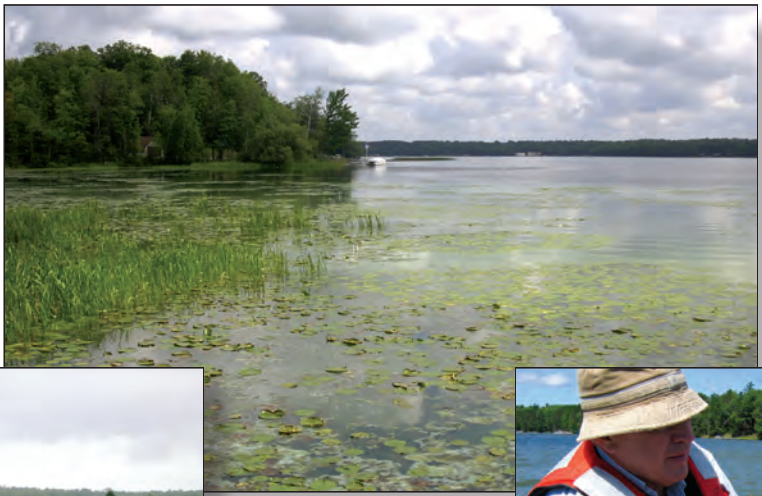
In Cooperation with Price County Land Conservation Committee

Water Quality, Hydrology, and Simulated Response to Changes in Phosphorus Loading of Butternut Lake, Price and Ashland Counties, Wisconsin, with Special Emphasis on the Effects of Internal Phosphorus Loading in a Polymictic Lake



Scientific Investigations Report 2008–5053

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

Water Quality, Hydrology, and Simulated Response to Changes in Phosphorus Loading of Butternut Lake, Price and Ashland Counties, Wisconsin, with Special Emphasis on the Effects of Internal Phosphorus Loading in a Polymictic Lake

By Dale M. Robertson and William J. Rose

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Conversion Factors

Multiply	By	To obtain
	Length	
micrometer (µm)	0.00003937	inch (in.)
centimeter (cm)	.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	2.471	acre
hectare (ha)	.003861	square mile (mi^2)
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
cubic centimeter (cm^3)	.06102	cubic inch (in^3)
cubic meter (m^3)	.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)
	Application Rate	
kilogram per square kilometer (kg/km^2)	5.7099	pound per square mile (lb/mi^2)
kilogram per square kilometer (kg/km^2)	.00892	pound per acre (lb/ac)
milligrams per square meter (mg/m^2)	.000000205	pounds per square foot (lb/ft^2)

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).

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Technical Reviewers

Herbert S. Garn, Assistant Center Director, U.S. Geological Survey, Middleton, Wis.

James Kreitlow, Water Resources Management Specialist, Wisconsin Department of Natural Resources, Rhinelander, Wis.

Chet Zenone, Hydrologist (retired), U.S. Geological Survey, Salem, Ore.

Local Project Coordinators

Robert “Butch” D. Lobermeier, County Conservationist, Price County Land and Water Conservation Department, Phillips, Wis.

Diane Daulton, County Conservationist, Price County Land and Water Conservation Department, Phillips, Wis.

Editorial and Graphics

Elizabeth A. Ciganovich, Technical Editor, U.S. Geological Survey Columbus Publishing Service Center, Ohio

Jennifer L. Bruce, Geographer, U.S. Geological Survey, Middleton, Wis.

Michelle M. Greenwood, Reports Specialist, U.S. Geological Survey, Middleton, Wis.

James L. Kennedy, Geographer, U.S. Geological Survey, Middleton, Wis.

Data Collection

Josef G. Schuler, Hydrologic Technician, U.S. Geological Survey, Rice Lake, Wis.

Approving Official

Dorothy Tepper, Bureau Reports Approving Official, Eastern Region, U.S. Geological Survey, Reston, Va.

Water Quality, Hydrology, and Simulated Response to Changes in Phosphorus Loading of Butternut Lake, Price and Ashland Counties, Wisconsin, with Special Emphasis on the Effects of Internal Phosphorus Loading in a Polymictic Lake

By Dale M. Robertson and William J. Rose

Abstract

Butternut Lake is a 393-hectare, eutrophic to hypereutrophic lake in northcentral Wisconsin. After only minor improvements in water quality were observed following several actions taken to reduce the nutrient inputs to the lake, a detailed study was conducted from 2002 to 2007 by the U.S. Geological Survey to better understand how the lake functions. The goals of this study were to describe the water quality and hydrology of the lake, quantify external and internal sources of phosphorus, and determine the effects of past and future changes in phosphorus inputs on the water quality of the lake.

Since the early 1970s, the water quality of Butternut Lake has changed little in response to nutrient reductions from the watershed. The largest changes were in near-surface total phosphorus concentrations: August concentrations decreased from about 0.09 milligrams per liter (mg/L) to about 0.05 mg/L, but average summer concentrations decreased only from about 0.055–0.060 mg/L to about 0.045 mg/L. Since the early 1970s, only small changes were observed in chlorophyll *a* concentrations and water clarity (Secchi depths).

All major water and phosphorus sources, including the internal release of phosphorus from the sediments (internal loading), were measured directly, and minor sources were estimated to construct detailed water and phosphorus budgets for the lake during monitoring years (MY) 2003 and 2004. During these years, Butternut Creek, Spiller Creek, direct precipitation, small tributaries and near-lake drainage area, and ground water contributed about 62, 20, 8, 7, and 3 percent of the inflow, respectively. The average annual load of phosphorus to the lake was 2,540 kilograms (kg), of which 1,590 kg came from external sources (63 percent) and 945 kg came from the sediments in the lake (37 percent). Of the total external sources, Butternut Creek, Spiller Creek, small tributaries and near-lake drainage area, septic systems, precipitation, and ground water contributed about 63, 23, 9, 3, 1, and 1 percent, respectively.

Because of the high internal phosphorus loading, the eutrophication models used in this study were unable to simulate the observed water-quality characteristics in the lake without incorporating this source of phosphorus. However, when internal loading of phosphorus was added to the BATHTUB model, it accurately simulated the average water-quality characteristics measured in MY 2003 and 2004. Model simulations demonstrated a relatively linear response between in-lake total phosphorus concentrations and external phosphorus loading; however, the changes in concentrations were smaller than the changes in external phosphorus loadings (about 25–40 percent of the change in phosphorus loading). Changes in chlorophyll *a* concentrations, the percentage of days with algal blooms, and Secchi depths were nonlinear and had a greater response to reductions in phosphorus loading than to increases in phosphorus loading. A 50-percent reduction in external phosphorus loading caused an 18-percent decrease in chlorophyll *a* concentrations, a 41-percent decrease in the percentage of days with algal blooms, and a 12-percent increase in Secchi depth. When the additional internal phosphorus loading was removed from model simulations, all of these constituents showed a much greater response to changes in external phosphorus loading.

Because of Butternut Lake's morphometry, it is polymictic, which means it mixes frequently and does not develop stable thermal stratification throughout the summer. This characteristic makes it more vulnerable than dimictic lakes, which mix in spring and fall and develop stable thermal stratification during summer, to the high internal phosphorus loading that

has resulted from historically high, nonnatural, external phosphorus loading. In polymictic lakes, the phosphorus released from the sediments is mixed into the upper part of the lake throughout summer. Once Butternut Lake became hypereutrophic (very productive), it became very difficult to alter its trophic state through reductions in external phosphorus loading because the high internal loading does not respond quickly to reductions in external nutrient loading. For Butternut Lake to become significantly less productive (change to a borderline mesotrophic/eutrophic state) a combined approach to reduce or eliminate internal phosphorus loading and reduce the external phosphorus loading by about 50 percent is needed.

