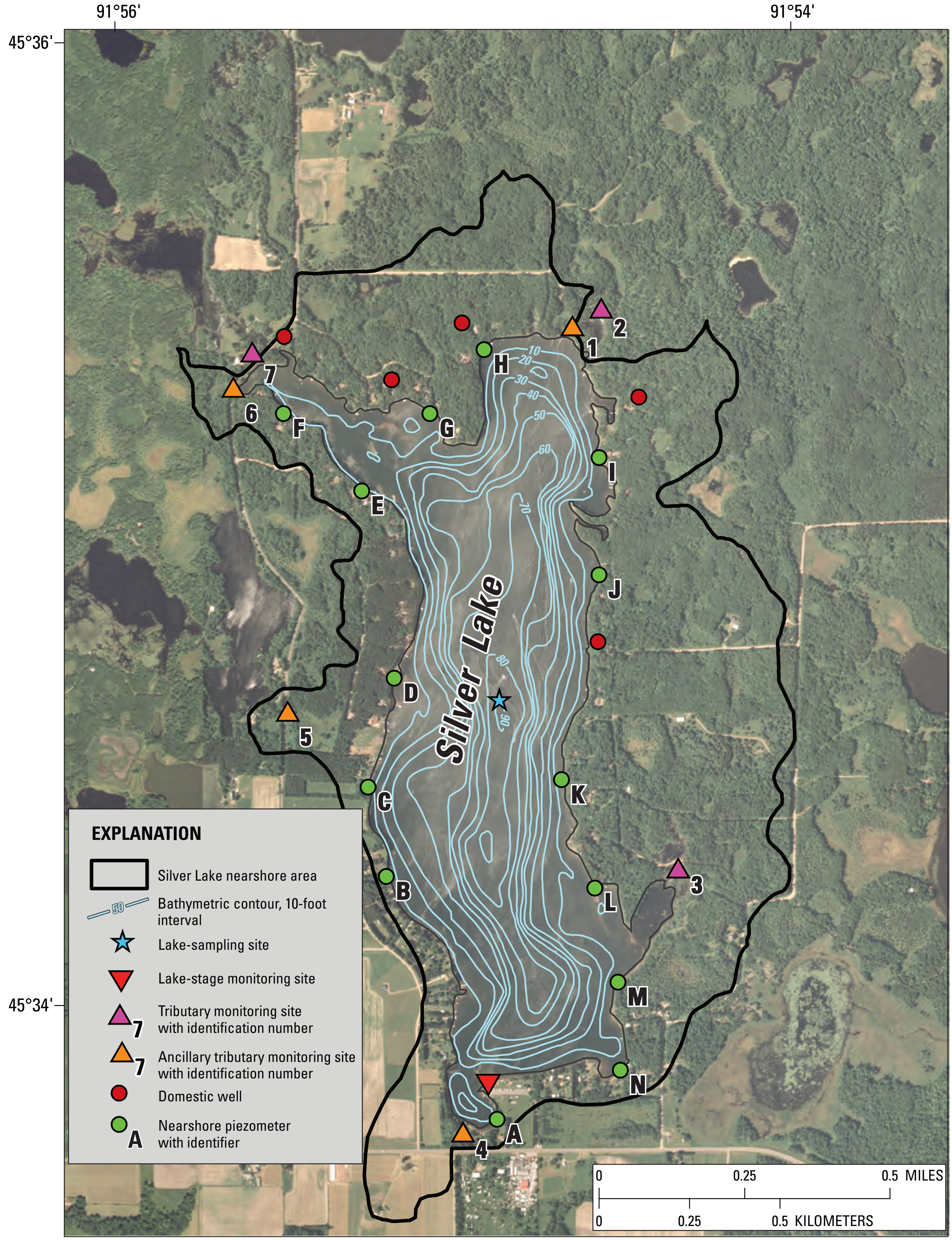
Study Methods and Sampling Sites

USGS personnel collected lake, groundwater, and meteorological data from 2004 to 2006. In addition, water-quality data for the lake were collected by the WDNR from 1987 to 1998 as part of their long-term trend-monitoring program (Wisconsin Department of Natural Resources, 2006) and from 1987 to 2008 by volunteers from the community as part of the WDNR's Wisconsin Citizen Lake Monitoring Network (Wisconsin Department of Natural Resources, 2008). Data collected by the WDNR were furnished by J. Vennie (Wisconsin Department of Natural Resources, written commun., 2006), and Citizen Lake Monitoring data were obtained from the WDNR's Web site (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 describe the lake-water quality and characterize long-term changes in water quality; however, only data collected from November 1, 2004, to October 31, 2006, were used to describe the hydrology and phosphorus inputs to the lake. This latter period was divided into two monitoring years (MY): November 2004 through October 2005 (hereafter referred to as MY 2005) and November 2005 through October 2006 (hereafter referred to as MY 2006). Little input of phosphorus from erosion occurred during the intense monitoring period; therefore, to estimate the potential input of phosphorus from erosion during periods of high water level, a separate erosion study was done during May 2005.

Lake-Stage and Water-Quality Monitoring

A continuously recording (15-minute interval) lake-stage gage was installed just south of the public boat landing on the south side of the lake (fig. 2). Lake stage was monitored by means of a gas-purge system with a pressure transducer. The gage was operated for the 2-year monitoring period.

From 1987 to 1998, the WDNR sampled the lake in spring, summer (monthly from May through September), and late winter. During 2005 and 2006, the USGS sampled the lake in spring and summer (monthly from May through September). The USGS and WDNR protocols for sampling the lake were similar. During each visit, profiles of water temperature, dissolved oxygen, specific conductance, and pH were collected



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

Figure 2. Aerial photograph of Silver Lake, Barron County, Wis., with sampling locations and 10-ft bathymetric contours identified.

with a multiparameter meter, and water clarity was measured with a standard 7.9-in.-diameter black and white Secchi disk (Secchi depth). Near-surface samples, which were collected with a Van Dorn sampler by the USGS and a Kemmerer sampler by the WDNR, were analyzed for total phosphorus and chlorophyll *a* concentrations. Near-bottom samples were collected about 3 ft above the sediment-water interface and were analyzed for total phosphorus concentration. Additional water samples were collected during spring by the USGS and analyzed for nutrients, common ions, and other characteristics such as color, turbidity, alkalinity, total dissolved solids, and silica. In addition, volunteers from the community (Citizen Monitoring) measured Secchi depths from 1987 to 2008 and total phosphorus and chlorophyll *a* concentrations from 2002 to 2008, in accordance with protocols described by Betz and Howard (2005). All water-quality data were collected near the deepest location in the lake (fig. 2).

Sampling by the USGS was done by the Lake Studies Team of the USGS Wisconsin Water Science Center. This team implements a quality-assurance plan each year that involves collecting three types of samples from a subset of the lakes studied each year, which include blanks, replicates, and spikes (U.S. Geological Survey, Wisconsin District Lake Studies Team, 2006; 2007). During the monitoring period, the replicates for total phosphorus were within 0.006 mg/L over a wide range in concentrations (except for one replicate from a eutrophic lake that was within 0.02 mg/L) and replicates for chlorophyll *a* were within 18 percent of each other. Concentrations of total phosphorus and chlorophyll *a* in the blanks analyzed in 2005 and 2006 were below the laboratory's detection limits (0.005 mg/L for total phosphorus and 0.26 µg/L for chlorophyll *a*).

All lake samples were analyzed by the Wisconsin State Laboratory of Hygiene in accordance with standard analytical procedures described in the "Manual of Analytical Methods, Inorganic Chemistry Unit" (Wisconsin State Laboratory of Hygiene, 1993). Lake-stage and water-quality data collected by the USGS were published in the annual data report series "Water Quality and Lake-Stage Data for Wisconsin Lakes," water years 2005 and 2006 (U.S. Geological Survey, Wisconsin District Lake Studies Team, 2006; 2007).

Lake Classification

One method of classifying the water quality of a lake is by computing trophic state index (TSI) values based on near-surface concentrations of total phosphorus and chlorophyll *a*, along with Secchi depths, as developed by Carlson (1977). TSI values were developed to place these three characteristics on similar scales to allow comparison among 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 (May through September) average TSI values:

$$TSI_P = 4.15 + 14.42\,[\ln \text{total phosphorus (in micrograms per liter)}], \tag{1}$$

$$TSI_C = 30.6 + 9.81[\ln \text{chlorophyll } a \text{ (in micrograms per liter)}], \text{ and} \tag{2}$$

$$TSI_{SD} = 77.12 - 14.41[\ln \text{Secchi depth (in feet)}]. \tag{3}$$

Oligotrophic lakes have TSI values less than 40, a limited supply of nutrients, very high clarity, low algal populations, and low phosphorus concentrations, and they generally contain oxygen throughout the year in their deepest zones (Carlson, 1977). Mesotrophic lakes have TSI values between 40 and 50, a moderate supply of nutrients, moderate clarity, a tendency to produce moderate algal blooms, and oxygen is occasionally depleted in the deepest zones of the lake. Eutrophic lakes have TSI values greater than 50, a large supply of nutrients, and severe water-quality problems—such as low clarity and frequent seasonal algal blooms—and oxygen is typically depleted in the deeper zones of the lake.

Stream Monitoring

Flows from three small tributaries to Silver Lake (tributaries 2, 3, and 7) were measured intermittently at sites 2, 3, and 7 (fig. 2) at approximately monthly intervals. The measured flows were statistically related to the daily average flows measured in the Yellow River at Barron, Wis., to develop regression relations between flow in the Yellow River and flow in each tributary. The regression relations for each site and the daily flows in the Yellow River were then used to estimate daily flows in each tributary. Temporally varying offsets were applied to all estimated flow data to force the estimated flows to equal those measured in the tributaries. Flows in four additional tributaries (tributaries 1, 4, 5, and 6) were also measured intermittently (fig. 2). Flow was zero or negligible at these sites during most of the visits except during snowmelt runoff. Flows at these sites did not correlate very well with flow in the Yellow River; therefore, runoff in these four tributaries were combined with runoff from the other ungaged near-lake areas and collectively were estimated as the amount of flow needed to balance the water-budget mass-balance equation during the snowmelt-runoff period of each monitoring year. Water samples at the stream sites were collected manually by means of the Equal-Width-Increment (EWI) method (Edwards and Glysson, 1999) or the grab method and were analyzed for concentrations of total phosphorus. In addition, four grab samples were collected near the outlet of Sylvan Lake during the spring of 2006 and analyzed for total phosphorus to determine the phosphorus concentration of water prior to entering the wetland system north of the lake.

Daily phosphorus loads for tributaries 2, 3, and 7 were determined by multiplying temporally varied concentrations (linearly interpolated between intermittently measured concentrations) multiplied by the estimated daily flows. Loads for the combined runoff from tributaries 1, 4, 5, and 6 and other near-lake ungaged areas were determined by multiplying the combined runoff by the flow-weighted average concentration of all samples collected in all tributaries during each monitoring year.

All stream samples were analyzed by the Wisconsin State Laboratory of Hygiene in accordance with standard analytical procedures described in the "Manual of Analytical Methods, Inorganic Chemistry Unit" (Wisconsin State Laboratory of Hygiene, 1993). All flow and concentration data were published in the annual USGS Water-Data Report series (Waschbusch and others, 2005; 2006).

Meteorology and Atmospheric Deposition Data

During the 2-year study period, precipitation was measured continuously (at 15-minute intervals) during most nonfreezing periods at the lake-stage monitoring site (fig. 2). During periods when continuous recorded precipitation data were not available, precipitation was estimated by averaging the daily data from the National Weather Service (NWS) stations (National Climatic Data Center, 2004–6) at Cumberland, Wis. (about 5 mi southwest of the lake) and Rice Lake, Wis. (about 9.5 mi southeast of the lake). Other meteorological data needed for simulating the thermal structure of the lake and computing daily evaporation rates were obtained from meteorological stations in the area operated by the USGS, WDNR, and the NWS. Daily total snowfall and average air temperature were obtained from the NWS station at Cumberland, Wis. Average daily wind speeds were obtained by averaging the data from the WDNR weather stations (James Barnier, Division of Forestry, unpublished data; *http://www.dnr.state.wi.us/forestry/fire/weather/*) at Minong, Wis. (about 35 mi north of Silver Lake) and Ladysmith, Wis. (about 40 mi southeast of Silver Lake). Total daily solar radiation data were obtained from a continuously recording meteorological station installed on a small peninsula in Whitefish Lake (about 40 mi north of Silver Lake) by the USGS (Robertson and others, 2009).

Phosphorus deposition on Silver Lake was determined from phosphorus concentrations measured in wetfall (rain and snow) and phosphorus dryfall deposition rates, both of which were measured at the USGS meteorological station on Whitefish Lake and operated during the entire 2-year monitoring period (Robertson and others, 2009). Wet samples were collected after a period with rainfall or snowfall, and dry samples were collected after several days (usually 7–10 days) with no precipitation. Phosphorus in precipitation was computed as the product of precipitation on the surface area of Silver Lake and the estimated seasonal phosphorus concentrations measured for snow (0.009 mg/L) and rain (0.017 mg/L). Phosphorus in dryfall was estimated from the surface area of Silver Lake and deposition rates measured at Whitefish Lake for a lake with few conifers in the surrounding area (26.1 lb/mi^2/yr).

Groundwater Monitoring

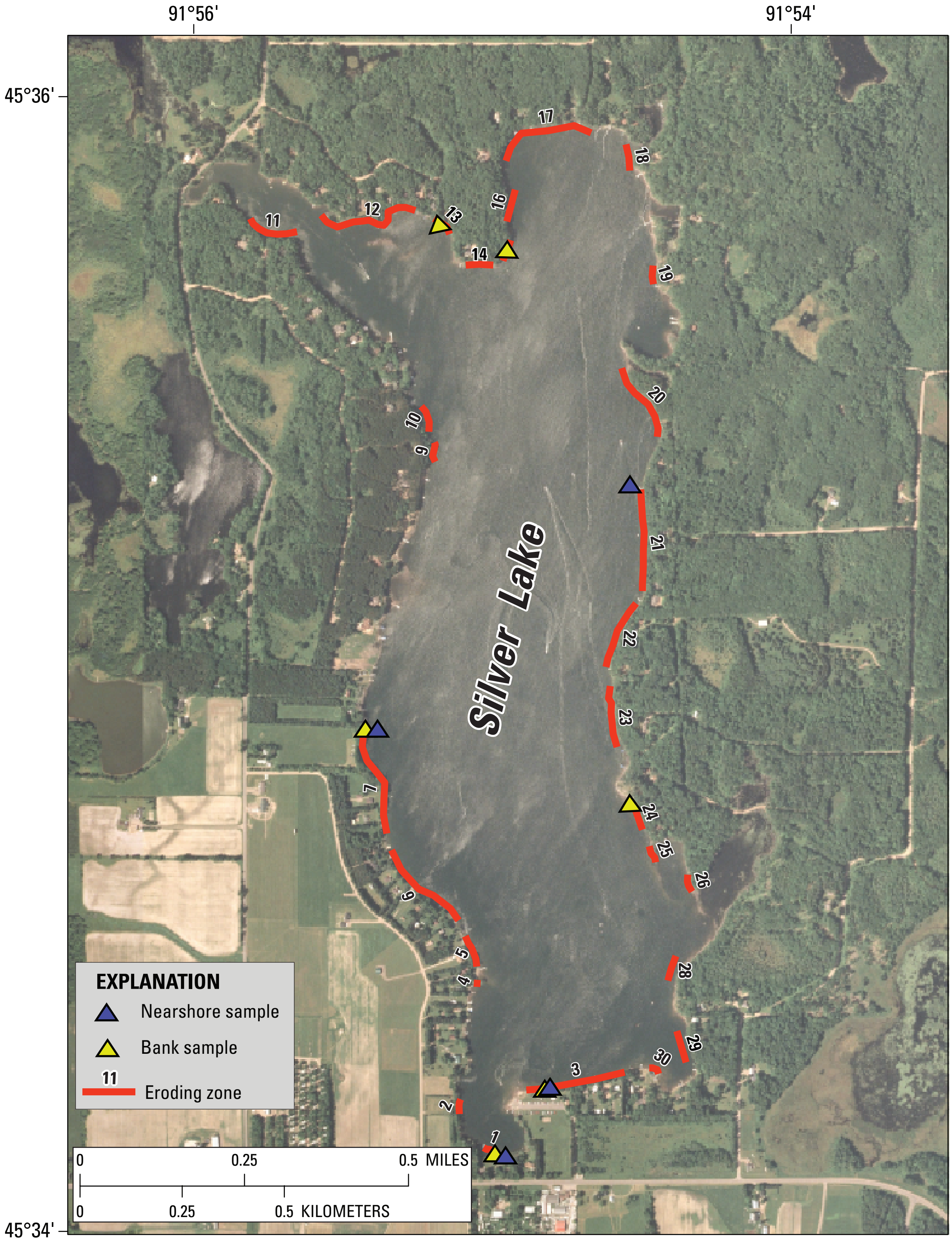
Fourteen shallow piezometers (0.5-in.-diameter observation wells) were installed around the periphery of the lake (fig. 2) in November 2004 to help define areas contributing groundwater to the lake. These piezometers were installed 2 to 19 ft from the edge of the lake to depths of 4 to 6 ft. At installation, the piezometers penetrated 3–4.5 ft below the water table except at four sites where the water table was too deep to be reached. To determine the direction of flow near each piezometer, groundwater gradients were determined from the differences in water elevation in the piezometers and elevation of the lake surface measured at approximately 3-month intervals from November 2004 to November 2006.