Introduction

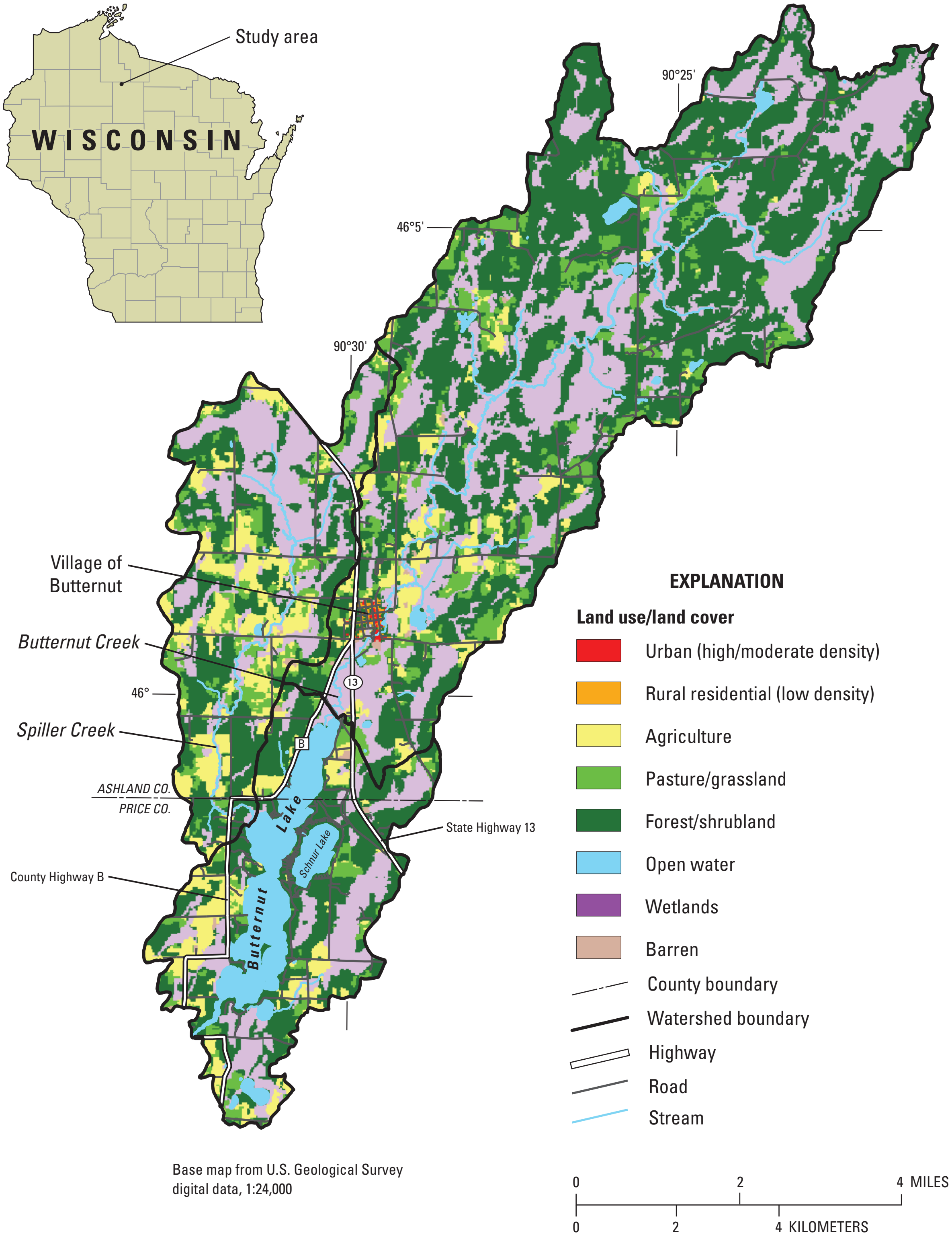
Butternut Lake is a relatively shallow, 393-ha lake in the Northern Lake and Forests ecoregion of northcentral Wisconsin (Omernik and others, 2000). The lake is about 5 km northwest of Park Falls, which is between the popular recreational areas near Hayward and Minocqua in northern Wisconsin. The lake is an important water resource in southern Ashland and northern Price counties (fig. 1), and it is popular for fishing and swimming.

Prior to about 1860, Butternut Lake was relatively pristine, and its watershed was populated by only a small band of Chippewa Indians who lived along the lake and its tributaries (Scott, 2005). However, with logging activities that began in the area in the mid to late 1800s and with construction of the railway through the area in the late 1870s, changes in many activities and land use affected the amount of nutrients input to the lake (table 1). In the 1870s, agricultural activities began in the watershed, and the Village of Butternut was established. Along with increased development in the watershed came additional nutrients from a sewage-treatment facility, a creamery, and two cheese factories. It is believed that nutrient input from the watershed peaked in the 1960s, when there were inputs from extensive agricultural activities in the watershed (including a barnyard with cattle immediately adjacent to the lake), from untreated effluent from the municipal-waste system, a creamery, and two cheese factories that released nutrients directly into Butternut Creek, and from deficient or poorly functioning septic systems that released effluent into nearshore areas around the lake. As a result of the high input of nutrients, the water quality of Butternut Lake degraded and extensive algal blooms were common. Massive algal blooms were reported in the 1960s and early 1970s (McKersie, and others, 1970; R. Jasinski, Wisconsin Department of Natural Resources, written commun., 1982).

In recent decades, area residents and authorities near Butternut Lake implemented several measures to improve the lake's water quality, which they felt had become degraded because of nutrient inputs from the watershed. Most of the intense agricultural activities were discontinued between the 1960s and 1980s, the creamery and cheese factories in the watershed were closed in the 1970s, and in 1983 sewage effluent from the Village of Butternut was directed to an on-land infiltration site that drains away from Butternut Creek (table 1). In addition, implementation and enforcement of a zoning ordinance that regulated septic systems likely has eliminated or significantly reduced the amount of nutrients from these sources. As a result of all of these measures, by the early 1980s, the number and intensity of algal blooms decreased from those during the 1960s and early 1970s, while the amount of macrophyte growth increased (R. Jasinski, written commun., 1982). The water quality of the lake, however, was still believed to be degraded compared to natural, presettlement conditions.

As of the early 2000s, the lake was still very productive, with occasional algal blooms and extensive macrophyte growth. Lake-area residents, lake users, and Price County officials would like to implement additional management or restoration efforts to return the lake to a more natural state. Recycling of phosphorus from bottom sediments (referred to as internal loading) rather than excessive inputs from external sources is now believed to be the cause of the continued poor water quality (R. Jasinski, written commun., 1982). Quantitative information, however, was not available to evaluate the significance of the various sources of phosphorus as a percentage of the total input to the lake. To aid future management decisions and development of a lake-management plan, a better understanding of the lakes's hydrology, phosphorus input by specific source, and the importance of the internal recycling of phosphorus from the lake's sediments is needed. In addition, information on the likely response of the lake to incremental increases or decreases in phosphorus loading would be useful for determining practices or actions to help restore the lake.

To provide a better understanding of the factors that affect the water quality of Butternut Lake, a detailed study of the lake and its watershed was begun in 2002 by the U.S. Geological Survey (USGS) in cooperation with the Price County Land Conservation Committee and the Wisconsin Department of Natural Resources (WDNR). The WDNR provided partial funding for this study through the



Base map from U.S. Geological Survey digital data, 1:24,000

Figure 1. Watershed of Butternut Lake, Price and Ashland Counties, Wis. Land use/land cover from the WISCLAND geographic information system coverage (Wisconsin Department of Natural Resources, 1998).

Table 1. Summary of activities affecting the loading of nutrients into Butternut Lake, Price and Ashland Counties, Wis.

[ha, hectare; m^3/d, cubic meter per day; mg/L, milligram per liter]

Year or period	Activity	Source
1860s	Logging activity documented in the Butternut watershed.	1
1870s	Farming in the Butternut watershed began.	1
1870s	Village of Butternut established.	1
1878	Rail service to Butternut established.	1
1879	1.2-ha reservoir constructed on Butternut Creek for grist mill operation.	1
1895	First creamery built in Butternut and effluent discharge to Butternut Creek.	1
1893–1902	Charcoal manufacturing industry in operation.	1
1902	Village of Butternut incorporated.	1
1900–1964	Various wood-products factories dominated industries in the area.	1
1910	Population of Butternut was 717.	5
1920s	Logging activity diminished.	1
1938	Waterworks and sewer system installed in Butternut.	1
1938–early 1970s	Relatively untreated municipal waste and creamery wastes discharged directly into Butternut Creek.	2
1938–early 1970s	Municipal-waste system consisted of a primary tank with effluent going into Butternut Creek.	3
Mid 1900s	Fluid wastes from paper mill dumped on farm fields as a fertilizer and on roads to settle dust.	4
1940–1950	Population of Butternut dropped from 669 to 522.	5
Before 1960	Deficient septic systems existed along lake.	2
1960s–1980s	Agricultural activity began to decline. Agriculture changed from dairying, to beef, to cropping, with some land going out of production.	4
1976	Dairying at farm on west shore of lake converted to beef farming.	4
1986	Beef farming at farm on west shore of lake ceased.	4
1960–1982	Deficient septic systems around the lake were improved.	2
1970s	Creamery closed operation. During last few years of operation, effluent dumped into ridge-and-furrow system on land.	3
Early 1970s–1983	Three-pond sewage treatment with effluent discharged (227–273 m^3/d at 2–5 mg/L) into Butternut Creek during open-water season.	3
1983	Effluent from three-pond municipal system directed to on-land-infiltration site away from Butternut Creek.	3
2000	Population of Butternut was 407.	5

Sources:
1. Scott, R., 2005, The written history of Butternut, Wisconsin, based on oral history of townspeople and an essay by Ruth Gear.
2. Jasinski, R., Wisconsin Department of Natural Resources, written commun., 1982.
3. Olson, C., Wisconsin Department of Natural Resources, oral commun., 2007.
4. Szymik, F., Butternut citizen, oral commun., 2007.
5. Wells, P., Wisconsin Department of Administration, Madison, written commun. 2007.

Lake Protection Grant program. The study had the following objectives:

- Describe the water quality of the lake.
- Define the hydrology of the lake.
- Quantify the external sources of phosphorus to the lake.
- Quantify the release of phosphorus from the lake sediment, and determine its relative importance to the phosphorus budget of the lake.
- Assess how the water quality of the lake should respond to changes in phosphorus inputs.

Butternut Lake and Its Watershed

Butternut Lake is a natural drainage lake in the Butternut Creek watershed about 2 km south of the Village of Butternut and about 5 km northwest of Park Falls. The lake is about 5.6 km long and has a maximum width of about 1.5 km (table 2). Butternut Creek flows into the north end of the lake and flows out of the south end of the lake (fig. 1).

The area and volume of Butternut Lake were given on the 1967 Wisconsin Conservation Department lake survey map as 407 ha and 17,284,000 m^3, respectively. The lake survey map listed the total shoreline length as 18.0 km and the maximum depth as 9.8 m. In this study, the morphometry of the lake was reevaluated on the basis of an aerial image obtained from the 2005 National Agricultural Imagery Program (U.S. Department of Agriculture, 2006). The resulting surface area of the lake was determined to be 393 ha and the volume to be 15,850,000 m^3. The surface delineation for this study did not include channeled areas at the northern and southern ends of the lake, which may account for the difference in the two determinations of area and volume. The area and volume values determined in this study were used for all of the computations in this report. The lake is divided into three major basins: the North, Middle, and South Basins (fig. 2). The morphometry of each basin is listed in table 2.

The major tributary to the lake is Butternut Creek, which flows into the north side of the North Basin. The drainage area of Butternut Creek at the inlet to the lake is 74.7 km^2 (table 3). The second largest tributary is Spiller Creek, which flows into southwest side of the North Basin, and has a total drainage area of 23.5 km^2. Six additional small tributaries, along with ungaged near-lake areas, have a combined drainage area of 20.5 km^2. The total drainage area of the watershed upstream from Butternut Lake's outlet, not including the lake, is 118.7 km^2. Drainage areas contributing to each of the lake basins are also identified in table 3.

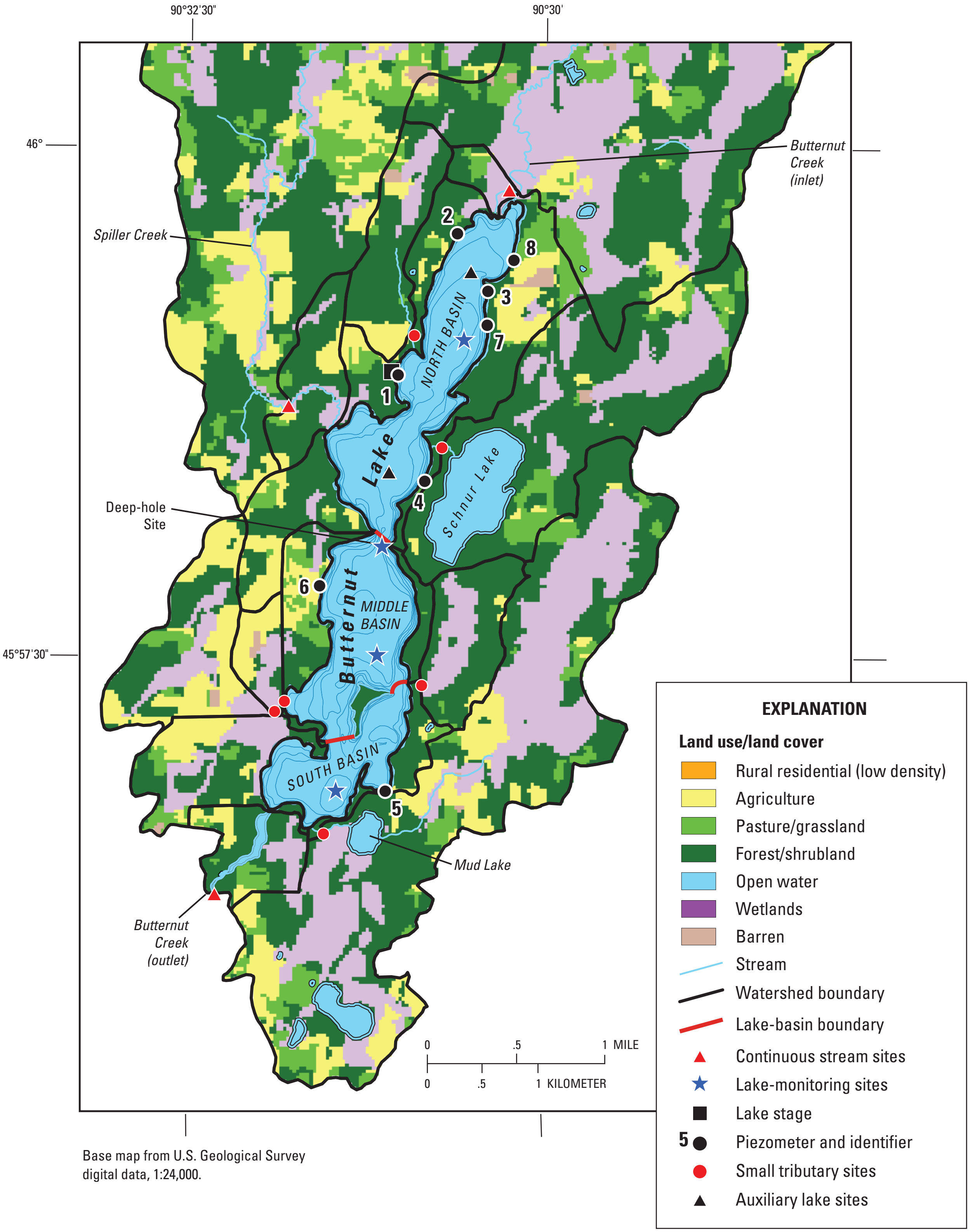
Land use/land cover in the Butternut Lake watershed is primarily a mixture of forest (46.6 percent) and wetland (31.3 percent), with areas of agriculture (9.9 percent), grassland (9.7 percent), and smaller areas of water, urban, nearshore residential, and barren land (table 3). Land use in the Butternut and Spiller Creek watersheds and the watersheds draining into each of the basins are given in table 3.