Estimation of Nearshore Erosion

A shoreline-erosion study was done during May 17–18, 2005, to determine the amount of sediment and phosphorus delivered to Silver Lake during the high water levels from 2001 to 2003. It was assumed that during 2001–3, the water had risen 2 ft higher than it had during any other recent period. As part of this study, the entire shoreline of the lake was examined for signs of erosion. Twenty-eight eroding areas along the shoreline (ranging from 50 to 950 ft in length and more than 2 mi total) were located with a global positioning system. Length, width, and estimated depth of retreat were measured for each eroding area. Field grading of texture was done by rubbing soil between the fingers (Milfred and others, 1967). The estimated total volume of sediment potentially eroded was calculated by summing the estimated eroded sediment from each of the 28 erosion sites. The estimated total mass of eroded sediment was computed by multiplying the volume of eroded sediment by the average aerated specific weight of sand/gravel/clay mixture of 90 lb/ft^3 (Chow, 1964; table 17-1-5).

Sediment cores were collected by hand from eroding shoreline areas and near-shore sandy depositional zones in the lake (fig. 3). A subset of core samples selected for laboratory analysis included eight samples from the banks and four samples from nearshore deposits. The sediment samples were analyzed for total phosphorus and phosphate (milligrams per kilogram of sediment) by the Wisconsin State Laboratory of Hygiene in accordance with standard analytical procedures described in the "Manual of Analytical Methods, Inorganic Chemistry Unit" (Wisconsin State Laboratory of Hygiene, 1993). It was assumed that the difference in phosphorus (and phosphate) concentrations from the bank samples and the nearby lake-bottom samples was the result of phosphorus being released into the lake.

To determine how the water and phosphorus inputs to the lake vary during different hydrologic conditions and the relative importance of phosphorus input from erosion during periods of very high water levels, water and phosphorus inputs were also estimated for 2002, 2003, and during a series of dry and wet years.



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

Figure 3. Aerial photograph of Silver Lake, Barron County, Wis., showing areas for which sediment and phosphorus input from erosion were observed and estimated.

Measured Lake-Water Quality

Temperature profiles collected in the lake indicated that strong thermal stratification develops during summer and thus limits the extent of vertical mixing. The maximum temperature in the upper layer of the lake (epilimnion) reached about 26ºC in early August. A thermocline developed in May and reached a depth of about 16–23 ft in July before descending in late summer and fall. During summer, near-bottom temperatures reached about 7–7.5ºC.

Dissolved oxygen concentrations of about 10–11 mg/L were near saturation throughout the lake during nonstratified periods in spring and about 8 mg/L throughout the epilimnion during summer. Once stratification developed, dissolved oxygen concentrations in the lower layer of the lake (hypolimnion) began to decrease. Near-bottom concentrations reached 0 mg/L by the beginning of August. The maximum extent of anoxic conditions (0 mg/L) occurred in September, when anoxia reached from the bottom to about 46–50 ft from the surface.

Silver Lake has soft water (alkalinity less than 10 mg/L as calcium carbonate) with a specific conductance typically about 25–26 µS/cm throughout the water column; however, when the deep areas became anoxic, the specific conductance increased to about 40 µS/cm near the bottom of the lake. The pH in the lake typically was about 7.5–8 (standard units) when the lake was unstratified, and about 8 in the epilimnion and 6 in the hypolimnion when the lake was stratified.

Water chemistry in Silver Lake is different from that of most northwestern Wisconsin lakes, as described by Lillie and Mason (1983), with softer water and lower concentrations of most constituents. Lillie and Mason collected data from a random set of 660 Wisconsin lakes, 282 of which were in northwestern Wisconsin. The average concentrations for the northwestern Wisconsin Lakes were 7 mg/L for calcium, 3 mg/L for magnesium, 4 mg/L for chloride, and 27 mg/L for alkalinity, compared to 2.1, 0.9 or less, 1.2, and 9 mg/L, respectively, for Silver Lake. The water color in Silver Lake ranged from 5 to 20 (platinum-cobalt units; based on two measurements), which is less colored than most other northwestern Wisconsin lakes (average value of 30).

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, high nutrient inputs can be the cause of accelerated eutrophication of lakes (that is, accelerated aging and increased productivity). Near-surface concentrations of total phosphorus less than about 0.012 mg/L indicate oligotrophic conditions, whereas concentrations greater than about 0.024 mg/L indicate eutrophic conditions; concentrations between these two concentrations indicate mesotrophic conditions (Carlson, 1977). During MY 2005 and MY 2006, phosphorus concentrations ranged from 0.008 to 0.018 mg/L (fig. 4). Near-surface total phosphorus concentrations had little seasonality. The near-surface summer (May–September) average phosphorus concentration was 0.013 mg/L in MY 2005 and MY 2006 (table 3). Therefore, based on total phosphorus concentrations, Silver Lake would be classified as oligotrophic to mesotrophic.

Near-bottom total phosphorus concentrations were similar to those near the surface during unstratified periods; however, the concentrations increased slightly after the near-bottom water became anoxic in summer and winter (fig. 5). Maximum concentrations in late summer in MY 2005 and MY 2006 were about 0.08 to 0.06 mg/L, respectively.

Since 1986, near-surface total phosphorus concentrations have ranged from 0.005 to 0.021 mg/L (fig. 4). The two concentrations measured in 1986 were 0.02 mg/L. Average June–August concentrations then consistently were about 0.007–0.008 mg/L during 1987–96. Concentrations began to increase in 1997 (0.009 mg/L) before reaching a maximum value in 2003 (0.018 mg/L). After 2003, concentrations decreased to about 0.010 in 2007 and 2008 (table 3). The highest total phosphorus concentrations occurred in 1986 and 2002–4 (when water levels in the lake were high). Maximum annual near-bottom total phosphorus concentrations were relatively constant from 1986 to 1998 (fig. 5). Maximum concentrations then increased to almost 0.16 mg/L in 2003 and gradually decreased to 0.055 mg/L in 2006. The high near-bottom concentrations coincided with the high near-surface total phosphorus concentrations measured in the lake.

Near-surface total nitrogen concentrations (computed as the sum of Kjeldahl nitrogen and dissolved nitrite plus nitrate) were measured during spring from 1988 to 1997 and during 2005 and 2006. Total nitrogen concentrations ranged from about 0.3 to 0.55 mg/L. No consistent trend in concentrations was observed.

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 different ambient conditions such as water temperature, light intensity, and nutrient deficiencies (Correll, 1998); however, a ratio greater than about 16:1 by weight indicates that phosphorus should be the potentially limiting nutrient. The N:P ratios for the 1988–1997 data ranged from 26:1 to 46:1, and ratios for the 2005–6 data ranged from 26:1 to 35:1. This indicates that phosphorus should typically be the potentially limiting nutrient and should be the nutrient of concern when considering management efforts to improve or prevent degradation of the water quality in Silver Lake.

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. Average concentrations less than 2 µg/L indicate oligotrophic conditions, and average concentrations greater than about 7 µg/L indicate eutrophic conditions (Carlson, 1977). During MY 2005 and MY 2006, concentrations ranged from less than 1 µg/L to about 10 µg/L (fig. 4). The highest concentrations were measured in fall; concentrations during summer were

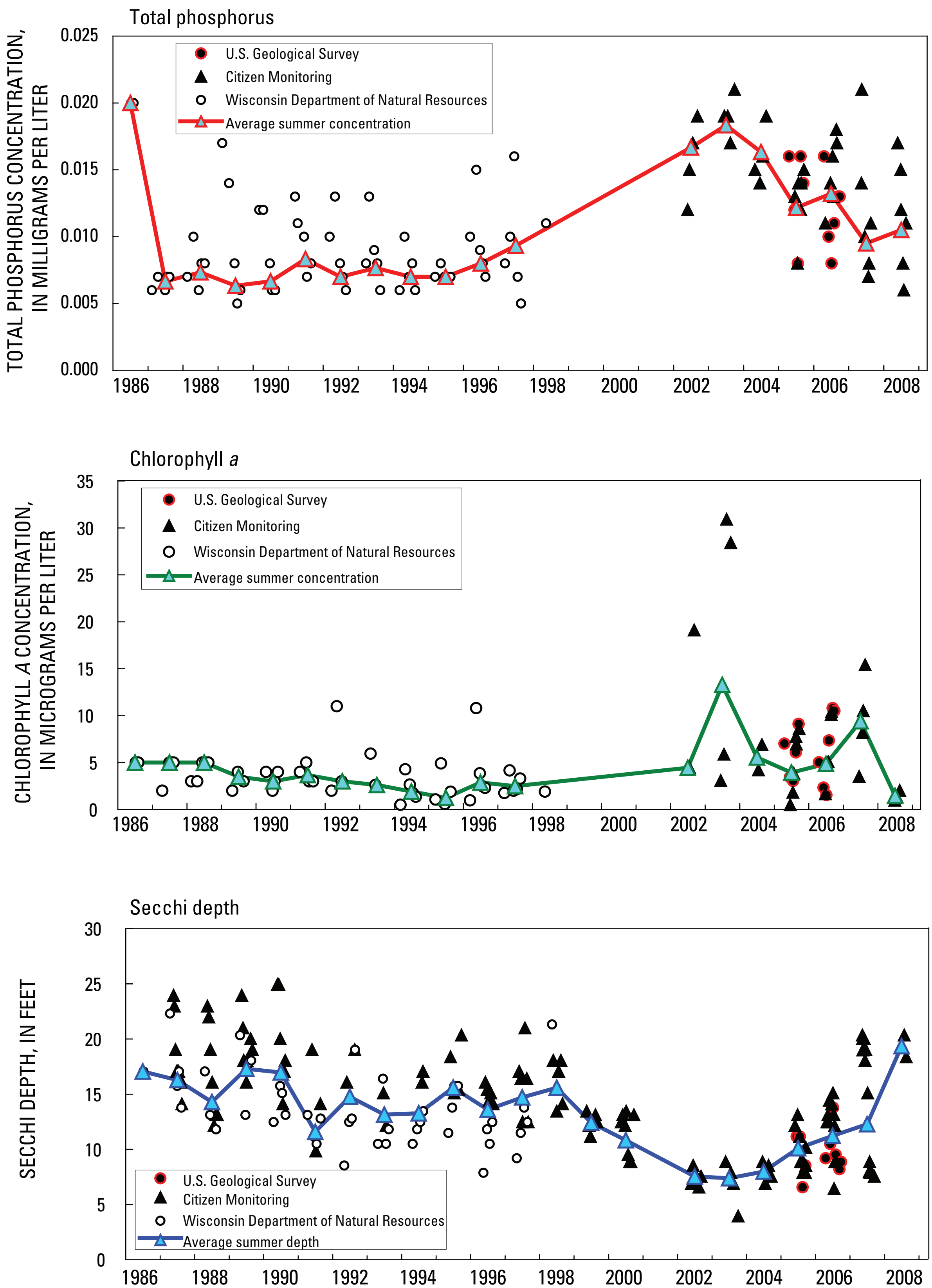


Figure 4. Near-surface total phosphorus concentrations, chlorophyll *a* concentrations, and Secchi depths in Silver Lake, Barron County, Wis., 1986 to 2008.

Table 3. Average near-surface water quality and trophic state index (TSI) values for Silver Lake, Barron County, Wis., 1986 to 2008.

[mg/L, milligrams per liter; µg/L, micrograms per liter]

				------------Trophic state index values--------------		
Year	**Total phosphorus (mg/L)**	**Chlorophyll *a* (µg/L)**	**Secchi depth (feet)**	**Phosphorus**	**Chlorophyll *a***	**Secchi depth**
June–August average						
1986	0.020	5.0	17.1	47	46	36
1987	.007	5.0	16.3	31	46	37
1988	.007	5.0	14.3	33	46	39
1989	.006	3.5	17.3	30	43	36
1990	.007	3.0	17.0	31	41	37
1991	.008	3.7	11.6	35	43	42
1992	.007	3.0	14.8	32	41	39
1993	.008	2.6	13.2	33	40	40
1994	.007	1.9	13.3	32	37	40
1995	.007	1.2	15.6	32	31	38
1996	.008	2.9	13.6	34	41	40
1997	.009	2.5	14.7	35	39	39
1998	--	--	15.6	--	--	38
1999	--	--	12.4	--	--	41
2000	--	--	10.8	--	--	43
2002	.017	4.5	7.5	44	45	48
2003	.018	13.3	7.4	46	51	48
2004	.016	5.6	8.0	44	47	47
2005	.012	3.9	10.1	40	41	44
2006	.013	4.9	11.2	41	43	43
2007	.010	9.4	12.3	36	51	42
2008	.011	1.5	19.4	37	34	34
May–September average						
2005	.013	5.0	10.2	41	44	44
2006	.013	5.8	11.1	41	46	43
Average 2005–6	.013	5.4	10.7	41	45	43

usually 3–7 µg/L. The near-surface summer (May–September) average chlorophyll *a* concentration was 5.0 µg/L in MY 2005 and 5.8 µg/L in MY 2006 (table 3). Therefore, on the basis of chlorophyll *a* concentrations, Silver Lake would usually be classified as mesotrophic.

Since 1998, near-surface chlorophyll *a* concentrations have ranged from less than 1 µg/L to greater than 30 µg/L (fig. 4). The highest chlorophyll *a* concentrations were measured in 2002 and 2003. Summer average concentrations appeared to gradually decrease from 1986 to 1995. Average June–August concentrations have fluctuated around 5 µg/L, except in 2003 (13.3 µg/L), 2007 (9.4 µg/L), and 2008 (1.4 µg/L; table 3).

During MY 2005 and MY 2006, Secchi depths in Silver Lake ranged from 6.4 to 15.1 ft, both extremes measured in July 2006 (fig. 4). No consistent seasonal variability was apparent. The near-surface summer (May–September) average Secchi depth was 10.1 ft in MY 2005 and 11.2 ft in MY 2006 (table 3). Since 1986, Secchi depths have ranged from 3.9 ft (October 2003) to 24.9 ft (June 1990). Average June–August Secchi depths were relatively steady from 1986 to 1998, then gradually decreased to about 7.5 ft in 2002–4, and then increased to 19.4 ft in 2008. The poorest clarity was measured in 2003 (average depth of 7.4 ft), and the best clarity was measured in 2008. Secchi depths greater than 13 ft indicate

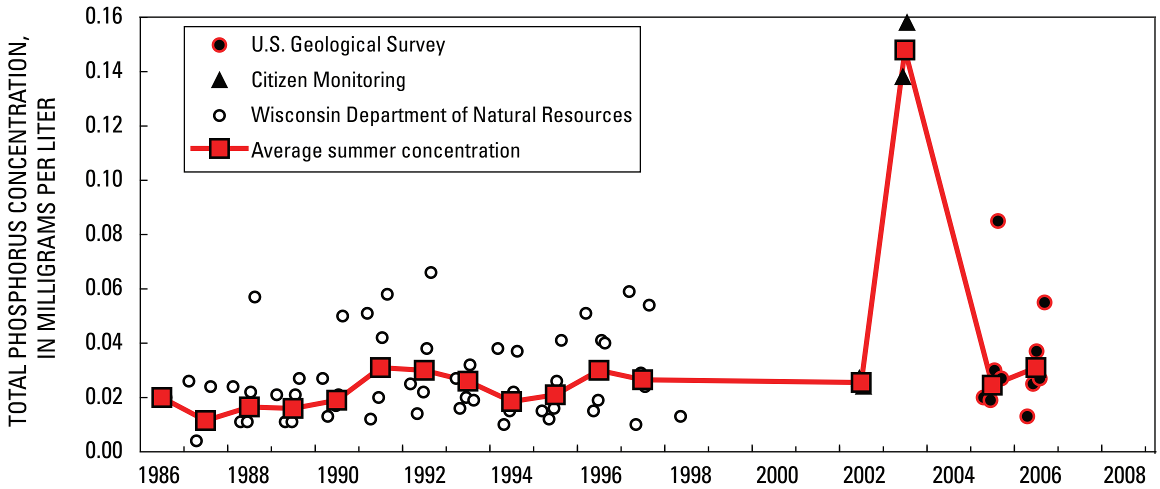


Figure 5. Near-bottom total phosphorus concentrations in Silver Lake, Barron County, Wis.,1986 to 2008.

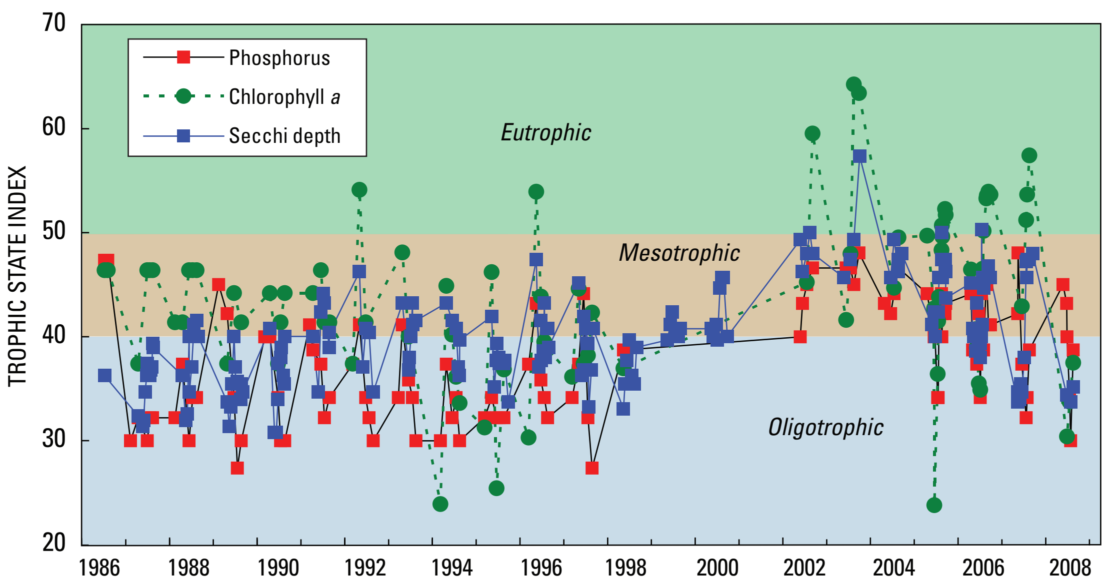


Figure 6. Trophic state index (TSI) values based on surface concentrations of total phosphorus and chlorophyll *a*, plus Secchi depths, in Silver Lake, Barron County, Wis., 1986 to 2008.

oligotrophic conditions and less than 6.6 ft indicate eutrophic conditions (Carlson, 1977). Therefore, based on Secchi depths, Silver Lake is usually classified as oligotrophic to mesotrophic except in 2002 to 2004 when the lake was mesotrophic to eutrophic.

All three TSIs, based on near-surface concentrations of total phosphorus and chlorophyll *a* and on Secchi depths, indicate that, in MY 2005 and MY 2006, Silver Lake was typically oligotrophic to mesotrophic (fig. 6 and table 3). Since 1986, Silver Lake has usually been classified as oligotrophic to mesotrophic; however, in 2002–4, the lake was classified as mesotrophic to eutrophic.

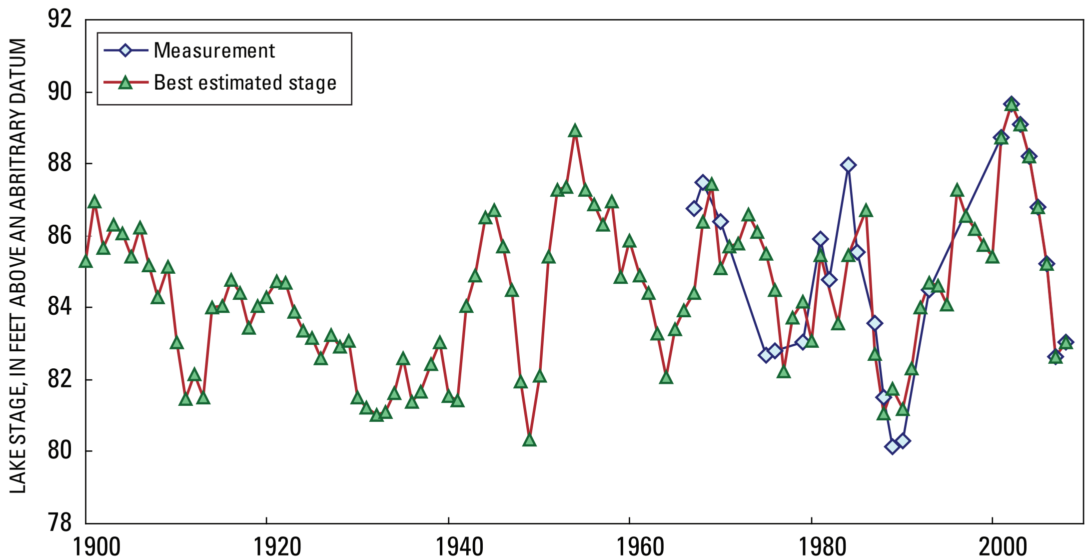


Figure 7. Estimated and measured average annual (May–October) lake stage (water level) in Silver Lake, Barron County, Wis., 1900 to 2008. [Altitude of the local datum is 1165.31 feet above the National Geodetic Vertical Datum of 1929.]

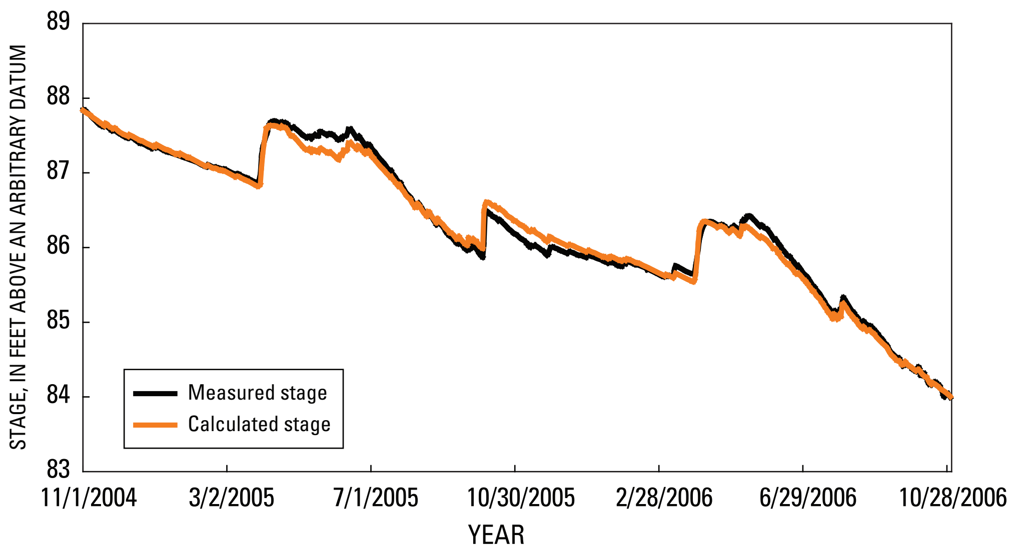


Figure 8. Daily water levels (stages) computed from the full water budget in comparison to measured water levels of Silver Lake, Barron County, Wis., from November 1, 2004, to October 31, 2006. [Altitude of the local datum is 1165.31 feet above the National Geodetic Vertical Datum of 1929.]

Historical Changes in the Water Level of Silver Lake

Detailed historical water-level measurements are available for only a few lakes in Wisconsin. Changes in the water level (stage) of Silver Lake have been intermittently measured since 1967 and were measured continuously from November 1, 2004, to October 31, 2006, as part of this study. Before this study, most water-level measurements were made during the period of open water; therefore, the available data were used to estimate average May through October water levels (fig. 7). Since 1967, the water level of Silver Lake has gone through almost three complete three cycles of rising and falling. During these cycles, water levels have fluctuated about 5 ft (1968–75), 8 ft (1975–89), and 10 ft (1989–2007). During the study period, the water level generally declined for the third time since 1967 (figs. 7 and 8); the highest stage recorded was 87.42 ft on the first day of monitoring (Nov. 1, 2004) and the lowest stage recorded was 83.99 ft on the last day of monitoring (Oct. 31, 2006). There were three relatively large rises and many other small rises in stage in response to rainfall and runoff during the study period. In late March and early April of both years, the stage increased about 0.7–0.8 ft over a few days in response to snowmelt and rainfall. In addition, rainfall during Oct. 4–5, 2005 (6.72 in., 0.56 ft) caused a 0.62-ft rise in stage.

The intermittent measurements in Silver Lake were insufficient for continuous annual estimates of water level before 2001. Therefore, to better describe how the water level of Silver Lake changed before 2001, two multiple-regression relations were developed to predict past average May–October water levels. The first relation used average May–October water levels measured in Shell Lake (9 mi north of Silver Lake) to estimate average May–October water levels in Silver Lake from 1936 to 2000. Detailed water-level measurements were available for Shell Lake from 1936 to 2007 (Krohelski and others, 1999; Shell Lake Chamber of Commerce, 2009); however, measurements after 2003 were not used to develop the relations because a diversion system was used to reduce the water level in Shell Lake starting in 2003. In all, 17 years of overlapping data were available to develop this linear-regression relation. A second relation was used to extend the Shell Lake and Silver Lake water levels back to 1900. In this second relation, the water levels of Shell Lake from 1900 to 1935 were first estimated by use of a time-series model that related the water level in Shell Lake to the total annual precipitation at Spooner, Wis. (5 mi north of Shell Lake), from the previous year and the average of the four previous years. The first relation was then applied with the estimated water levels in Shell Lake to estimate the average May–October water levels in Silver Lake from 1900 to 1935.

The final constructed water levels for Silver Lake indicate about seven cycles of rising and falling water levels since 1900 (fig. 7). The fluctuation in water level of 10 ft after 1990 was a little more extreme than what occurred between 1900 and 1990. Large fluctuations in water level have been known to occur in Silver Lake and have affected the area and the behavior of people around the lake. After prolonged low-water levels in the early 1930s (fig. 7), residents near the lake constructed a channel to divert water leaving Sylvan Lake into Silver Lake. This channel was also used during other periods of low water since the 1940s (table 2). The measured high water levels around 1968 and 1984 are similar to those predicted with the relations described above; therefore, it appears that the diversion channel was being used in a manner similar to that from around 2000. If the channel was not used around 1968 and 1984, the estimated stage in the lake would have been expected to be higher than that measured. The estimated changes in water level before 1935, especially the periods with high water levels, may be greater than what actually occurred in the lake because of the linear-regression assumption that the relation between water levels in Shell Lake and Silver Lake was similar to that after 1967, when water leaving Sylvan Lake was occasionally diverted into Silver Lake.

Hydrology and Water Budget

Because the productivity in Silver Lake should be limited or potentially limited by the input of phosphorus (as indicated by N:P ratios), phosphorus should be the nutrient of concern when considering management efforts to improve or prevent degradation of the water quality of the lake. Most of the phosphorus entering the lake is transported by water inputs; therefore, to quantify phosphorus inputs, water inputs first need to be quantified. Water and phosphorus budgets for the lake were quantified for each of the two detailed monitoring years. This information is then used to estimate water and phosphorus budgets for two years with high water levels for which monitoring data were available (2002 and 2003) and for years during very dry and wet conditions.

The hydrology of a terminal lake, like Silver Lake, can be described in terms of components of its water budget. The water budget for a period of interest may be represented by:

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

where ΔS is change in the volume of water stored in the lake and is equal to the sum of the volumes of water entering the lake minus the sum of the volumes leaving the lake. Water enters the lake as precipitation (P), surface-water inflow (SW_{In}), and groundwater inflow (GW_{In}). Water leaves the lake through evaporation (E) and groundwater outflow (GW_{Out}). Daily values for each term in the water budget were measured or estimated.

Change in Storage

Changes in the volume of the lake were determined from water elevations (fig. 8) measured continuously at the lake-stage gage near the south end of the lake (fig. 2). To simplify computations of changes in volume, an average area of the lake was used for each year of the study: 354.6 acres in MY 2005 and 343.1 acres in MY 2006. The amount of water stored in the lake decreased by 593 acre-ft in MY 2005 and by 749 acre-ft in MY 2006 (table 4).

Precipitation

Precipitation on the lake surface during MY 2005 was 30.11 in. (890 acre-ft) and during MY 2006 was 22.36 in. (639 acre-ft; table 4). During both years, precipitation was below normal: 90 percent of the long-term average (1971–2000) of 33.56 in. measured at Cumberland, Wis., during MY 2005 and 67 percent during MY 2006. Monthly precipitation during each monitoring year is compared to the 1971–2000 average monthly precipitation in figure 9. In MY 2005, precipitation totals for all months were at or below normal except in June and October. In MY 2006, totals for all months were below normal except for December and January.

Table 4. Water budget for Silver Lake, Barron County, Wis., measured for monitoring years 2005 and 2006, and estimated for 2002, 2003, and a series of dry and wet years.

[Monitoring year, November–October; MY, monitoring year; all data in acre-feet or percentage of total]

Budget component	Measured						Estimated			
	MY 2005	MY 2005 (percent)	MY 2006	MY 2006 (percent)	Two-year average	Two-year average (percent)	2002	2003	Series of dry years	Series of wet years
Change in storage										
Change in storage	-593		-749		-671		345	-202	-442	-63
Inputs to lake										
Precipitation	890	68.6	639	68.9	765	68.7	1,260	1,210	737	1,170
Surface-water inflow (total)	407	31.4	288	31.1	348	31.3	1,210	659	93	824
By surface-water component:										
Tributary 2	89	6.9	53.3	5.7	71	6.4				
Tributary 3	35	2.7	11.7	1.3	24	2.1				
Tributary 7	141	10.9	121	13.0	131	11.7				
Ungaged nearshore area	142	10.9	103	11.1	122	11.0				
Groundwater	0	0	0	0	0	0	0	0	0	0
Total input	1,300	100	928	31.1	1,110	100	2,470	1,870	831	1,990
Outputs from lake										
Evaporation	690	37.7	731	42.2	711	39.9	748	743	639	742
Groundwater	1,140	62.3	1,000	57.8	1,070	60.1	1,380	1,320	635	1,310
Total output	1,830	100	1,730	100	1,780	100	2,120	2,070	1,270	2,060

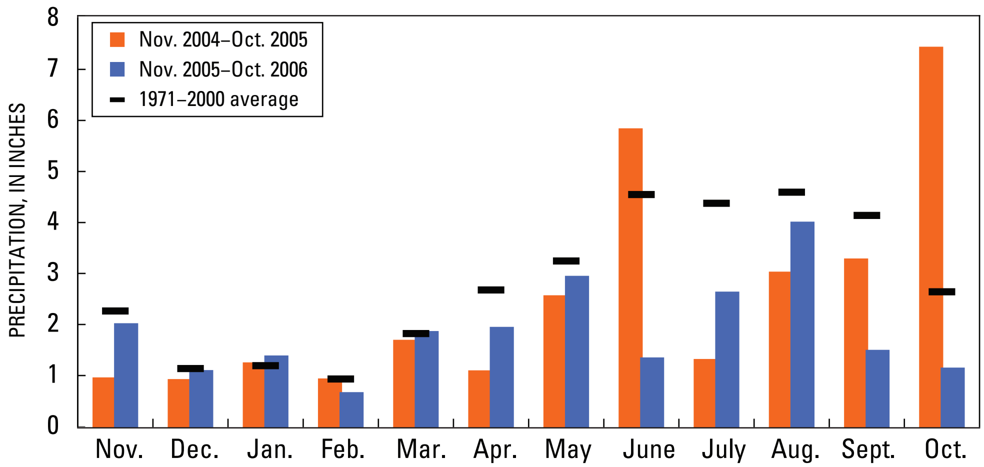


Figure 9. Precipitation at Silver Lake, Barron County, Wis., November 2004 to October 2006, relative to long-term average precipitation at Gordon, Wis.

Evaporation and Net Groundwater Inflow

Because Silver Lake is deeper than many nearby lakes, its water temperature increases more slowly in spring and decreases more slowly in fall than in most other lakes; therefore, rates of evaporation from the surface of the lake may differ from those of other nearby lakes. In addition, evaporation varies among years depending on meteorological conditions. Therefore, evaporation rates from other nearby lakes or evaporation estimated from nearby evaporation-pan data that are typically used to estimate evaporation for small lakes may provide misleading information. As an alternative, daily evaporation was estimated for the 2-year detailed monitoring period by use of the one-dimensional hydrodynamic model, the Dynamic Lake Model (DLM; McCord and others, 2000; Robertson and others, 2002). In the process of simulating the hydrodynamics of the lake, the model computes detailed energy and hydrologic budgets, which includes heat transfer from the lake associated with evaporation. Therefore, if the detailed energy budget is accurate, the amount of evaporation should be correctly estimated.

DLM is a lake and reservoir model, which was modified from the DYnamic REservoir Simulation Model, DYRESM (Imberger and Patterson, 1981) by McCord and others (2000). Both DLM and DYRESM are process based and have been successfully used to simulate vertical changes in water temperatures and ice cover of many lakes and reservoirs around the world. DLM is based on parameterizations of each of the individual mixing processes, so site-specific model calibration is generally not necessary. For a more complete description of the DLM model and its application to estimate evaporation rates, see Robertson and others (2002).