Table 2. Morphometric characteristics of the basins in Butternut Lake, Price and Ashland Counties, Wis.

[ha, hectare; km, kilometer; m, meter; m^3, cubic meter; km^2, square kilometer; --, not available]

Basin	Area (ha)	Length (km)	Maximum depth (m)	Mean depth (m)	Volume (1,000,000s of m^3)	Osgood Index[1]	Drainage area (km^2)	Residence time (days)	Phosphorus-turnover ratio (annual loading)
North	183	3.09	7.6	4.23	7.75	1.26	107	86	--
Middle	126	1.96	9.8	4.46	5.61	2.82	3.57	60	--
South	84	1.55	5.5	2.97	2.49	4.24	8.28	26	--
Entire lake	**393**	**5.60**	**9.8**	**4.04**	**15.9**	**.26**	**119**	**165**	**5.4**

[1] Osgood Index: mean depth ÷ $\text{area}^{0.5}$ (Osgood, 1988)



Base map from U.S. Geological Survey digital data, 1:24,000.

Figure 2. Subbasins and land use/land cover (Wisconsin Department of Natural Resources, 1998) of the near-lake drainage area of Butternut Lake, Wis., with locations and types of data-collection sites identified.

Shallow Polymictic Lakes and Internal Phosphorus Loading

Butternut Lake and each of its basins are relatively shallow with respect to their surface areas. Shallow lakes, defined as having a maximum depth less than 6 m (Osgood and others, 2002), typically experience only short periods of stratification rather than a single extended period of stratification from early summer through early fall. Lakes that mix only during spring and fall are called dimictic, and lakes that mix frequently throughout the open-water period are called polymictic. Deeper lakes with relatively large surface areas may also be prone to frequent deep mixing. Osgood (1988) described the functional aspects of mixing based on the mean depth and surface area of lakes in terms of the Osgood Index. The Osgood Index is defined as the mean depth (z, in meters) of a waterbody divided by the square root of the surface area (A, in km^2), or $z/A^{0.5}$. The Osgood Index is used to describe the degree to which a lake or reservoir is likely to mix because of the forces of wind. Lakes with Osgood Index values greater than 9 generally are dimictic, and lakes with Index values less than 4 tend to be polymictic. All of the basins in Butternut Lake have either a maximum depth less than 6 m or have Osgood Indices less than 4 (table 2); therefore, the entire lake should be polymictic.

When the deep water of a productive lake becomes anaerobic (devoid of dissolved oxygen) because of the loss of oxygen associated with the decomposition of organic materials, the rate of phosphorus release from the deep sediments often increases dramatically (Mortimer, 1941). Typically, in deeper, dimictic lakes, phosphorus released from the deep sediments is contained in the hypolimnion (deep, cold layer) of the lake and is released to the epilimnion (surface layer) primarily at fall overturn. Therefore, near-surface phosphorus concentrations in dimictic lakes usually remain stable or decrease as summer progresses (Welch and Cooke, 1995). In polymictic lakes, however, when the deeper water becomes anaerobic during the short periods of stratification and phosphorus is released from the sediments, the frequent mixing events deliver the phosphorus to the surface of the lake throughout summer. This frequent mixing results in near-surface concentrations of phosphorus increasing throughout the summer and the lake being very productive in late summer (Welch and Cooke, 1995). Polymictic lakes are extremely vulnerable to high external phosphorus loading and difficult to rehabilitate because the high rate of internal loading usually does not quickly respond to reductions in external phosphorus inputs (Newton and Jarrell, 1999; Nurnberg, 1998; Welch and Cooke, 1995).

Polymictic lakes typically have two alternative stable states—phytoplankton (algae)-dominated or macrophyte (plant)-dominated (Newton and Jarrell, 1999). In moderate densities, macrophytes are beneficial in these lakes. Macrophytes keep sediment from being resuspended by the wind and, therefore, help keep the water less turbid. Macrophytes also provide a place for attached algae to grow and remove phosphorus from the water column. If the macrophytes are removed or if external phosphorus

Table 3. Land use/land cover in the Butternut Lake, Wis., watershed from classifications defined by WISCLAND (Wisconsin Department of Natural Resources, 1998).

[km^2, square kilometer; %, percent]

Basin/drainage	Area (km^2)	Agriculture (%)	Barren (%)	Forest (%)	Grassland (%)	Nearshore residential area (%)	Wetland (%)	Urban (%)	Water (%)
Gaged drainage areas									
Butternut Creek	74.7	6.2	0.5	62.1	11.0	0.0	41.0	0.5	1.3
Spiller Creek	23.5	20.9	.8	35.5	13.3	.0	32.5	.0	.2
Watersheds of individual basins									
North	106.8	8.9	0.6	47.4	9.8	0.1	31.4	0.3	1.4
Middle	3.6	26.0	1.6	43.4	6.6	1.0	21.4	.0	.1
South	8.3	14.9	.4	37.9	8.7	.8	33.7	.0	3.5
Entire watershed									
Entire lake	**118.7**	**9.9**	**0.6**	**46.6**	**9.7**	**0.2**	**31.3**	**0.2**	**1.5**

inputs increase, the lake can shift from a macrophyte-dominated state to an algal-dominated state. Once a lake is in the algal-dominated state, macrophytes have a difficult time re-establishing themselves because algae reduce the penetration of light. In the 1960s and early 1970s (and presumably several years before that), Butternut Lake was believed to be in the algal-dominated state with frequent massive algal blooms. After the mid 1970s, however, the actions taken in the watershed lake (table 1) are believed to have reduced the nutrient input to the lake and switched the lake to a macrophyte-dominated state (R. Jasinski, written commun., 1982). Of these two conditions, it is commonly believed that the present-day macrophyte-dominated state is more desirable for human and biological use than the previous algal-dominated state (Newton and Jarrell, 1999).

Purpose and Scope

This report describes the water quality of Butternut Lake, quantifies the water and phosphorus budgets for the lake based on data collected from November 2002 through October 2004, provides an estimate of the phosphorus released from the bottom sediments, and presents the results of model simulations that demonstrate the potential effects of changes in phosphorus inputs on the lake's water quality.

The water-quality data and water and phosphorus budgets described in this report improve the understanding of the hydrologic system of Butternut Lake and aid in the understanding of how shallow lakes respond to changes in nutrient inputs. Results of the study should be useful to Price and Ashland Counties and local officials 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 stream and lake data from 2002 to 2004 as part of this study. In addition, water-quality data for the lake were collected by the U.S. Environmental Protection Agency (USEPA), U.S. Forest Service (USFS), WDNR (Wisconsin Department of Natural Resources, 2006), and volunteers from the community as part of the WDNR's Wisconsin Citizen Lake Monitoring Program (Wisconsin Department of Natural Resources, 2008). Data collected by the USEPA were obtained from U.S. Environmental Protection Agency (1974), data collected by the USFS and the WDNR were provided by J. Vennie (Wisconsin Department of Natural Resources, written commun., 2004), 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*, and Secchi depths, were used to characterize long-term changes in the water quality of the lake; however, only data collected from November 1, 2002 to October 31, 2004 were used to describe the hydrology and phosphorus inputs to the lake. This latter period was divided into two monitoring years (MY): November 2002 through October 2003 (hereafter referred to as MY 2003) and November 2003 through October 2004 (hereafter referred to as MY 2004).

Lake-Stage and Water-Quality Monitoring

A continuously recording (15-minute interval) lake-stage gage was installed and operated near the public boat landing on the west side of the lake (fig. 2). The gage was operated for the 2-year monitoring period.