Inputs to DLM include data descriptions of lake morphometry, meteorological conditions, inflow and outflow (outflow was assumed to be equivalent to groundwater leaving the lake), average light extinction in the lake, and initial water temperature and salinity (or specific conductance) profiles in the lake. Daily average air temperature, vapor pressure, wind speed, and inflow characteristics (temperature and specific conductance or salinity) are used, whereas daily total values for inflows, outflows, longwave radiation (or average percent of clear sky), shortwave radiation, rainfall, and snowfall are used. Meteorological data were obtained from meteorological stations in the area operated by the USGS, WDNR, and the NWS. An average Secchi depth of 10.7 ft (the average during the open-water period during the simulation period) was used to estimate a light-extinction coefficient of 0.523 ft^{-1}. Water temperature and conductivity profiles measured on April 19, 2005, were used as the initial conditions for the simulation. Daily evaporation rates, before the start of the simulation, were assumed to be equal to the average of that estimated in 2005 and 2006 for each calendar day. Evaporation was assumed not to occur when the lake was frozen.

To demonstrate that DLM accurately simulated the energy balance of the lake, the simulated thermal structure of the lake was compared with that measured (fig. 10). The model accurately simulated the changes in the thermal structure of the lake during the entire simulation period (onset of stratification, surface and deep temperatures, and the depth of the thermocline); therefore, DLM should have correctly simulated the energy and hydrologic balances of the lake. Results from the model can also be used to describe changes in the thermal structure of the lake during periods when the lake was not monitored, such as in late fall and winter. During the simulation period, the model required an additional loss of 1.48 ft^3/s (1,070 acre-ft/year) of water to properly simulate the changes in water level measured in the lake. The additional loss of water was assumed to be caused by the net loss of water from the lake to the groundwater system. The net loss of water to the underlying aquifer was assumed to be equal to the total loss to the groundwater system because, as described below in “Groundwater Inflow and Outflow” section, there was no groundwater inflow to the lake.

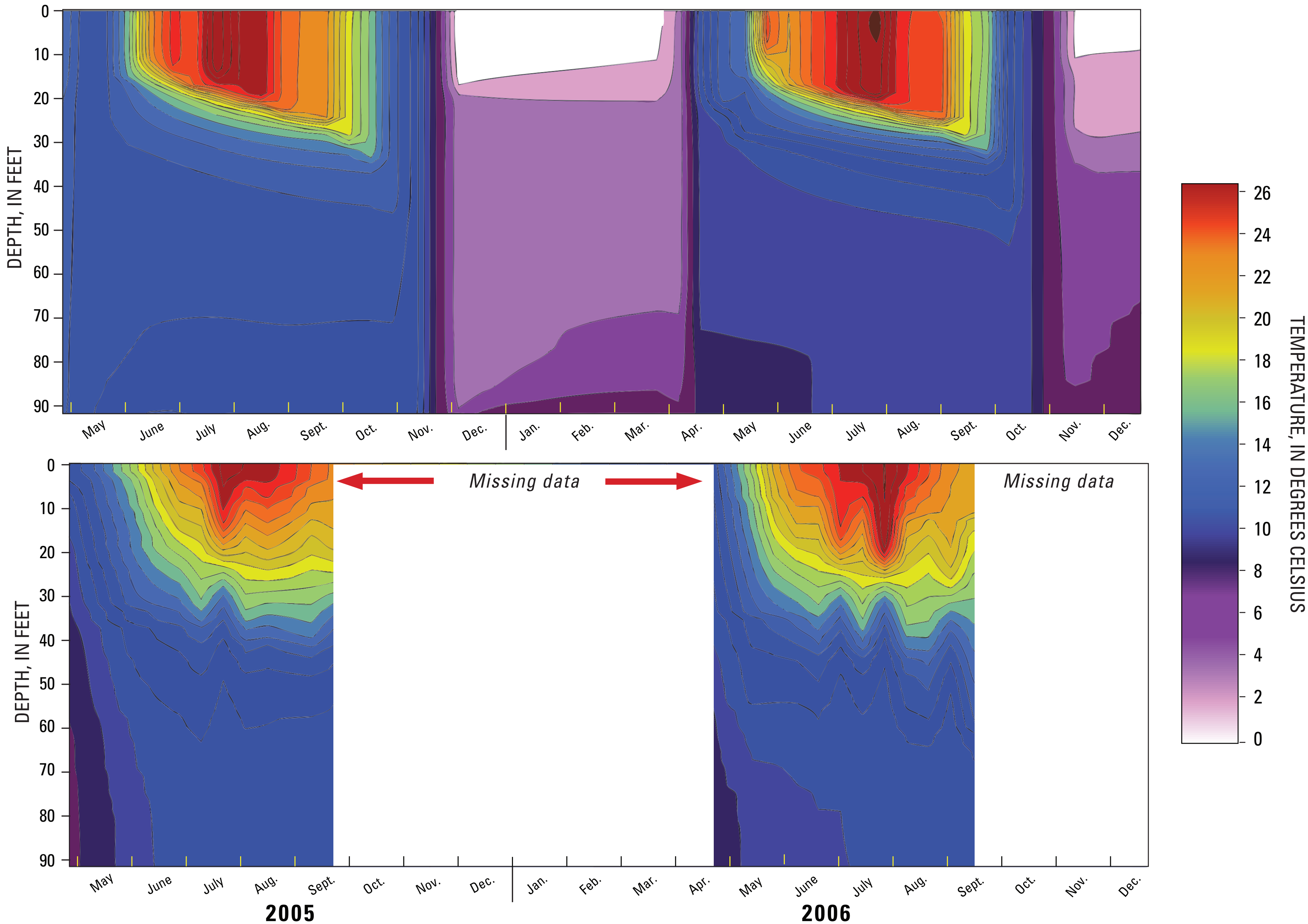


Figure 10. Measured and modeled (with the Dynamic Lake Model; McCord and others, 2000) distribution of water temperature, April 19, 2005, to December 31, 2006.

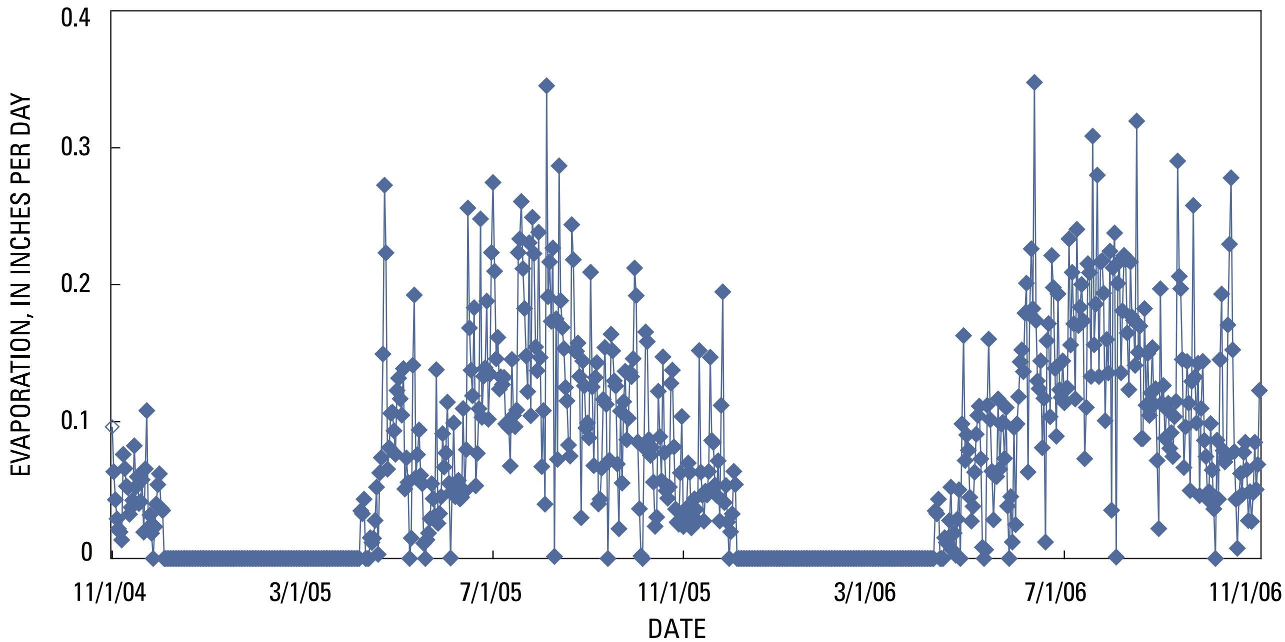


Figure 11. Daily evaporation from the surface of Silver Lake, Barron County, Wis., November 2004 through October, 2006, based on output from the Dynamic Lake Model.

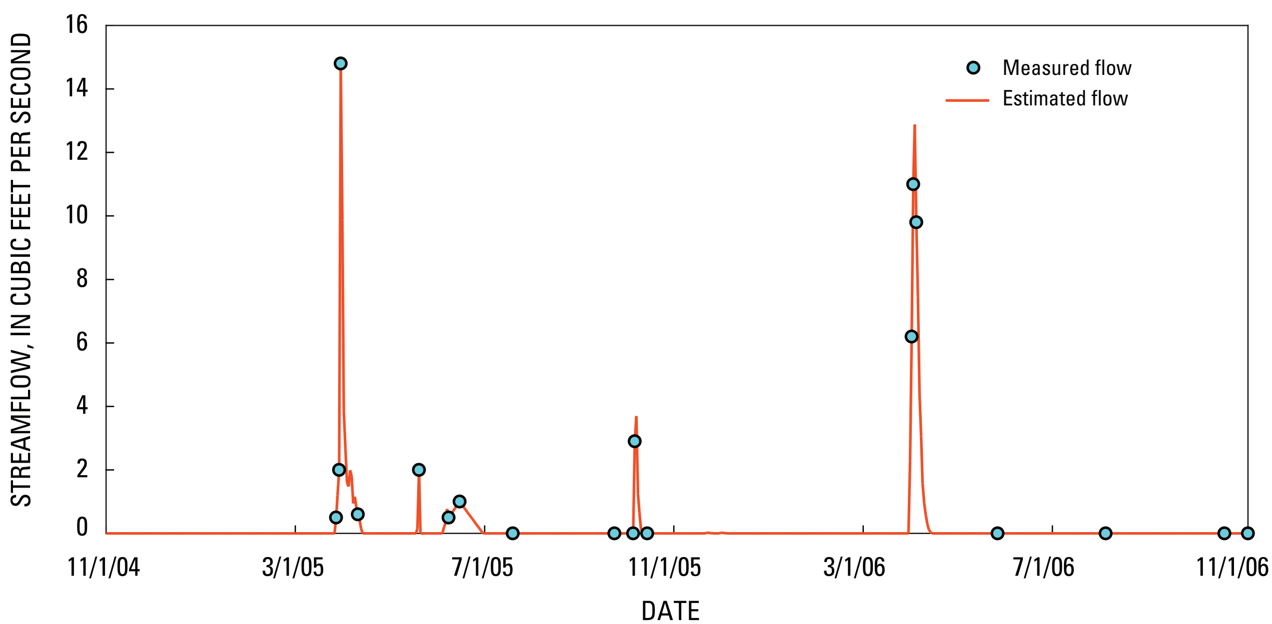


Figure 12. Estimated streamflow in tributary 7 (fig. 2) to Silver Lake, Barron County, Wis., November 1, 2004, to October 31, 2006.

Daily evaporation, computed by DLM from Nov. 1, 2004, through Dec. 31, 2006, was variable but demonstrated a strong seasonal pattern, with highest evaporation in summer (especially July–August; fig. 11). The highest daily evaporation was about 0.35 in/d. The annual evaporation from the surface of the lake was 23.4 in. (690 acre-ft) in MY 2005 and 25.6 in (731 acre-ft) in MY 2006 (table 4). These estimates are a little less than the average total annual free-surface evaporation estimated for the area (approximately 28 in.) by Farnsworth and Thompson (1982).

Surface-Water Inflow

Seven small tributaries to the lake were identified (fig. 2) and monitored intermittently. None of these tributaries flowed continuously. The most significant of these tributaries in terms of flow and duration of flow after storms were tributaries 7, 2, and 3, listed in descending order of importance. Tributary 7 drains most of the northern part of the watershed and flows through extensive wetlands before entering the lake. Tributary 2 drains a small mostly forested area northeast of the lake.

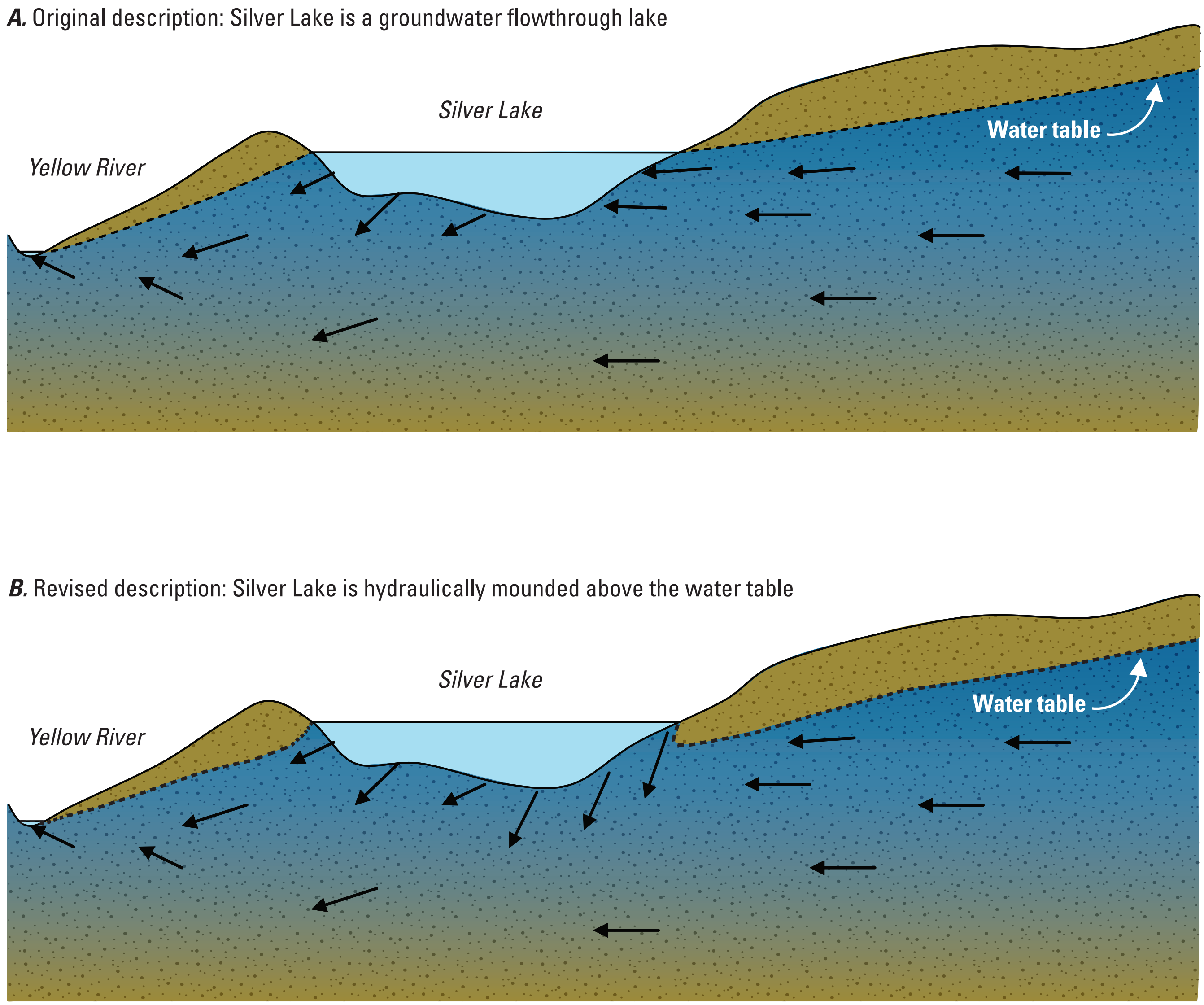


Figure 13. Groundwater flow near Silver Lake, Barron County, Wis. *A*, Original description of flow, with Silver Lake as a groundwater flowthrough lake. *B*, Revised description of flow, with Silver Lake hydraulically mounded above the water table.

Tributary 3 drains a small part of the watershed southeast of the lake. Approximately one-third of the total surface-water inflow comes from tributary 7. The estimated daily flows from tributary 7 are shown in figure 12. Total runoff volumes for tributaries 2, 3, and 7 are summarized in table 4. Runoff volumes from tributary 7 were 141 acre-ft in MY 2005 and 121 acre-ft in MY 2006, which were more than those from all of the other tributaries combined except during spring snowmelt.