Water-quality data for the lake were collected by the USEPA and WDNR from 1972 to 1975 as part of two statewide assessments (Lillie and Mason, 1983). Data also were collected by the WDNR from 1986 through 1997 as part of their long-term trend monitoring program (Wisconsin Department of Natural Resources, 2006). These data were collected at the deepest location (the Deep-hole Site between the North and Middle Basins) in the lake (fig. 2). Volunteers from the community (Citizen Monitoring) collected water-quality data from 1992 to 2006. The USGS collected data from 2002 to 2004 as part of this study. The USGS protocols for sampling at the Deep-hole Site from 2002 to 2004 were similar to those of the WDNR long-term trend monitoring program. Each year, the lake was sampled in late winter, spring, and summer (monthly from May through September). During each visit, profiles of water temperature, dissolved oxygen, specific conductance, and pH were collected with a multiparameter meter, and water clarity was measured with a standard 20-cm diameter black and white Secchi disk (Secchi depth). Near-surface samples, which were collected with a Van Dorn sampler by USGS and a Kemmerer sampler by WDNR, were analyzed for total phosphorus and chlorophyll *a* concentrations and, during midsummer, for various nitrogen species. Near-bottom samples were collected about 1 m above the sediment/water interface and were analyzed for total phosphorus concentration. Water samples collected during spring were analyzed for common ions and other characteristics such as color, turbidity, alkalinity, total dissolved solids, and silica.

During this study, three additional lake-monitoring sites also were sampled (fig. 2). Sampling protocols for two of these sites, the North and Middle Sites, were the same as those for the Deep-hole Site, except that the spring sample was not analyzed for common ions and other characteristics such as color, turbidity, alkalinity, total dissolved solids, and silica. At the other auxiliary site, the South Site, only Secchi depth and profiles of water temperature, dissolved oxygen, specific conductance, and pH were measured.

Butternut Lake was sampled 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, 2004; 2005). Quality-assurance samples are not collected in each of the lakes sampled; however, replicates were collected in Butternut Lake in 2003. The replicates for total phosphorus and chlorophyll *a* were within 5 percent of each other, which is consistent with replicates collected in other lakes in Wisconsin. Concentrations of total phosphorus and chlorophyll *a* in the blanks analyzed in 2003, and in other years, were below the laboratories' detection limits (0.004–0.005 mg/L for total phosphorus and 0.03–0.1 µg/L for chlorophyll *a*).

Lake-stage, water-quality, and quality-assurance data collected during this study were published in the USGS annual data report series “Water Quality and Lake-Stage Data for Wisconsin Lakes, Water Years 2003 and 2004 (U.S. Geological Survey, Wisconsin District Lake Studies Team, 2004; 2005).

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

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

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

$$TSI_{SD} = 60.0 - 14.41[\ln \textit{Secchi depth} \text{ (in meters)}] \quad (3)$$

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

Lake-Sediment Analyses

Internal release rates of phosphorus from the sediments during aerobic and anaerobic conditions were determined from analysis of sediment cores collected at six locations in the lake (lake-monitoring sites and auxiliary sites, fig. 2) using the sediment-core-incubation techniques described by James and Barko (1991). A Wildco sediment-core sampler equipped with acrylic core liners was used to collect either two or four sediment cores from each location. At three locations, four cores were collected: two for aerobic analysis and two for anaerobic analysis. At three additional locations, only two cores were collected for aerobic analysis. After retrieval, the core liners, containing both sediment and overlying water, were immediately sealed using rubber stoppers and stored in a protective container for shipping to the Wisconsin State Laboratory of Hygiene. Additional lake water was collected for incubation with the collected sediment.

At the State Laboratory of Hygiene, the sediment cores were carefully drained of overlying water. Then additional water, collected from the lake, was filtered and siphoned onto the sediment contained in each of the core liners. All of the liners containing the sediment were placed in the dark and incubated at a constant temperature (approximately 22ºC) for 1 to 2 weeks. The incubation temperature was a constant temperature similar to that above the original sediment during summer.

The aerobic/anaerobic environment of each core was controlled in the laboratory by gently bubbling either air (aerobic environment) or nitrogen (anaerobic environment) through an air stone placed just above the sediment surface. The limited bubbling action insured complete mixing of the water column but did not disrupt the sediment. Twelve of the cores (two from each location) were subjected to aerobic conditions and six of the cores (two from each of three stations) were subjected to anaerobic conditions. Therefore, all incubations were run in duplicate.

Samples for soluble reactive phosphorus analysis were collected daily from water above the sediment in each core and filtered through a 0.45-μm filter. The volume of water that was removed was replaced with an equivalent volume of lake water (with a measured phosphorus concentration). Rates of phosphorus release from the sediments ($mg/m^2/d$) were then calculated as a linear change in mass in the overlying water divided by the time and the cross-sectional area of the incubation core liner. All results were corrected for the water (and phosphorus) that was removed from above the core and replaced with lake water. Aerobic and anaerobic sediment release rates were then averaged for each basin. The rate of release of phosphorus from aerobic and anaerobic sediments is typically a function of the temperature of the sediments and overlying water, with a higher release rate at warmer temperatures than at lower temperatures. Release rates from the sediments of Butternut Lake were computed only at 22ºC; however, release rates from the sediments of the Upper Mississippi River were examined as a function of water and sediment temperatures (James and Barko, 2004). Therefore, the release rates were adjusted by a ratio computed from the release-rate equations obtained for the sediments of the Upper Mississippi River (fig. 3). The release rate at 22ºC was used as a reference; therefore, the release-rate ratio at 22ºC was set to 1.0. Daily water temperatures at the sediment/water interface in Butternut Lake were assumed to be similar to that estimated at 2 m for a nearby lake (Whitefish Lake in Douglas County, Wis.; unpublished results) through the use of the Dynamic Lake Model (Robertson and others, 2002). Daily aerobic and anaerobic release rates were then obtained by multiplying the rates measured at 22ºC by the estimated daily release-rate ratios.

For each basin, the amount of phosphorus released from the sediment was obtained by summing the amount released from the aerobic and anaerobic areas of the basin. The area of anaerobic sediment in each basin was estimated from the area at the depth at which a dissolved oxygen concentration of less than or equal to 0.5 mg/L was measured in the profiles collected in the deepest area of each basin, assuming that the dissolved oxygen concentrations were horizontally uniform throughout the basin. The area of aerobic sediment was computed by subtracting the area of anaerobic sediment and the area of sediment at depths less than 1 m from the total area of the basin. It was assumed that no phosphorus was released from areas less than 1-m deep because these areas typically have little accumulated organic sediment. From the 2 years of profile data, the areas of aerobic and anaerobic sediment were estimated for specific dates throughout the year. The daily sediment release was then computed as the product of the temperature-adjusted release rates and the respective aerobic and anaerobic areas.

A separate paleoecological study of the lake-bottom sediments of Butternut Lake was done by the WDNR, Bureau of Integrated Science Services, to age-date specific sediment depths and to quantify historical changes in the external sediment and nutrient loading to the lake, the sedimentation rates in the lake, and the chemistry of the lake (Garrison, 2006). Sediments from a deep region of the North Basin (fig. 2) were extracted with a piston-coring device in February 2005 and then analyzed to reconstruct the water-quality history of the lake. Analysis of diatom assemblages was used to assess historical changes in phosphorus concentrations in the lake.