Observations of flow in tributaries 1, 4, 5, and 6 were infrequent and flow was mostly only associated with runoff during snowmelt in spring; therefore, estimating flows in these tributaries was not possible. Hence, these tributaries were grouped with other ungaged near-lake areas and referred to as the “ungaged nearshore area.” Runoff from the ungaged nearshore area was estimated by determining the amount of runoff needed to balance the mass-balance equation during the spring snowmelt period. Runoff volumes for the ungaged nearshore area were estimated to be 0.4 ft (142 acre-ft, table 4) in MY 2005 (assumed to occur over the 4 days from April 1 to April 4, 2005) and 0.3 ft (103 acre-ft) in MY 2006 (assumed to occur over the 3 days from April 1 to April 3, 2006).

Groundwater Inflow and Outflow

Before this study began, Silver Lake was described as a groundwater flowthrough lake (fig. 13*A*), with groundwater entering the lake from the northern one-third of its periphery and water leaving the lake from the southern two-thirds of its periphery (Young and Hindall, 1972). This interpretation seemed plausible without the availability of detailed groundwater data and considering the water level in Silver Lake in

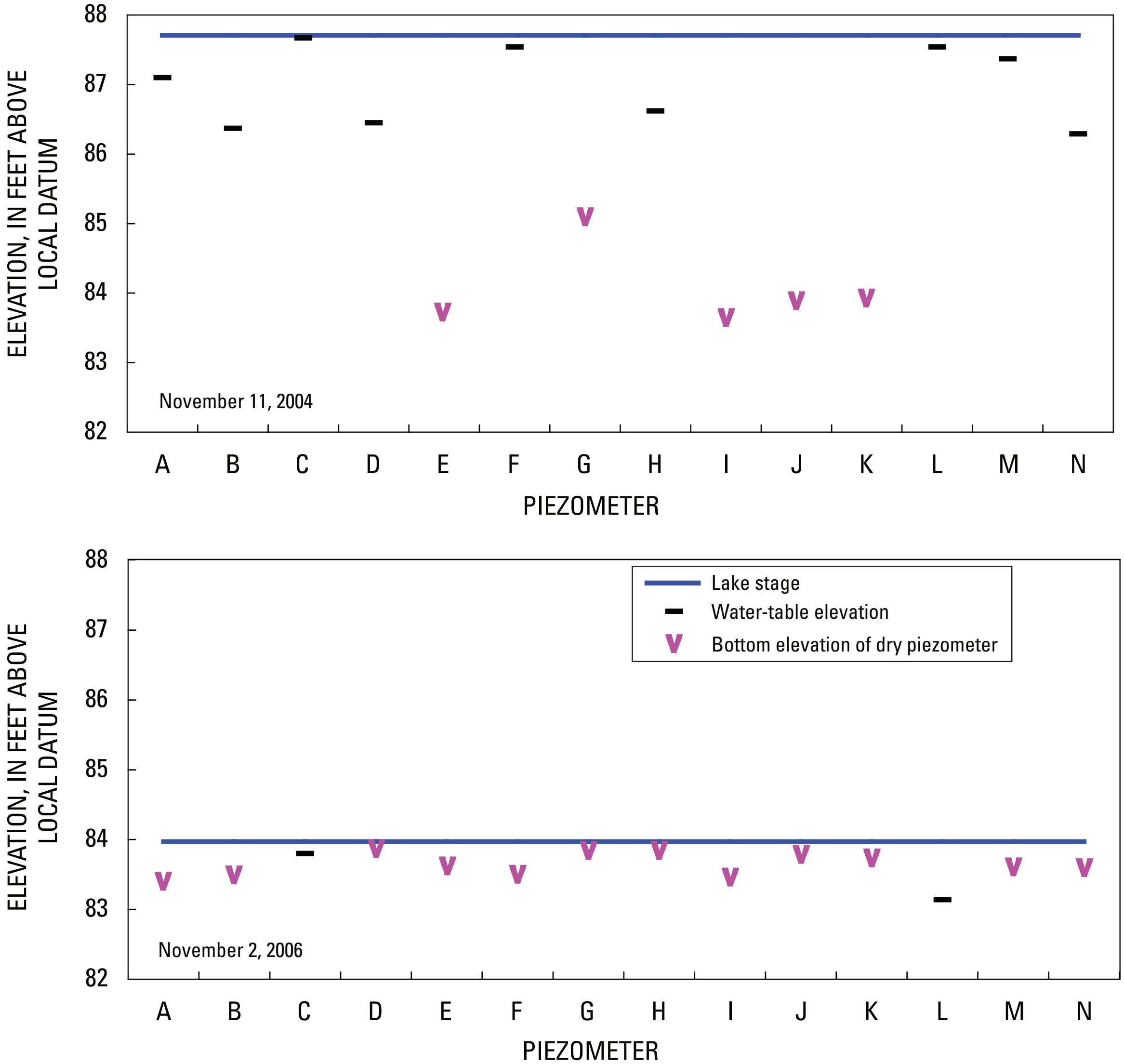


Figure 14. Water levels in Silver Lake, Barron County, Wis., and in nearshore piezometers during periods with high water (November 11, 2004) and low water levels (November 2, 2006) in the lake. For some piezometers, the water table was below the bottom elevation of the piezometer. [Altitude of the local datum is 1165.31 feet above the National Geodetic Vertical Datum of 1929.]

relation to those of nearby streams and lakes, especially with the strong gradient between the water level of the lake and that of the nearby Yellow River. Water levels measured in 14 near-lake piezometers installed around the periphery of the lake (fig. 2) and those recorded during nearby domestic well installation, however, were consistently at an elevation lower than the lake surface, which indicates the hydraulic gradient was downward or away from the lake to the ground. Water elevations in the piezometers are compared with that in the lake during periods with high and low water levels in figure 14. In addition, water levels in five selected domestic wells, located 80 to 250 ft to the north and northeast of the lake (fig. 2), were 5–25 ft below the lake surface at the time of well construction. Therefore, it is clear that, rather than being a groundwater flowthrough lake, Silver Lake is hydraulically mounded above the water table (fig. 13*B*) and there is no groundwater inflow to the lake.

Discharge of water from the lake to the ground was estimated from the DLM simulations and as the residual in the water-budget equation when all of the other variables were measured or estimated. Leakage of water from the lake to the ground over the entire 2-year period was approximately 1.48 ft^3/s, or 0.0084 ft/d. The amount of groundwater leaving the lake is expected to increase as the water level in the lake increases because, at higher lake levels, the water would likely be in contact with more permeable sandy deposits (for

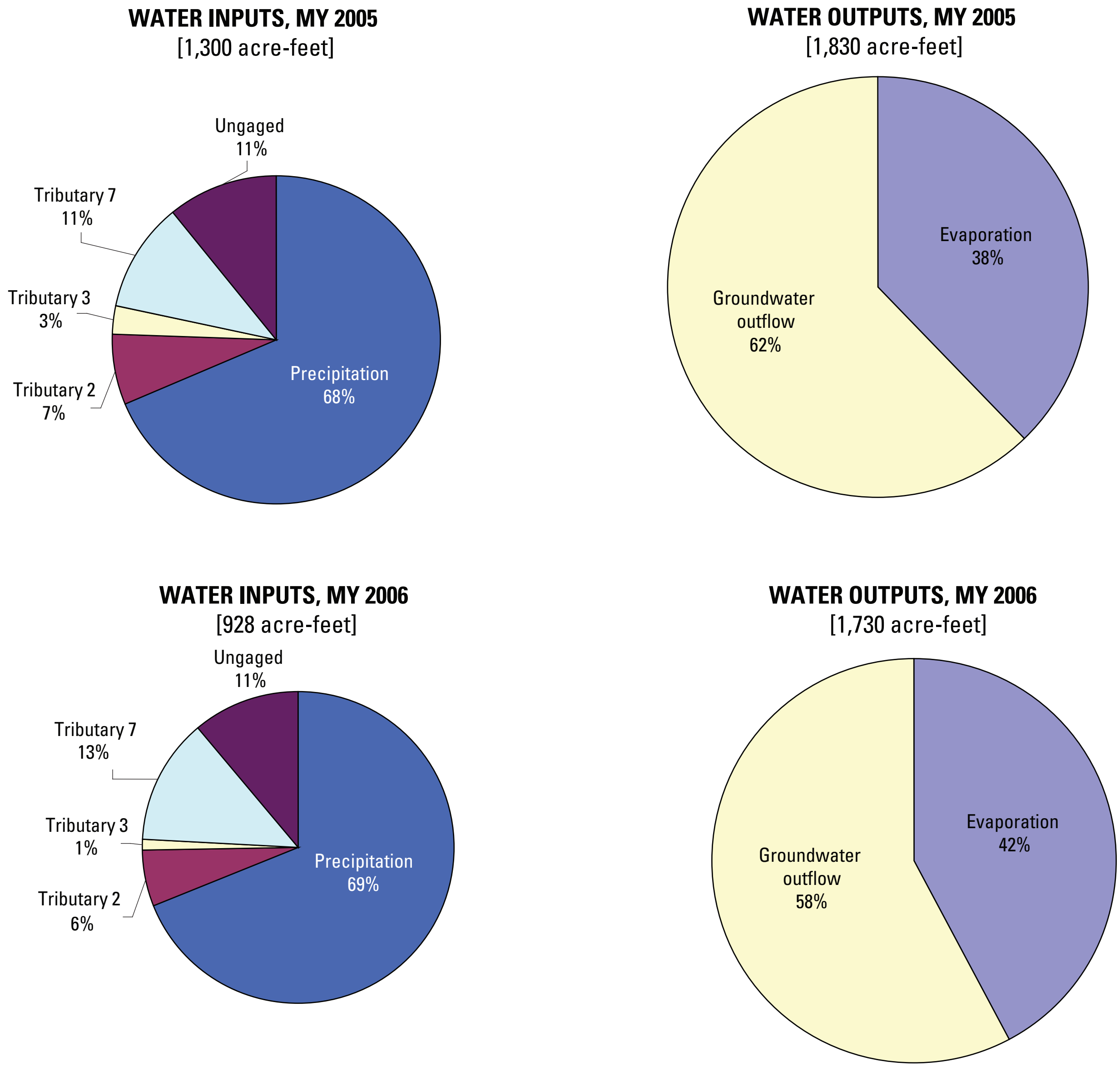


Figure 15. Water budgets for Silver Lake, Barron County, Wis., for monitoring years (MY) 2005 and 2006. [%, percentage]

example, Krohelski and others, 1999). To estimate how the rate of water leakage from the lake may have varied between MY 2005 and MY 2006, the annual rates in MY 2005 (higher water level) were increased and the rates in MY 2006 (lower water level) decreased by constant incremental rates, and the overall errors in the daily water budget (eq. 4 and fig. 8) were then compared. The optimum estimation for water leakage to the groundwater was 0.0088 ft/d in MY 2005 and 0.0080 ft/d in MY 2006. Therefore, the total water outflow from the lake to groundwater was 1,140 acre-ft in MY 2005 and 1,000 acre-ft in MY 2006 (table 4).

Water-Budget Summary

During the 2-year study period, precipitation was the largest source of water to the lake, supplying 68.7 percent of the total input (table 4; fig. 15). Surface runoff supplied 31.3 percent of the water entering the lake. The total input of water in MY 2005 (1,300 acre-ft) was more than in MY 2006 (928 acre-ft), reflecting near-normal precipitation during MY 2005 and below-normal precipitation in MY 2006. The residence time, or the length of time required for water entering the lake to completely replace the volume of water in the lake, was 9.7 and 13.1 years on the basis of the total inflows for MY 2005 and MY 2006, respectively, or an average residence time of 11.4 years.

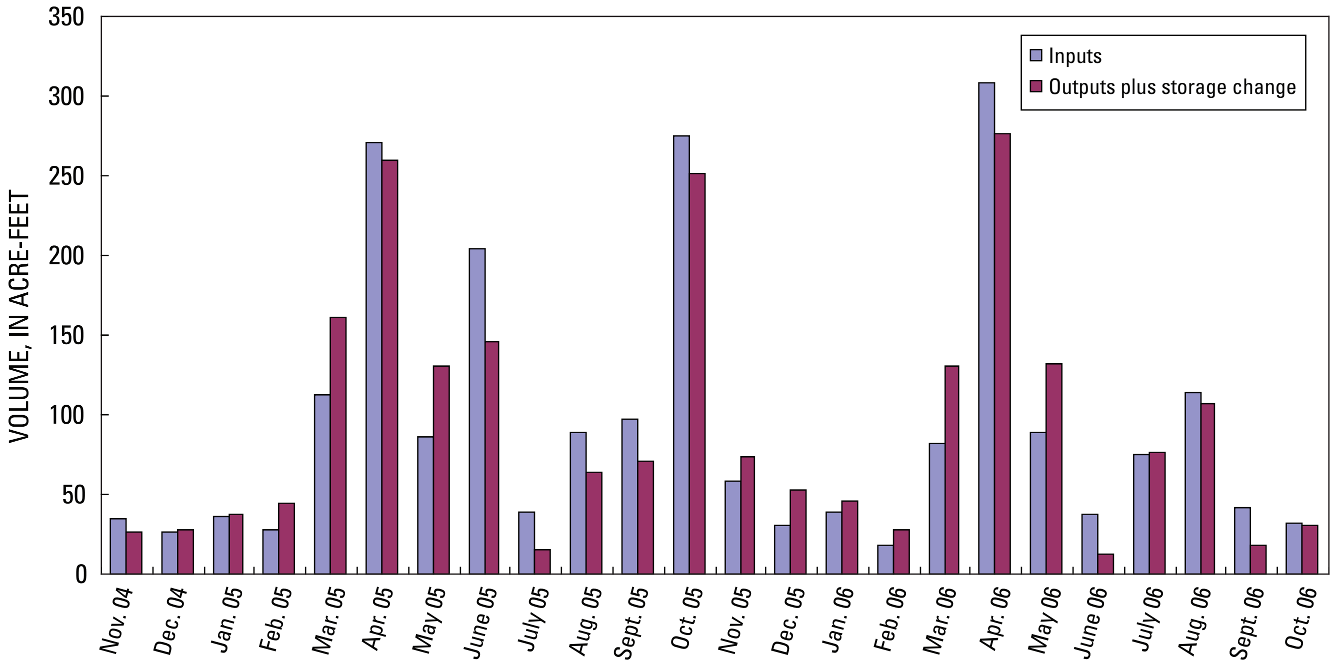


Figure 16. Monthly total water inputs and outputs plus storage change for Silver Lake, Barron County, Wis., based on results from the water-balance model (equation 4). The difference between inputs and outputs indicates the cumulative error for all components of the water budget for each month.

The total annual outputs of water from the lake were greater than the total inputs, which resulted in a decrease in storage from the beginning to the end of each monitoring year. This resulted in a decrease in lake stage of 3.43 ft or 1,340 acre-ft of storage in the lake over the 2-year period. On average, outflow to the groundwater system accounted for about 60 percent of the total water output from the lake, and evaporation accounted for about 40 percent (table 4; fig. 15).

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 lake, expressed in acre-feet (fig. 16). The differences between calculated inputs and outputs reflect the cumulative errors in the estimates of all of the components in the water budget for each month. The largest monthly differences were 50–60 acre-ft. On an annual basis, the percentage errors were less than 3 percent.

Sources of Phosphorus

To help define where the phosphorus in Silver Lake originates and how much may be controllable, a detailed daily phosphorus budget was computed for each monitoring year. The external sources of phosphorus to the lake examined included precipitation, surface- and groundwater inflow, and contributions from septic systems and erosion. In addition to these external sources, phosphorus can be released from the bottom sediments of the lake; this release is considered an internal source of phosphorus (internal loading). Very little phosphorus from internal loading is released into the epilimnion during summer because of the strong thermal stratification (fig. 10), which prevents mixing, and because of the relatively low phosphorus concentrations in the hypolimnion (fig. 5); therefore, this source was not considered. Phosphorus is removed from the lake through deposition to the lake sediments.

Precipitation

Phosphorus deposition on Silver Lake was determined from phosphorus concentrations measured in wetfall (rain and snow) and phosphorus deposition rates measured in dryfall at the weather station at Whitefish Lake (Robertson and others, 2009). Phosphorus in precipitation was estimated from the seasonal phosphorus concentrations measured for snow (0.009 mg/L; Dec.–Mar.) and rain (0.017 mg/L; Apr.–Nov.). Monthly wetfall deposition was computed by multiplying the monthly average phosphorus concentrations by the estimated precipitation on the lake. Wetfall deposition was highest during summer, when phosphorus concentrations were highest and precipitation was greatest. A dryfall deposition rate of 26.1 lb/mi^2/yr was used, which represented deposition on a lake with few conifers in the surrounding area. The total phosphorus contributed by precipitation was 53.4 lb in MY 2005 and 41.0 lb in MY 2006 (table 5); approximately 75 percent of the deposition was from wetfall.