Stream Monitoring

Three stream sites (fig. 2) were equipped with instrumentation to continuously monitor flow (15-minute intervals). At two of the sites, Spiller Creek at County Highway B and Butternut Creek at County Highway B (just downstream of the lake's outlet), water level (stage) was measured to determine flow by use of standard stage-discharge relations (Rantz and others, 1982). The third site, Butternut Creek at Cutoff Road at the lake's inlet, was not suited to flow determination by standard stage-discharge methods because of backwater conditions. This site was equipped with an acoustic doppler velocity meter and a water level sensor and was operated as a velocity-index station (Sauer,

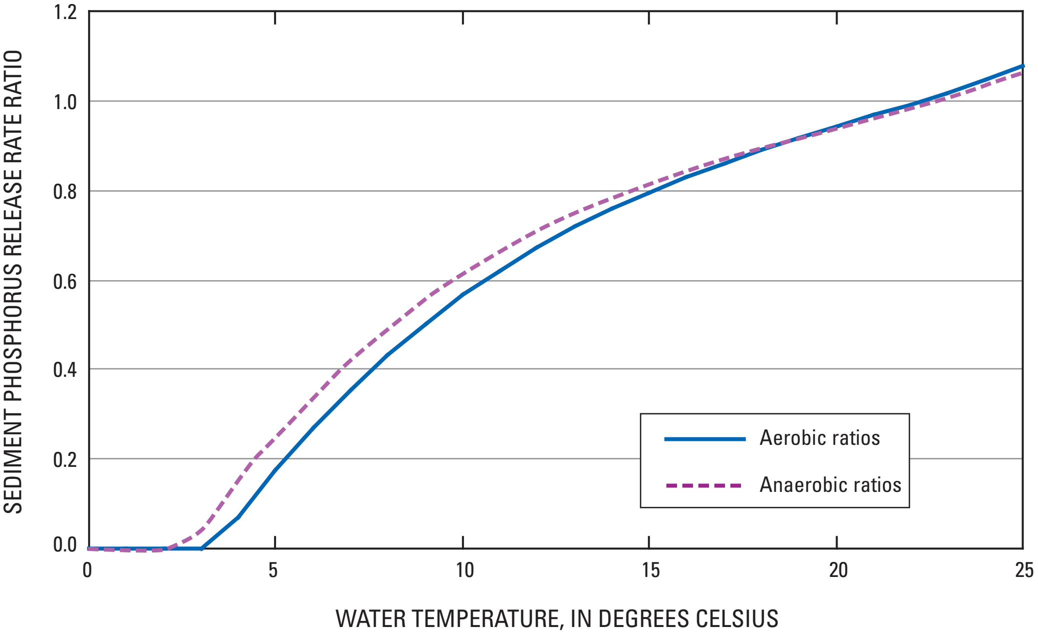


Figure 3. Changes in phosphorus release rates (ratio) from aerobic and anaerobic sediments of the Upper Mississippi River as a function of water temperature, estimated from the equations in James and Barko (2004), using the release rate at 22°C as a reference value (ratio of 1.0).

2002). From the 15-minute data, average daily flows for each site were computed. The data are stored and maintained in the USGS National Water Information System (NWIS) database.

Flow at six small tributaries to Butternut Lake (fig. 2) was measured intermittently at approximately monthly intervals. The measured flows at each tributary were correlated with the continuously recorded flow at Spiller Creek to develop a regression relation between flow at each tributary and flow at Spiller Creek. The regression relations for each site and the daily flows at Spiller Creek were then used to estimate daily flows in each tributary. Temporally varying offsets were then applied to all estimated flow data to force estimated flows to equal those measured in the tributaries.

Water samples were collected at the stream sites and analyzed for concentrations of phosphorus. Water samples were collected by three different methods. Automated water samplers were used to collect samples at Butternut Creek (inlet) and at Spiller Creek. Additional samples at these two sites were collected manually by the Equal-Width-Increment (EWI) method (Edwards and Glysson, 1999) to compare with the automated samples. Butternut Creek near the lake outlet was sampled approximately monthly by the EWI method. Sites on the additional small tributaries were sampled approximately monthly by either EWI or grab methods.

Phosphorus loads for the continuously monitored sites at the Butternut Creek inlet, Spiller Creek, and the Butternut Creek outlet were computed by use of techniques for integrating streamflow and concentration described by Porterfield (1972). Phosphorus loads for the small tributaries were determined by multiplying temporally varied concentrations (computed on the basis of concentrations of intermittently collected samples) multiplied by the estimated flow. Loads for the near-lake ungaged area were determined by multiplying the average unit-area load (load divided by drainage area) for the six tributaries by the ungaged near-lake area. All concentration data and daily flows and loads were published in the annual USGS water-data report series (Waschbusch and others, 2004; 2005).

Ground-Water Monitoring

Eight shallow piezometers (1.25-cm diameter observation wells) were installed around the periphery of the lake (fig. 2) to help define areas contributing ground water to the lake, to determine the phosphorus concentration in the ground water entering the lake, and to quantify the phosphorus loading from ground water. The piezometers were installed approximately 1 m below the water table, to depths of 1.5 to 2 m. Five piezometers were on the eastern shore and three were on the western shore. Ground-water gradients, which were determined from the differences in water elevation in the piezometers and elevation of the lake surface, and dissolved phosphorus concentrations in the ground water were measured twice in 2003 and twice in 2004 for each piezometer.

All lake, stream, and ground-water samples and water from above the sediment cores 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).

Measured Lake Water Quality

Temperature profiles collected throughout the lake confirmed that the North, Middle, and South Basins were polymictic, which means that they do not develop stable thermal stratification during summer and thus allowed a great deal of vertical mixing throughout that period. This mixing resulted in only a few degrees Celsius of thermal stratification during most summer sampling periods. Changes in temperature are shown for the Deep-hole Site in figure 4*A*. The bottom temperatures at all of the sites warmed throughout summer. In each of the basins, the bottom temperatures reached a maximum temperature of about 20ºC in August. Thermal stratification was most extensive when the lake was frozen. Temperatures just under the ice were about 4ºC cooler than near the bottom by late winter. During the presence of weak stratification, the near-bottom water was often anaerobic (fig. 4*B*). However, due to frequent vertical mixing, the area of the lake that was anaerobic was never large. Thermal stratification in the South Basin was less extensive than in the other basins, because this basin is shallower and probably had more deep-mixing events.

The area of anaerobic sediment in each basin was estimated from the depth at which a dissolved oxygen concentration of 0.5 mg/L was found in the profiles collected in their deepest areas. From the 2 years of data, the area of aerobic and anaerobic sediment were estimated for specific dates throughout the year (table 4); daily estimates of these areas were then obtained by linearly interpolating between these dates.

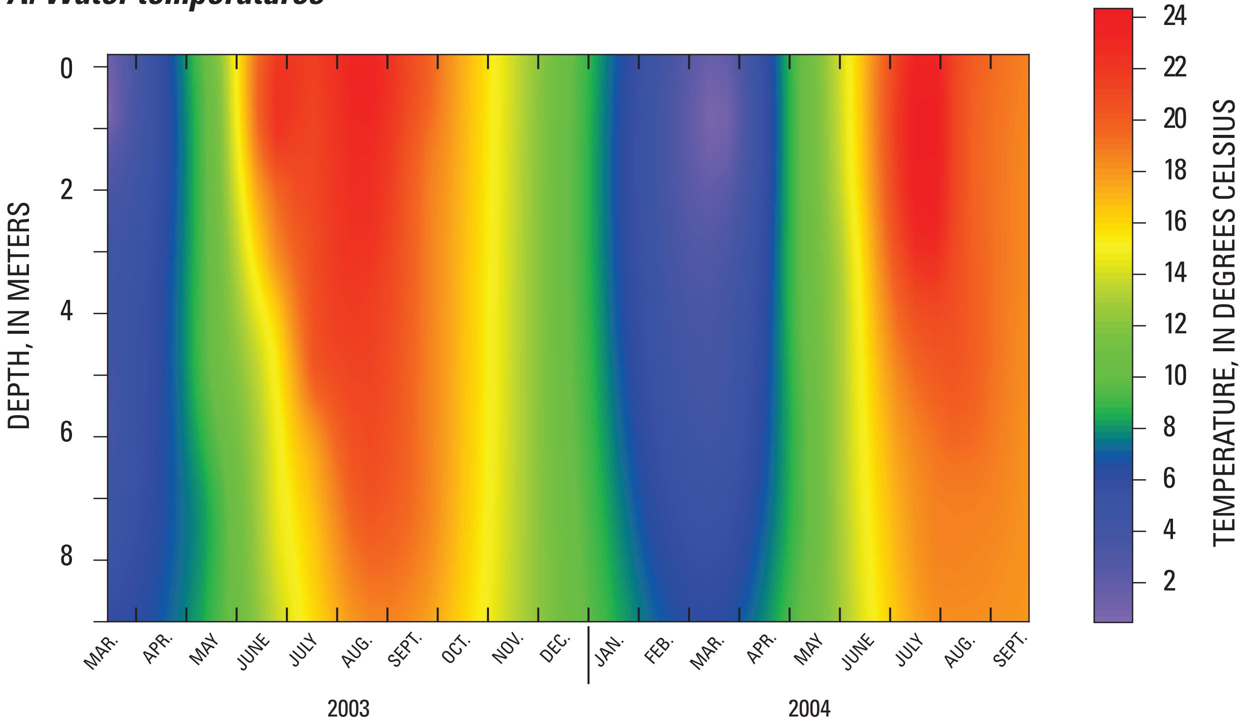
Specific conductance typically was about 80 μS/cm throughout the lake, but increased to about 200 μS/cm near the bottom when these areas were anaerobic. The pH in the lake typically ranged from 7 to 8 (standard units), with the lowest pH values measured during cooler periods and the highest pH values were measured during summer when productivity was highest. The lowest pH value (6.4) was measured on May 4, 2004, near the bottom in the North Basin, and the highest value (9.4) was measured on Aug. 13, 2003, near the surface in the South Basin.

Table 4. Estimated area of aerobic sediment (greater than 1 meter in depth) and anaerobic sediment in the three basins in Butternut Lake, Wis.

[All values given in thousands of square meters]

Date	North Basin		Middle Basin		South Basin	
	Aerobic	Anaerobic	Aerobic	Anaerobic	Aerobic	Anaerobic
Jan.1	1,710	0	1,180	0	754	0
Feb. 1	1,710	0	777	400	754	0
Mar. 31	1,710	0	777	400	754	0
Apr. 1	1,710	0	1,180	0	754	0
June 1	1,710	0	1,180	0	754	0
June 15	1,330	377	1,180	2	704	50
July 15	937	552	606	571	539	215
Aug. 15	1,170	539	606	571	539	215
Sept. 1	1,710	0	1,180	0	754	0
Dec. 31	1,710	0	1,180	0	754	0

A. Water temperatures



B. Dissolved oxygen

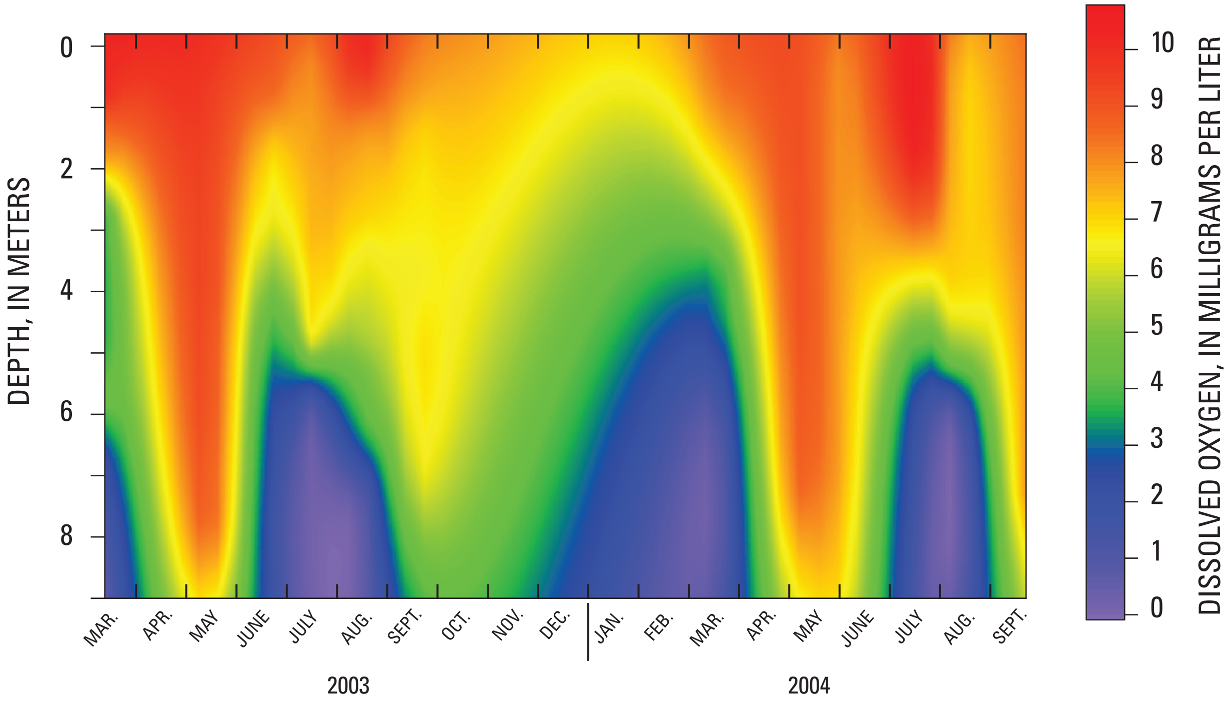


Figure 4. Distributions of ***A***, water temperature and ***B***, dissolved oxygen from March 10, 2003, through September 21, 2004, at the Deep-hole Site in Butternut Lake, Wis.

Water chemistry in Butternut Lake is fairly typical of northwestern Wisconsin lakes, as described by Lillie and Mason (1983). Lillie and Mason collected data from a random set of about 660 Wisconsin lakes, 282 of which were in northwestern Wisconsin. The average concentrations of calcium, magnesium, chloride, and alkalinity in Butternut Lake were 10, 3, 3, and 32 mg/L, respectively. The average concentrations for these constituents for 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. The water color in Butternut Lake averaged 85 (platinum-cobalt units) from two measurements made during this study, which is more colored than the average value of 30 for the northwestern Wisconsin lakes.

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 (that is, accelerated aging and increased productivity) of lakes. Concentrations of near-surface total phosphorus greater than about 0.024 mg/L indicate eutrophic conditions, and concentrations greater than about 0.050 mg/L indicate hypereutrophic conditions. The near-surface phosphorus concentrations in Butternut Lake had distinct seasonality (fig. 5*A*). During MY 2003 and MY 2004, concentrations ranged from about 0.03 mg/L in late winter and early spring to more than 0.060 mg/L in late summer of both years. Concentrations increased throughout the summer, which is typical for polymictic lakes (Welch and Cooke, 1995). The average near-surface summer (May–September) phosphorus concentration during MY 2003–04 ranged from 0.044 mg/L at the Deep-hole Site to 0.048 mg/L in the North Basin (table 5). No consistent differences were found among basins. Therefore, based on total phosphorus concentrations, Butternut Lake would typically be classified as on the border between eutrophic and hypereutrophic.

In general, phosphorus concentrations measured near the bottom of the water column were similar to those measured near the surface; however, a few very high concentrations were measured near the bottom. The highest near-bottom concentrations were measured in June, July, and August, with the highest phosphorus concentration of

Table 5. Summer (May through September) average water quality throughout Butternut Lake, Wis., for monitoring years 2003 and 2004.

[mg/L, milligram per liter; µg/L, microgram per liter; c.v.; coefficient of variation; m, meter; --, no data]

Basin/site	Total phosphorus		Secchi depth		Chlorophyll *a*	
	(mg/L)	(c.v.)	(m)	(c.v.)	(µg/L)	(c.v)
			2003			
North Basin	0.043	--	1.18	--	20.88	--
Deep-hole Site	.039	--	1.24	--	20.72	--
Middle Basin	.044	--	1.20	--	23.92	--
South Basin	.044[a]	--	1.25	--	23.92[a]	--
			2004			
North Basin	0.053	--	1.10	--	18.01	--
Deep-hole Site	.049	--	1.14	--	18.92	--
Middle Basin	.050	--	1.16	--	17.58	--
South Basin	.050[a]	--	1.18	--	17.58[a]	--
			2003–2004			
North Basin	0.048	0.20	1.14	0.15	19.4	0.38
Deep-hole Site	.044	.20	1.24	.15	19.8	.38
Middle Basin	.047	.20	1.18	.15	20.8	.38
South Basin	.047[a]	.20[a]	1.22	.15	20.8[a]	.38[a]

[a] Assumed to be similar to the Middle Basin.