Surface-Water Inflow

The total input of phosphorus from surface water in the watershed was estimated from the flows and total phosphorus concentrations measured at the monitoring sites on tributaries 2, 3, and 7 (fig. 2). Flow-weighted average total phosphorus concentrations in MY 2005 (wetter year) ranged from 0.080 mg/L in tributary 2 to 0.149 mg/L in tributary 3 to 0.280 mg/L in tributary 7; in MY 2006 (drier year) concentrations ranged from 0.060 mg/L in tributary 2 to 0.080 mg/L in tributary 3 to 0.139 mg/L in tributary 7. The flow-weighted average concentration of all of the discrete samples was 0.252 mg/L in MY 2005 and 0.150 mg/L in MY 2006. These concentrations were used to compute phosphorus input from the ungaged nearshore area. Because of the higher volume of water and higher phosphorus concentrations in tributary 7 than in the other tributaries, most of the phosphorus in surface water enters the lake through this tributary. Most of the phosphorus in surface water entered the lake in March and April, especially during snowmelt (fig. 17). The total quantity of phosphorus delivered from tributary 7 was 107 lb in MY 2005 and 45.7 lb in MY 2006 (table 5). The total quantities of phosphorus from tributaries 2 and 3 were 19.4 and 14.4 lb, respectively, in MY 2005 and 8.8 and 2.5 lb, respectively, in MY 2006. The ungaged nearshore area is estimated to have contributed 97.3 and 42.0 lb of phosphorus in MY 2005 and MY 2006, respectively. Therefore, the total quantity of phosphorus delivered from surface water in the watershed was 238 lb in MY 2005 and 99 lb in MY 2006, almost half of which entered the lake during the short snowmelt period.

Phosphorus yields from the tributary 7 watershed were 58.6 lb/mi^2 in MY 2005 and 25.0 lb/mi^2 in MY 2006. These yields are lower than those from 48 of the 50 rural watersheds that were monitored in Wisconsin and lower than 4 of the 5 watersheds monitored in the Northern Lakes and Forests ecoregion by Corsi and others (1997). Yields from the tributary 2 watershed were a little higher than from the tributary 7 watershed: 130 lb/mi^2 in MY 2005 and 58.9 lb/mi^2 in MY 2006. These yields, however, are still lower than those estimated from 45 of the 50 rural watersheds in Wisconsin and lower than 2 of the 5 watersheds in the Northern Lakes and Forests ecoregion.

Total phosphorus concentrations were also measured near the outlet of Sylvan Lake during spring 2006 prior to the stream entering the wetland system north of the lake. The flow-weighted average phosphorus concentration in the four samples was 0.055 mg/L.

Groundwater and Septic Systems

On the basis of measured gradients between the lake and 14 nearshore piezometers, it is evident that water leaks from all areas of the lakebed into the groundwater system; therefore, groundwater and septic systems would not supply phosphorus to the lake. The only condition for which a septic system may

Table 5. Phosphorus inputs to Silver Lake, Barron County, Wis., measured for monitoring years 2005 and 2006, and estimated for 2002, 2003, and a series of dry and wet years.

[Monitoring year, November–October; MY, monitoring year; all data in pounds or percentage of total]

	Measured						Estimated			
Budget component	MY 2005	MY 2005 (percent)	MY 2006	MY 2006 (percent)	Two-year average	Two-year average (percent)	2002	2003	Series of dry years	Series of wet years
Precipitation	53.4	18.3	41.0	29.3	47.2	21.9	69.0	66.7	44.5	65.1
Surface-water inflow (total)	238	81.7	99.0	70.7	169	78.1	586	319	45.2	399
By surface-water component:										
Tributary 2	19.4	6.7	8.8	6.3	14.1	6.5				
Tributary 3	14.4	4.9	2.5	1.8	8.5	3.9				
Tributary 7	107	36.7	45.7	32.6	76.4	35.4				
Ungaged nearshore area	97.3	33.4	42.0	30.0	69.7	32.3				
Shore erosion	.0		.0		.0		93.1	93.1	0.0	93.1
Groundwater	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Total input	292	100	140	100	216	100	749	479	89.7	557

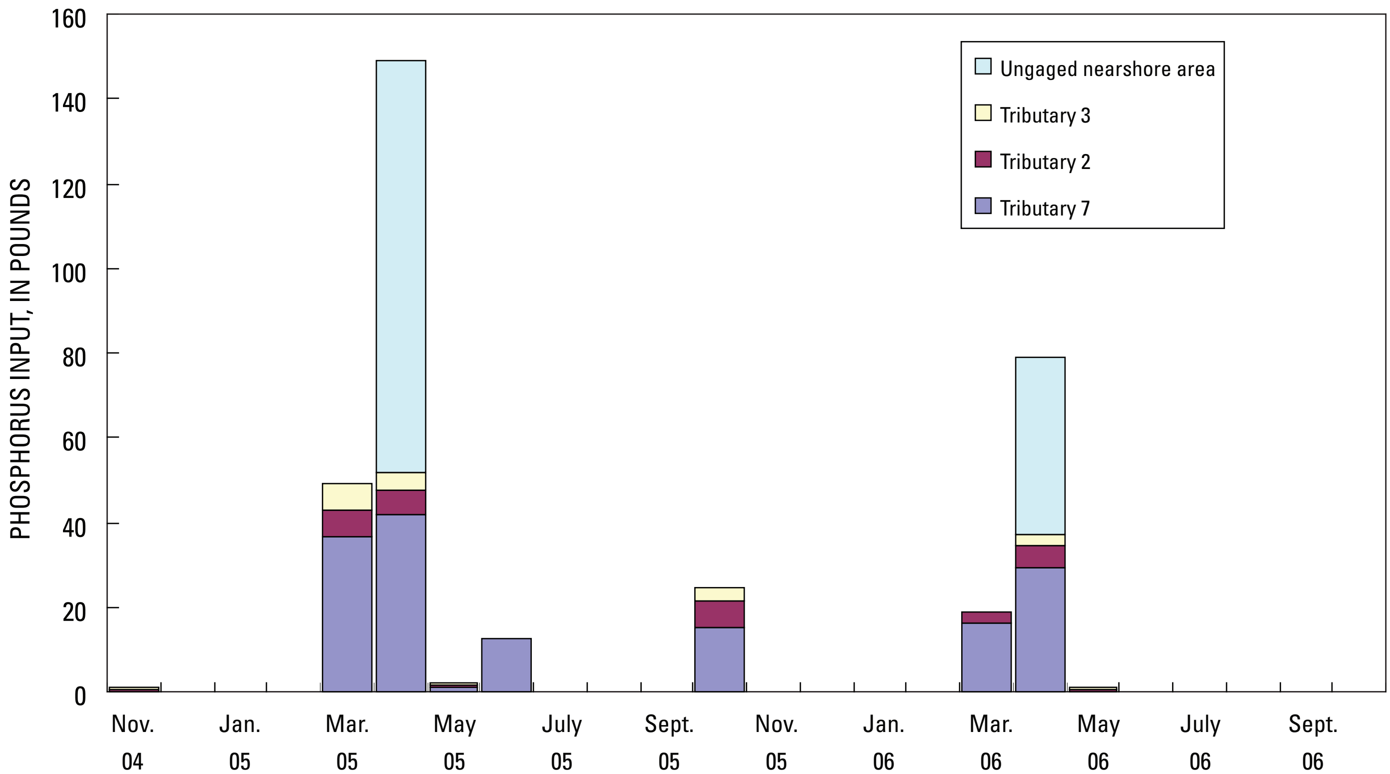


Figure 17. Total monthly phosphorus input from three main tributaries and ungaged nearshore area to Silver Lake, Barron County, Wis., November 2004 to October 2006.

supply phosphorus to the lake would be if the system were totally flooded or directly discharged to the lake.

Nearshore Erosion

Because the water level of Silver Lake had dropped during MY 2005 and MY 2006 from that in 2001–3, there was little, if any, erosion of the shoreline of Silver Lake during the two detailed monitoring years. Phosphorus from nearshore erosion may be important in years with high water levels; therefore, the phosphorus input to the lake during 2001–3 was estimated and compared with the loading of phosphorus estimated during two of these years. Approximately 50 percent of the shoreline (28 areas with a total length of approximately 12,000 ft) showed signs of erosion. The height of the eroded areas was typically 1 to 2.5 ft, with a retreat of 1 to 2 ft. The shoreline is steeper on the east and south sides of the lake than on the other sides of the lake, which resulted in slumps or block failures being more evident in these areas. Effects of erosion at site 3 (near the county park) and site 21 (on the east side of the lake) are shown in figure 18. The total amount of sediment eroded from these areas was estimated to be 34,400 ft^3, or 1,550 tons (assuming an aerated specific weight of the sand/clay/gravel to be 90 lb/ft^3; Chow, 1964).

The amount of phosphorus released from the eroded sediment was needed to determine how much phosphorus was introduced into the water column of the lake. Phosphorus concentrations were measured in the sediment near the lake (eight sites) and in the nearby lake bottom (four sites), and the difference in the average concentrations of these two areas was assumed to be the result of phosphorus being released into the water column. The estimated change in phosphorus concentrations was based on (1) total phosphorus concentrations, which may lead to a high estimate because part of this phosphorus may not be available to the water column, and (2) phosphate concentrations, which may lead to a low estimate because other forms of phosphorus also may dissolve into the water column. The average total phosphorus content in the bank sediment was 265 mg/kg and nearby lake sediments was 132 mg/kg; therefore 133 mg/kg of total phosphorus should have been released into the water column. The average phosphate content (as phosphorus) in the bank sediment was 71 mg/kg and in the lake sediments was 25 mg/kg; therefore, 47 mg/kg of phosphate should have been released into the water column. The changes in concentrations of total phosphorus and phosphate in the sediment were then multiplied by the total mass of eroded sediment. This resulted in a total phosphorus release of 414 lb and total phosphate release of 145 lb. If the average of these two estimates is used to determine the amount of phosphorus introduced to the water column, then 279 lb would have been delivered into the lake. If this erosion is assumed to have taken place over the three years from 2001

A

B

Figure 18. Erosion at two locations on Silver Lake, Barron County, Wis. *A*, Site 3 near county park, with erosion around the support beams of the steps down to the water. Notice that the middle support beams are hanging in the air. *B*, Site 21, demonstrating examples of erosion on the east side of the lake. Site locations shown in figure 3.

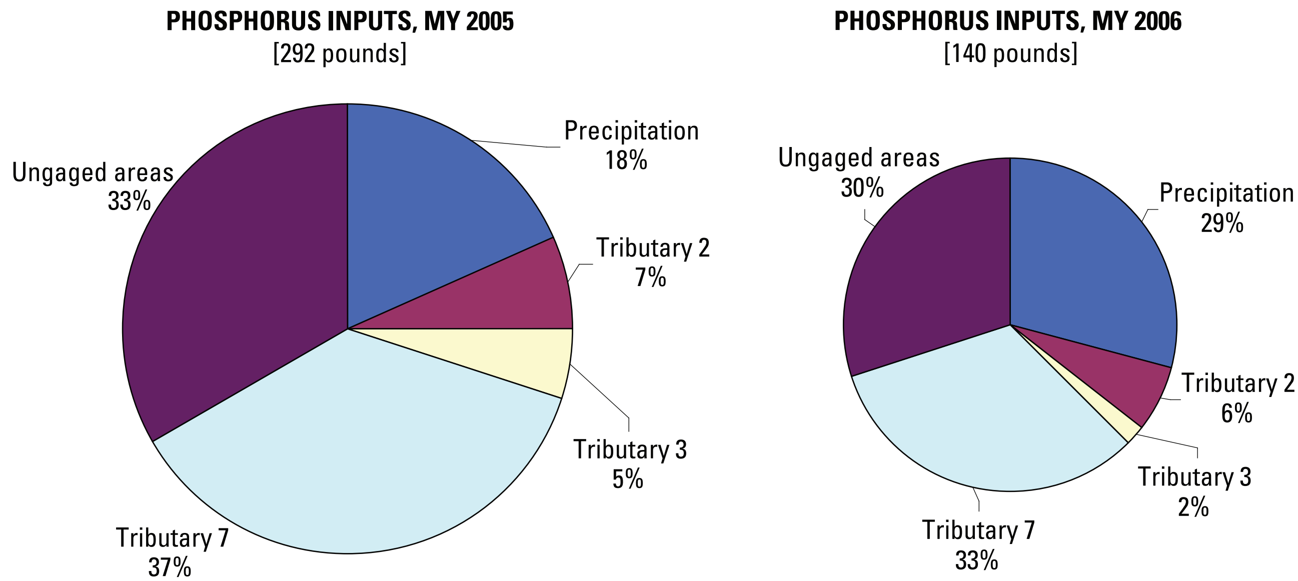


Figure 19. Phosphorus budgets for Silver Lake, Barron County, Wis., for monitoring years (MY) 2005 and 2006. [%, percentage of total input]

to 2003 when water levels were highest, then 93 lb/yr would have been introduced into the lake during these years.

Phosphorus-Budget Summary

During MY 2005 and MY 2006, the average annual input of phosphorus to the lake was 216 lb, of which 47 lb came from precipitation (21.9 percent) and 169 lb (78.1 percent) came from surface-water inflow (table 5). About 50 percent of the phosphorus in surface-water inflow came from tributary 7 (fig. 19). The total phosphorus input to the lake ranged from 292 lb in MY 2005 (the wetter year) to 140 lb in MY 2006 (the drier year). During these years, there was no phosphorus input from groundwater, septic systems, or erosion.

To determine how the water and phosphorus inputs to the lake vary when hydrologic conditions differ, the information from the detailed monitoring years was used to estimate water and phosphorus inputs for two years with high water levels for which water-quality data were available for the lake (2002 and 2003), and for a series of dry and wet years. The series of dry and wet years were the three consecutive years with the lowest and highest precipitation from 1960 to 2007. The three consecutive years with the lowest precipitation were from 1988 to 1990 (average precipitation of 28.2 in.), and the three consecutive years with the highest precipitation were from 2002 to 2004 (average precipitation of 38.5 in.). For each of these years, the surface area of the lake was estimated from the water levels in figure 7 and the morphometry of the lake (fig. 2). Phosphorus from wetfall was estimated by multiplying the total volume of precipitation (surface area of the lake multiplied by the precipitation at Cumberland) by an average annual phosphorus concentration in precipitation of 0.016 mg/L (Robertson and others, 2009). Phosphorus from dryfall was assumed to be deposited at a constant rate of 26.1 lb/mi$_2$/yr (Robertson and others, 2009). The total phosphorus from precipitation was 69.0 lb for 2002, 66.7 lb for 2003, 44.5 lb/yr for the three dry years, and 65.1 lb/yr for the three wet years (table 5).

The volume of surface-water inflow to the lake was computed for each year using a water-budget approach; in other words, solving for the surface-water-inflow (sum of all tributaries and ungaged area) term in equation 4. The changes in storage (table 4) were computed from changes in the estimated water elevations for consecutive years (fig. 7), with volumes computed from the morphometric map of the lake (fig. 2). The total water removed by evaporation was computed by using the surface area of the lake and assuming a constant evaporation rate of 24.5 in/yr (the average rate for MY 2005 and MY 2006). The total water added by precipitation was computed by multiplying the surface area of the lake by the precipitation measured at Cumberland. The rate of water outflow to groundwater was assumed to be directly related to the water level of the lake. The leakage rates for MY 2005 (1,140 acre-ft for an elevation of 87.07 ft) and MY 2006 (1,000 acre-ft for an elevation of 85.56 ft) were used to estimate leakage at other elevations based on the assumption that these two rates were sufficient to define a linear relation between elevation and leakage.

Therefore on the basis of the water-budget approach, the surface-water inflow in 2002 was 1,210 acre-ft, in 2003 was 659 acre-ft, the average annual inflow during the dry years was 93 acre-ft, and during the wet years was 824 acre-ft (table 4). The phosphorus concentration in the inflow was assumed to be 0.178 mg/L, which was the volumetrically weighted concentration for all of the tributary input during MY 2005 and MY 2006. Therefore, the total annual phosphorus input from surface inflow during 2002 was 586 lb, during 2003 was 319 lb, during the dry years was 45.2 lb/yr, and during the wet years was 399 lb/yr (table 5). In addition to these sources, it was assumed that during 2002, 2003, and during the wet years, 93 lb/yr of phosphorus was contributed from erosion.

In 2002, the total water input to the lake was 2,470 acre-ft and total phosphorus input was 749 lb (tables 4 and 5). In 2003, the total water input was 1,870 acre-ft and total phosphorus input was 479 lb. During the dry years, the average annual water input was 831 acre-ft and phosphorus input was 89.7 lb. During the wet years, the average annual water loading to the lake was 1,990 acre-ft and phosphorus input was 557 lb. The total water input to the lake, therefore, ranged by a factor of 2.4 and total phosphorus input ranged by a factor of 6.2. The residence time of water in the lake was 5.5 years in 2002, 7.2 years in 2003, 12.9 years during the dry years, and 6.5 years during the wet years.

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

Empirical eutrophication models that relate phosphorus loading to specific water-quality characteristics can be used to determine how natural and anthropogenic changes in phosphorus loading could modify the water quality of Silver Lake. These models were developed on the basis of comparisons of hydrologic and phosphorus loading determined for many kinds of lake systems with specific measures describing lake-water quality, such as near-surface phosphorus and chlorophyll *a* concentrations and Secchi depth (Reckhow and Chapra, 1983; Cooke and others, 1993; Panuska and Kreider, 2003). Most of the phosphorus models were derived from analyses of many lakes with widely differing phosphorus-loading rates and hydrologic conditions (for example, Vollenweider, 1975; and Canfield and Bachmann, 1981). Most empirical models that predict phosphorus concentrations are very sensitive to the residence time of water in the lake, and they are not capable of simulating water quality in closed-basin, terminal lakes—lakes without continuous outlets and therefore with relatively long residence times. One empirical model that has been shown by Robertson and Schladow (2008) to be relatively insensitive to residence time is the Canfield and Bachman (1981) natural-lake model. This model has also been shown to be one of the best empirical models for predicting the phosphorus concentrations of lakes in Wisconsin (Robertson and others, 2002, 2005; Robertson and Rose, 2008). Therefore, the Canfield and Bachman natural-lake model (1981; eq. 5) was applied to Silver Lake to determine how changes in phosphorus loading are expected to affect phosphorus concentrations in the lake:

$$\text{Total phosphorus concentration (micrograms per liter)} = \frac{L}{Z(1.62 \text{ x } (L/Z)^{0.458}+1/\tau)} \quad (5)$$

where L is the phosphorus-loading rate (in milligrams per square meter per year), Z is the mean depth of the lake (in meters), and τ is the residence time of the water in the lake (in years). In this application, the average of the annual hydrologic and phosphorus inputs measured in MY 2005 and MY 2006 were used as a base case for comparison with results from other scenarios.

The total phosphorus concentrations predicted with the Canfield and Bachman model were then used to predict chlorophyll *a* concentrations and Secchi depths through the use of Carlson's (1977) TSI equations (eqs. 1–3). In other words, the chlorophyll *a* concentrations and Secchi depths were computed that yielded a similar TSI value as that computed from the predicted total phosphorus concentration. There are no true calibration factors when Carlson's TSI equations are used to estimate chlorophyll *a* concentrations and Secchi depths; however, the output can be adjusted to account for model biases by adjusting the results by the percentage of bias in the results for a base scenario.

Modeling Approach

To estimate how the water quality of Silver Lake may respond to changes in phosphorus loading, 20 scenarios were simulated with the Canfield and Bachman model and Carlson TSI equations (table 6 and fig. 20). Scenario 1 simulated the average water-quality conditions for MY 2005 and MY 2006, which established a base or reference condition (concentration) for which results from the other simulations or scenarios can be compared. Nine scenarios (2–10) were used to determine the general response of the lake to basinwide changes in phosphorus loading: simulated decreases in controllable external phosphorus loading by 75, 50, and 25 percent and increases in controllable external phosphorus loading by 25, 50, 75, 100, 200, and 300 percent. Controllable external loading excludes phosphorus input from atmospheric deposition.

Four scenarios (11–14) were used to evaluate how well the model simulated water quality in specific years with high water and evaluate the importance of erosion. These scenarios simulated the conditions for 2002 and 2003, with and without phosphorus input from nearshore erosion.

Six scenarios were then used to determine how natural and anthropogenic changes in water level and associated changes in phosphorus loading may have modified or could modify the water quality of the lake. Two scenarios (15–16) were used to simulate the effects of natural (climatic) changes: following a series of three dry years and a series of three wet years (described earlier). Four scenarios (17–20) were simulated to determine how anthropogenic changes in the hydrology may affect water quality, which included diverting water to the lake during periods of low water levels and pumping water from the lake during periods of high water levels.

Table 6. Estimated water quality in Silver Lake, Barron County, Wis., in response to various phosphorus-loading scenarios based on the Canfield and Bachman natural-lake model (1981) and Carlson (1977) trophic-state-index equations.

[mg/L, milligrams per liter; µg/L, micrograms per liter]

Simulations	Scenario number	Annual phosphorus load (pounds)	Water elevation (feet)	Surface area (acres)	Mean depth (feet)	Residence time (years)[a]	Predicted total phosphorus concentration (mg/L)	Predicted chlorophyll *a* concentration (µg/L)	Predicted Secchi depth (feet)
General response									
Percent change in controllable load:									
- 75%	2	89	86.3	349	35.4	11.1	0.008	2.3	18.8
- 50%	3	132	86.3	349	35.4	11.1	.010	3.4	14.6
- 25%	4	174	86.3	349	35.4	11.1	.012	4.4	12.2
0% - Base or reference[b]	**1**	**216**	**86.3**	**349**	**35.4**	**11.1**	**.014**	**5.4**	**10.7**
+ 25%	5	258	86.3	349	35.4	11.1	.015	6.4	9.5
+ 50%	6	300	86.3	349	35.4	11.1	.017	7.3	8.7
+ 75%	7	342	86.3	349	35.4	11.1	.018	8.2	8.0
+ 100%	8	385	86.3	349	35.4	11.1	.020	9.1	7.4
+ 200%	9	553	86.3	349	35.4	11.1	.024	12.6	6.0
+300%	10	722	86.3	349	35.4	11.1	.029	16.0	5.1
Simulations of specific years with and without erosion									
2002–High-runoff year	11	749	89.7	367	36.9	5.5	.025	12.8	5.9
2002–Without erosion	12	655	89.7	367	36.9	5.5	.023	11.3	6.5
2003–High-runoff year	13	479	89.1	364	36.7	7.2	.020	9.2	7.4
2003–Without erosion	14	386	89.1	364	36.7	7.2	.017	7.5	8.5
Natural scenarios									
Series of dry years (3 years ending 1991)	15	90	81.4	312	34.4	12.9	.009	2.8	16.5
Series of wet years (3 years ending 2004)	16	557	88.2	360	36.2	6.5	.022	10.6	6.7
Anthropogenic-change scenarios									
Lower water elevation by 5 feet (compared to MY 2005)	17	137	82.2	317	34.6	12.5	.011	4.1	12.9
Lower elevation by 5 feet plus 2 feet from out of basin (full tributary 7 concentration)	18	530	84.2	333	35.0	7.4	.023	11.6	6.3
Lower elevation by 5 feet plus 2 feet from out of basin (Sylvan Lake concentration)	19	239	84.2	333	35.0	7.4	.014	5.5	10.5
Higher water elevation (2002), with 2 feet removed from the basin	20	654	87.7	358	35.9	5.2	.023	11.6	6.3

[a] Residence time is based on hydrologic conditions in monitoring year 2006, but with the specified water level.

[b] Scenario 1 established a base or reference condition for which results from other simulations or scenarios can be compared.

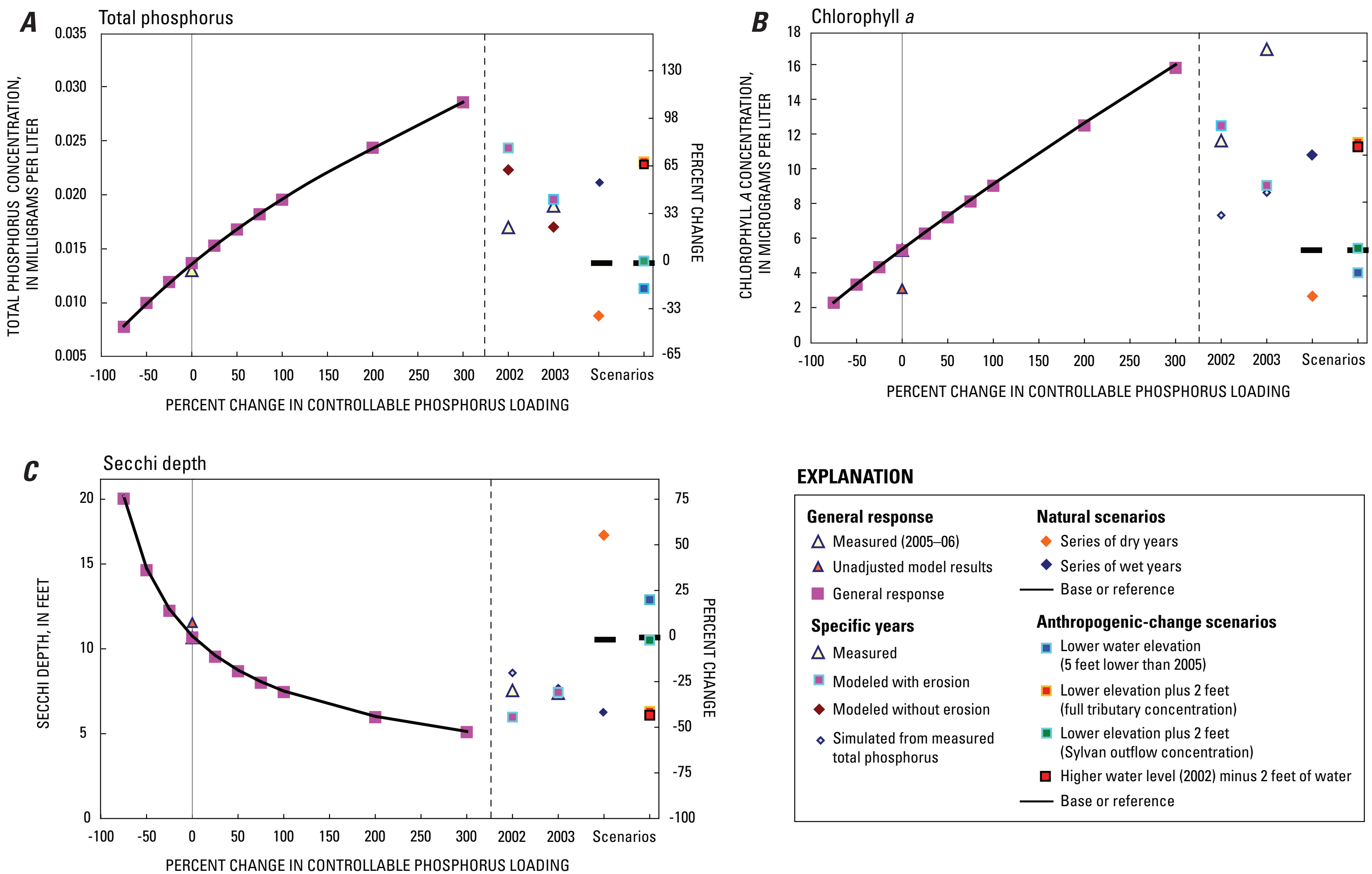


Figure 20. Measured and simulated average summer near-surface concentrations of *A*, total phosphorus, *B*, chlorophyll *a,* and C, Secchi depths in Silver Lake, Barron County, Wis., in response to various phosphorus-loading scenarios. Phosphorus concentrations were simulated with the Canfield and Bachman natural-lake model (1981), and chlorophyll *a* concentrations and Secchi depths were simulated with Carlson (1977) trophic state index equations. See table 6 for a description of each scenario.

Four types of data are required as input into the Canfield and Bachman model (eq. 5): water-quality data in table 3, and morphometric data (mean depth), hydrologic data (residence time), and nutrient-loading data in table 6. Although loading data are summarized for the entire year, this model and the Carlson TSI equations simulate water quality only for the growing season (May through September); therefore, the water-quality data in table 3 were used for comparison with model results.

Verification and Adjustments for Model Biases

The capability of the Canfield and Bachman (1981) model at simulating phosphorus concentrations in this closed-basin terminal lake was evaluated by inputting the morphometry of the lake and the average hydrologic and phosphorus inputs for MY 2005 and MY 2006 into the model (eq. 5) and simulating the near-surface total phosphorus concentration. The simulated total phosphorus concentration (0.014 mg/L; fig. 20*A*; and scenario 1 in table 6) is similar to the average of that measured in the lake during these years (0.013 mg/L; table 3). This similarity confirms that the model is expected to accurately simulate changes in Silver Lake in response to changes in phosphorus loading.

Determining how well the Carlson (1977) TSI equations simulate chlorophyll *a* concentrations and Secchi depths in Silver Lake was accomplished by using the TSI value based on the simulated total phosphorus concentration to compute the chlorophyll *a* concentration and Secchi depth in the lake with equations 2 and 3. Given a TSI value of 41.9 (from eq. 1 with the simulated phosphorus concentration of 0.014 mg/L), the unadjusted modeled chlorophyll *a* concentration was 3.15 µg/L and Secchi depth was 11.5 ft (fig. 20*B* and 20*C*). The unadjusted modeled chlorophyll *a* concentration was 41 percent lower than that measured (5.4 µg/L). The unadjusted modeled Secchi depth was 8 percent higher than that measured (10.7 ft). These discrepancies indicate that the measured chlorophyll *a* concentrations and Secchi depths in Silver Lake are slightly worse than would be expected given the phosphorus concentration measured in the lake. Because of the discrepancies in measured and simulated chlorophyll *a* concentrations and Secchi depths, all of the simulated chlorophyll *a* concentrations from equation 2 were increased by 41 percent, and Secchi-depth values from equation 3 were decreased by 8 percent.

Response in Water Quality to Basinwide Changes in Phosphorus Loading

On the basis of model simulations for basinwide changes in controllable phosphorus loading (scenarios 1–10), phosphorus concentrations in the lake should have a curvilinear response to a linear change in loading, with a larger response to reductions in phosphorus loading than to increases in phosphorus loading (fig. 20*A*; table 6). Changes in in-lake phosphorus concentrations are about 40–50 percent of the changes in phosphorus loading. For example, a 50-percent increase in controllable external phosphorus loading causes a 23-percent increase in in-lake phosphorus concentrations.

Simulated summer average chlorophyll *a* concentrations responded linearly to changes in controllable external phosphorus loading (fig. 20*B*). The changes in chlorophyll *a* concentrations, on a percentage basis, are smaller than the changes in external phosphorus loadings. For example, a 50-percent change in controllable external phosphorus loading causes about a 35-percent change in chlorophyll *a* concentrations.

Simulated summer average Secchi depths also showed a curvilinear response to changes in controllable external phosphorus loading and responded slightly more strongly to reductions in loading than to increases in loading (fig. 20*C*). The changes in Secchi depths, on a percentage basis, were smaller than the changes in external phosphorus loadings. For example, a 50-percent increase in controllable external phosphorus loading causes about a 20-percent reduction in Secchi depths.

The relatively small response in each of the TSI variables to changes in controllable phosphorus loading is partly because some of the phosphorus that is presently input into Silver Lake is from uncontrollable sources, not that Silver Lake is unresponsive to external loading. In fact, a 100-percent increase in controllable phosphorus loading increases the total phosphorus load by 78 percent (from 216 lb for the base case to 385 lb) and increases the total phosphorus concentrations in the lake by 43 percent, increases chlorophyll *a* concentrations by 69 percent, and decreases Secchi depths by 30 percent. Therefore, changes in phosphorus loading may have a large impact on the water quality of Silver Lake.

Model Validation and Sensitivity of Lake-Water Quality to Phosphorus Inputs from Erosion

The eutrophication models were used to simulate the conditions during 2002 and 2003 to determine how well these models predict changes during different hydrologic conditions (scenarios 11 and 13). In 2002, the water level of the lake had just reached its maximum (fig. 7), and nutrient input was expected to be near its highest level. In 2003, water levels of the lake were just beginning to drop, and nutrient input had been high for a few years. Shoreline erosion was expected to occur in both years. During both years, only a few chlorophyll *a* samples were collected early in the year, when concentrations are typically lower than in late summer; therefore, the average of the measured chlorophyll *a* concentrations may result in a summer average that is biased high.

The simulated total phosphorus concentration for 2002 (scenario 11, 0.025 mg/L; fig. 20*A* and table 6) was higher than that measured in the lake (0.017 mg/L; table 3). This discrepancy may have been caused by the lake not being in equilibrium with the inputs from the watershed. Researchers have found that higher phosphorus concentrations in a lake occur after several years of high inputs from the watershed, rather than after a single year of high inputs (Lathrop and others, 1998). The simulated and measured total phosphorus concentrations for 2002 were then used to predict the average chlorophyll *a* concentration and Secchi depth. On the basis of the TSI values computed from the simulated (scenario 11) and measured phosphorus concentrations, the predicted chlorophyll *a* concentrations in the lake from equation 2 were 12.8 µg/L and 7.4 µg/L, respectively, whereas the measured concentration in the lake was 11.8 µg/L. Although the simulated phosphorus concentration appears to have more acccurately predicted the chlorophyll *a* concentrations in the lake than the measured phosphorus concentration, it is believed that the computed summer average chlorophyll *a* concentration is biased high and the actual summer average concentration was probably closer to that predicted from the measured phosphorus concentration. On the basis of the simulated and measured phosphorus concentrations, the summer average Secchi depths in the lake computed from equation 3 were 5.9 ft and 8.6 ft, respectively, whereas the measured value in the lake was 7.5 ft. Therefore, the Secchi depth in 2002 was predicted slightly better with the actual measured phosphorus concentration than with the predicted phosphorus concentration.

The simulated total phosphorus concentration for 2003 (scenario 13, 0.020 mg/L; fig. 20*A* and table 6) was similar to that measured in the lake (0.019 mg/L; table 3). This similarity may indicate that by 2003, after a few years with high phosphorus inputs, the lake was now in equilibrium with the inputs from the watershed. The simulated and measured total phosphorus concentrations for 2003 were then used to predict average chlorophyll *a* concentration and Secchi depth in the lake. On the basis of both concentrations, the chlorophyll *a* concentration in the lake (predicted to be 9.2 and 7.4 µg/L, respectively) should have been lower than the summer average based on measurements in the lake (11.8 µg/L). Once again, the summer average chlorophyll *a* concentration based on measurements was believed to be biased high and the actual summer average concentration in the lake may have been closer to that estimated by the model (9.2 µg/L). On the basis of the simulated and measured phosphorus concentrations, the predicted summer average Secchi depth in the lake was 7.4 ft, similar to that measured in the lake. Therefore, the models seem to do well at predicting phosphorus, chlorophyll *a*, and Secchi depth after a series of years of higher loading and higher water levels.

The models were then used to determine the importance of the additional phosphorus from shoreline erosion on the water quality of the lake (scenarios 11–14, table 6). This was done by reducing the nutrient loading in 2002 and 2003 by the amount estimated to have been contributed by erosion (93 lb). In both years, removing the phosphorus input from erosion resulted in predicted summer average total phosphorus concentrations being reduced by about 0.002–0.003 mg/L, chlorophyll *a* concentrations being reduced by about 1.5–1.7 µg/L, and Secchi depth increasing by about 0.6–1.1 ft. Therefore, phosphorus input from erosion has a measurable affect on water quality.

Response in Water Quality to Specific Natural and Anthropogenic-Change Scenarios

The Canfield and Bachman model (eq. 5) was then used to predict how total phosphorus concentrations in Silver Lake should respond to several natural and anthropogenic changes that would affect the water level of the lake. This was done by modifying the annual phosphorus loadings, morphometry, and residence time of water in the lake (scenarios 15–20; table 6).

In simulating the conditions during 2002 and 2003, the models were shown to accurately simulate the water quality in Silver Lake after a few years of sustained high water levels and high inputs, when the lake has come into equilibrium with its inputs from the watershed. Scenarios 15 and 16 were used to determine how a wide range in natural changes (changes in lake level resulting from a series of three years of below- or above-normal precipitation and inflow) should affect the water quality of the lake (fig. 20; table 6). Sustained low water levels (scenario 15, with a water level 5.8 ft lower than in fig. 1) and low phosphorus inputs, caused by a series of dry years with below-normal precipitation, should improve the water quality of the lake. The reduction in phosphorus loading resulted in phosphorus concentrations decreasing to 0.009 mg/L, chlorophyll *a* concentrations decreasing to 2.8 µg/L, and Secchi depths increasing to 16.5 ft. Sustained high water levels (scenario 16, with a water level 1.0 ft higher than in fig. 1 and similar to that in 2004) and increased inflow and phosphorus inputs, caused by a series of wet years with above-normal precipitation, increased the phosphorus concentrations to 0.022 mg/L, increased chlorophyll *a* concentrations to 10.6 µg/L, and decreased Secchi depths to 6.7 ft. Therefore, natural changes in precipitation and inflow can have a large affect on the water quality of Silver Lake.

Four scenarios were then performed to simulate the effects of adding water to the lake during relatively dry years and removing water from the lake during relatively wet years (scenarios 17–20). Scenarios 17–19 were used to determine the effects of diverting water into the lake during relatively dry years when the water level had been lowered by reduced precipitation and inflow. To do this, first the water quality of the lake was simulated with a water level being 5 ft less than the full level of the lake (fig. 1; about 5 ft less than in 2005). The hydrology and tributary input were assumed to be similar to that in 2006 (a relatively dry year); however, the atmospheric input was reduced from 2006 because of the smaller surface area of the lake. The results of the simulation indicate that the water quality in the lake should improve during this low water-level condition compared to the base or reference condition (the average of that measured in MY 2005 and MY 2006): average total phosphorus concentration of 0.011 mg/L, chlorophyll *a* concentration of 4.1 µg/L, and Secchi depth of 12.9 ft (scenario 17, table 6 and fig. 20). If 2 ft of water (672 acre-ft) were then added to the lake from outside the natural Silver Lake watershed at a total phosphorus concentration of 0.215 mg/L (the average concentration in tributary 7 during MY 2005 and MY 2006), the water quality of the lake should degrade: the summer average total phosphorus concentration should increase to 0.023 mg/L, chlorophyll *a* concentration should increase to 11.6 µg/L, and Secchi depth should decrease to 6.3 ft. If, however, the additional 2 ft of water (672 acre-ft) could be delivered to the lake at an average concentration similar to that leaving Sylvan Lake (0.055 mg/L; scenario 19), the water quality in the lake should be similar to the average of the conditions in MY 2005 and MY 2006: average summer total phosphorus concentration of 0.014 mg/L, chlorophyll *a* concentration of 5.5 µg/L, and Secchi depth of 10.5 ft.

A comparison among three scenarios was used to evaluate the effects of removing water from the lake during relatively wet years when the water levels are high because of increased precipitation and runoff. To do this, the results from the previous simulation of 2002 (scenarios 11 and 12, a very wet year with and without erosion) are compared with those from when the water level of the lake in 2002 was reduced 2 ft (scenario 20). In scenario 20, the hydrology and tributary input were assumed to be similar to that in 2002; however, 2 ft of water (726 acre-ft) were assumed to be pumped from the surface of the lake. Because 2 ft of water were removed from the lake, the surface area was reduced to that for an elevation of 87.7 ft and, therefore, atmospheric inputs were reduced because of the smaller surface area of the lake. Water quality in the lake during this lowered-water-level condition was slightly better than that predicted for 2002 when the input of phosphorus from erosion was included, but similar to that estimated for 2002 when erosion was not included in the simulation. Therefore, the primary benefit to water quality of lowering the water level of the lake is to remove the phosphorus input from shoreline erosion.

TSI values, based on near-surface concentrations of total phosphorus and chlorophyll *a* and on Secchi depths, indicate that Silver Lake is typically oligotrophic to mesotrophic; however, increases in phosphorus loading during periods of high precipitation, high inflow, and high water levels can degrade water quality (fig. 6). Results of model simulations indicate that increasing the input of water from the watershed (such as from tributary 7) can also have detrimental affects on the water quality of the lake unless the phosphorus concentrations in this water can be maintained at a relatively low concentration. During periods of high natural water inputs or diversion of water through the wetland system north of Silver Lake (if this were done), the increased input of phosphorus may result in eutrophic conditions in Silver Lake.

Relative Importance of Anthropogenic Changes in the Watershed to Natural Hydrologic Changes

One purpose of this study was to evaluate how natural changes in hydrology, water level, and phosphorus inputs affect the water quality of Silver Lake in comparison with water-quality effects caused by anthropogenic changes in the watershed. Model results indicate that most of the measured deterioration in water quality between 2002 and 2004 was caused by the large increase in phosphorus input to the lake that occurred during the sustained high water levels. After an extended period of high inflow and increased water levels, measured phosphorus concentrations increased by at least 0.010 mg/L, water clarity decreased by about 8 ft, and chlorophyll *a* concentrations increased. Because of the limited monitoring program during 2002–4, quantifying the increase in chlorophyll *a* concentrations is difficult. The decreased water quality measured in 2003 was similar to that predicted with the eutrophication models; therefore, the models appear to accurately estimate changes in water quality after several years of high or low phosphorus inputs. The increased input of water and phosphorus from the diversion of water leaving Sylvan Lake into Silver Lake and the increased input of phosphorus from shoreline erosion that accounted for about 13–20 percent of the total phosphorus input collectively contributed to the poor water quality during the very high water levels.

The improvements in water quality since water levels began to drop in 2003 (fig. 4) also indicate that most of the deterioration in the water quality of Silver Lake during 2002–4 was caused by the increase in water and phosphorus input into the lake from the watershed and by shoreline erosion caused by the higher water levels. Although the degradation in water quality appears to be associated primarily with increased inflow and high water levels, the lake is still susceptible to degradation associated with changes in its watershed. The estimated annual yields of phosphorus from the watershed are quite low (25.0–130 lb/mi^2); however, future land development that does not consider mitigation of nutrients in runoff could increase these yields.

Before the 1960s, the watershed around Silver Lake was different than it is now in the 2000s. Much of the area immediately adjacent to the lake in 1940s and 1950s was agricultural. About 25 dairy cows were pastured immediately adjacent to the lake, and about 40–50 beef cows were pastured close to the lake (Edward Jacobson, local resident, oral commun., 2008). If one dairy cow produces about 45 to 48 lb of phosphorus annually (Hollman and others, 2008; Hermanson and Kalita, 1994) and one beef cow produces 26 lb (Hermanson and Kalita, 1994), then an additional 2,300 lb of phosphorus may have been input to the watershed annually during that time (equivalent to about 1,500 people living near the lake). If only 10 percent of this phosphorus reached the lake, then the total amount of phosphorus input to the lake (446 lb) would be about twice that estimated in MY 2005 and MY 2006 (216 lb). From model results in table 6 and fig. 20 (this input would be similar to an increase in controllable phosphorus of about 150 percent), the average phosphorus concentration in the lake would likely have been about 0.022 mg/L, and the water clarity would likely have been about 7 ft. Therefore, during the 1940s and 1950s, the lake may have been typically classified as borderline mesotrophic to eutrophic and possibly classified as moderately eutrophic during wet years with high water levels, such as around 1945 and 1954 when water levels were estimated to be quite high (fig. 7).

Given the results from General Circulation Models, many scientists believe that climate change will cause systematic decreases or increases in the hydrologic budgets and water levels of lakes or cause water levels to fluctuate more widely than they have previously, in response to larger fluctuations in precipitation and runoff (Mulholland and Sale, 1998; Bates and others, 2008). This study has shown that previous natural changes in the water and phosphorus input to this terminal lake from a series of dry years to a series of wet years has ranged by factors of 2.5 and 6, respectively. These changes in hydrology and phosphorus loading, alone, were sufficient to cause the lake to change from being classified as oligotrophic to mesotrophic during very dry conditions to borderline mesotrophic to eutrophic during very wet conditions. In many lakes, changes in nutrient inputs of this magnitude may be expected only from anthropogenic changes to the watershed; however, because of the unique hydrology and land use in Silver Lake's watershed, changes in phosphorus loading associated with natural variability in precipitation are very large. The changes in phosphorus input from a series of dry years to a series of wet years may be of similar magnitude to the additional loading from agriculture in the watershed in the 1940s and 1950s. The natural variability in loading, however, is currently larger than the phosphorus input from controllable sources in the watershed. Therefore, variability in precipitation patterns has affected the trophic state of Silver Lake in the past, and climatic change may have a large influence on its trophic state in the future.

Summary and Conclusions

Silver Lake is typically a mesotrophic-to-oligotrophic, soft-water, terminal lake in northwestern Wisconsin. Data collected as part of the ongoing monitoring program by the local community demonstrated that the water quality of the lake had degraded during 2002–4 (increased phosphorus and chlorophyll *a* concentrations). The decrease in water quality coincided with very high water levels in the lake. To gain a better understanding of what may have caused the apparent degradation in water quality and, therefore, provide information for management of the lake should development increase or the climate change, the USGS did a detailed study during 2004–8. The goals of this study were to describe past and present lake-water quality, describe changes in the water level in the lake since 1900, construct water and phosphorus budgets for the lake, simulate the potential effects of changes in water and phosphorus inputs on lake-water quality, and compare the relative importance of natural changes in phosphorus inputs and water level and anthropogenic changes in the watershed to lake-water quality.

After about 1996, summer average total phosphorus concentrations increased from about 0.008 mg/L to about 0.018 mg/L in 2003, before decreasing to about 0.010 mg/L in 2007–8. From 1996 to 2003, Secchi depths decreased from about 14 ft to about 7.5 ft before increasing to about 12–19 ft in 2007–8. Therefore, Silver Lake would typically be classified as mesotrophic to oligotrophic; however, during 2002–4, the lake approached being classified as mesotrophic to eutrophic.

Reconstructed water levels of Silver Lake indicated that the measured changes in water level since 1967 are representative of fluctuations that have occurred since 1900; however, the most extreme fluctuation occurred between about 1989 and 2002. Fluctuations in water levels of about 4–10 ft have occurred about every 15 years.

Because the productivity in Silver Lake should be limited by phosphorus, it should be the nutrient of concern when management efforts to improve or prevent degradation in the lake-water quality are considered. Most phosphorus enters the lake with water inputs; therefore, both water and phosphorus budgets were constructed as part of the study. Precipitation and surface-water inflow were the predominant sources of water; precipitation and surface-water inflow contributed about 70 and 30 percent, respectively. Before this study, groundwater was believed also to be a major source of water and phosphorus to the lake; however, results of this study indicate that Silver Lake is hydraulically mounded above the water table and that groundwater does not enter the lake. The average annual load of phosphorus to the lake during the two monitoring years was 216 lb, of which 169 lb came from tributary and nearshore areas (78 percent) and 47 lb (22 percent) came from atmospheric deposition. Because Silver Lake is hydraulically mounded above the water table, there is no input of phosphorus from groundwater and septic systems. To determine how the hydrologic and phosphorus loading to the lake has varied in association with fluctuations in water level, water and phosphorus budgets were constructed for a series of dry years (low water levels) and during a series of wet years (high water levels). The total water input to the lake ranged by a factor of about 2, and total phosphorus input to the lake ranged by a factor of about 6.

Results from the Canfield and Bachman eutrophication model and Carlson TSI equations demonstrated that changes in controllable phosphorus loading have curvilinear relations with phosphorus concentrations and Secchi depths in the lake. A larger change in phosphorus concentrations and Secchi depths was simulated with decreases in phosphorus loading than with increases in loading. The relation between changes in phosphorus loading and changes in chlorophyll *a* concentrations was linear. The changes in water quality were less than the changes in phosphorus inputs, however, on a percentage basis. For example, a 50-percent increase in controllable external phosphorus loading should cause about a 23-percent increase in total phosphorus concentrations, a 35-percent increase in chlorophyll *a* concentrations, and a 20-percent reduction in Secchi depths. Part of the reason for the relatively small response was caused by part of the phosphorus input coming from uncontrollable sources (atmospheric deposition), not because the lake is unresponsive to external loading. For example, a 78-percent increase in total phosphorus input should cause phosphorus concentrations in the lake to increase by 43 percent, chlorophyll *a* concentrations to increase by 69 percent, and Secchi depths to decrease by 30 percent. Therefore, changes in phosphorus loading may have a large impact on the water quality of Silver Lake.

Specific scenarios were used to simulate the effects of natural climatic and anthropogenic changes on lake-water quality. Sustained low water levels caused by a series of dry years with low precipitation and low inflow improved the water quality of the lake, whereas sustained high water levels caused by a series of wet years with more precipitation and increased inflow dramatically degraded the water quality of the lake. Therefore, natural changes in the input of phosphorus from precipitation and inflows to the lake can have a large effect on lake-water quality. Additional scenarios showed that the degraded water quality during periods with very high water level was partly caused by the phosphorus input from shoreline erosion. Diverting water into the lake during periods with low water levels could measurably degrade the water quality unless a strategy can be found to import water with low phosphorus concentrations, whereas withdrawing water during periods of high water levels should slightly improve the lake-water quality because of the reduction in phosphorus input from shoreline erosion. During periods of high natural water inputs, possibly accentuated by water diverted through the wetland system north of Silver Lake, high inputs of phosphorus can result in eutrophic conditions in Silver Lake.

Water levels have fluctuated by as much as 10 ft during several wet/dry cycles since 1900. During periods of high phosphorus input associated with very high water levels, results from the eutrophication models indicated that lake-water quality should degrade (to mesotrophic-to-eutrophic conditions); during periods with low phosphorus input and low water levels, however, lake-water quality should improve (to oligotrophic-to-mesotrophic conditions). During the 1940s and 1950s, because of likely agricultural inputs from the watershed, the lake may have been typically classified as borderline mesotrophic to eutrophic and possibly classified as moderately eutrophic during wet years with high runoff, especially around 1945 and 1954 when water levels were likely to have been very high.

Silver Lake is typically classified as oligotrophic to mesotrophic because of the small input of phosphorus from its watershed. Natural changes in the water and phosphorus input to this terminal lake, however, were sufficient to cause the lake to change from being classified as oligotrophic to mesotrophic during very dry conditions to borderline mesotrophic to eutrophic during very wet conditions. In many lakes, changes in nutrient inputs of this magnitude are expected only from anthropogenic changes to the watershed; however, because of the unique hydrology and land use in Silver Lake's watershed, the natural variability in loading is currently larger than the phosphorus input from controllable sources in the watershed. Therefore, variability in precipitation patterns has affected the trophic state of Silver Lake in the past, and climatic change may have a large influence on its trophic state in the future. Although the degradation in lake-water quality appears to be caused primarily by high inflow and high water levels, the lake is still susceptible to degradation associated with small changes in its watershed. Because of the limited phosphorus that is presently input into the lake, increases in phosphorus loading could have a large effect on the lake-water quality. Therefore, management actions to minimize future phosphorus input to this lake are likely to greatly benefit water quality.

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