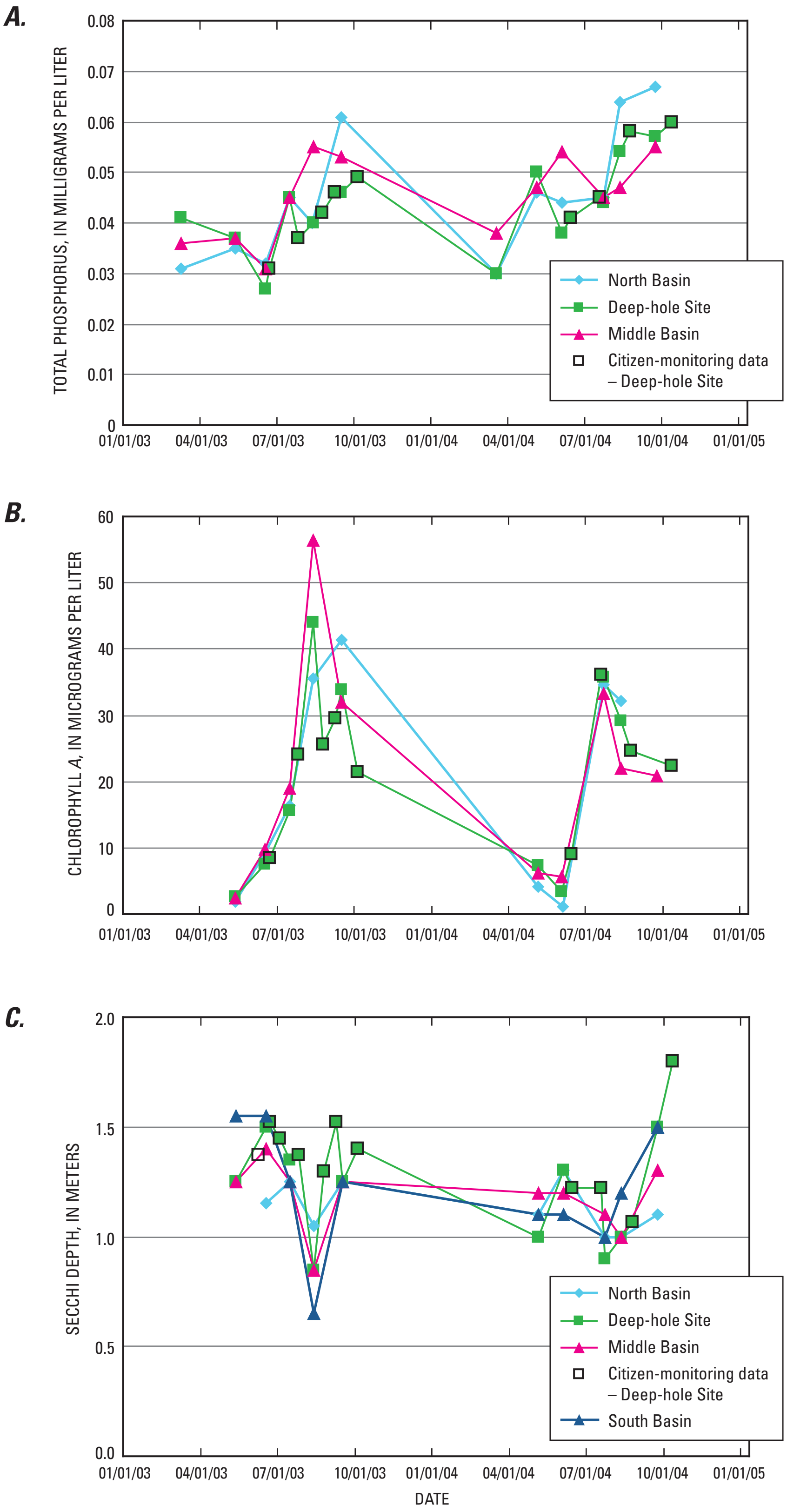


Figure 5. Near-surface ***A***, total phosphorus concentrations, ***B***, chlorophyll *a* concentrations, and ***C***, Secchi depths at various locations in Butternut Lake, Wis., during 2003 and 2004.

0.351 mg/L measured on August 10, 2004, at the Deep-hole Site. The high near-bottom phosphorus concentrations do not persist throughout the summer in polymictic lakes, because the frequent deep-mixing events redistribute the phosphorus that is released from the bottom sediments throughout the water column.

Since 1972, near-surface total phosphorus concentrations have ranged from 0.018 mg/L to greater than 0.15 mg/L (fig. 6*A*). All of the concentrations greater than 0.10 mg/L were measured during the ice-covered period. Although few data were available prior to 1986, it appears that phosphorus concentrations have declined since 1972. During each year, concentrations increased throughout summer; therefore, to demonstrate how near-surface concentrations have changed, the concentrations measured in August (the month most consistently sampled) were identified on figure 6*A* and summarized in table 6. During August, total phosphorus concentrations decreased from about 0.09 mg/L in the early 1970s, to about 0.06–0.08 in the 1980s, to about 0.05 mg/L in the 2000s (fig. 6*A*). From the 1980s to the 2000s, average summer concentrations also decreased, but only from about 0.055–0.060 mg/L to about 0.045 mg/L. These decreases in near-surface phosphorus concentrations are consistent with those expected with the discontinuation of discharge of sewage effluent from the Village of Butternut into Butternut Creek, the upgrading of near-lake septic systems, and the general decline in agricultural activity in the watershed (table 1).

During the summers of 2003 and 2004, near-surface total nitrogen concentrations (computed as the sum of Kjeldahl nitrogen and dissolved nitrite plus nitrate) ranged from 0.49 to 0.88 mg/L; Kjeldahl nitrogen represented more than 70 percent of the total nitrogen. These values are similar to those measured in the late 1980s (0.52 to 0.72 mg/L), but less than those measured prior to 1986. The high nitrogen concentrations measured prior to 1986 were primarily caused by high concentrations of Kjeldahl nitrogen, which often exceeded 1 mg/L.

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 usually indicates that phosphorus should be the potentially limiting nutrient. The N:P ratios for 1970s data ranged from 15:1 to 35:1, with an average ratio of 23:1. This indicates that phosphorus should have been the potentially limiting nutrient. Incremental additions of nitrogen and phosphorus (bioassays) also can be used to indicate whether phosphorus or nitrogen may be the limiting nutrient. During 1972, bioassay experiments indicated that nitrogen was the limiting nutrient in the lake (U.S. Environmental Protection Agency, 1974). Since 1986, the N:P ratios have ranged from 12:1 to 21:1, with an average of 17:1. These ratios indicate that phosphorus typically should be the limiting nutrient. Based on the earlier bioassays and the few low N:P ratios, however, algal productivity may often be colimited by both nitrogen and phosphorus.

Further reductions in phosphorus concentrations should not only increase the N:P ratio, but also favor the growth of green algae over the growth of blue-green algae. Blue-green algae usually are not limited by nitrogen because they can fix nitrogen from the atmosphere. Blue-green algae are the least desirable type of algae because they commonly form extensive blooms or scums on the surface, are potentially toxic, and are usually the least preferred by grazing zooplankton. Therefore, phosphorus should be the nutrient of concern when considering management efforts to improve the water quality of Butternut 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 between about 2 and 7 µg/L indicate mesotrophic conditions, and average concentrations between 7 and 20 µg/L indicate eutrophic conditions. Concentrations greater than 20 µg/L indicate hypereutrophic conditions and are usually associated with frequent algal blooms. During MY 2003 and MY 2004, concentrations ranged from 1 to 2 µg/L in early spring to more than 30 µg/L in late summer of both years (fig. 5*B*). The average near-surface summer chlorophyll *a* concentration measured throughout the lake during MY 2003–04 was about 20 µg/L (table 5). Therefore, based on chlorophyll *a* concentrations, Butternut Lake would typically be classified as on the border between eutrophic and hypereutrophic.

Since 1972, chlorophyll *a* concentrations ranged from less than 1 µg/L to more than 90 µg/L (fig. 6*B*). The few chlorophyll *a* data prior to 1986 indicated two different conditions: low concentrations in 1972 and high concentrations in 1978. From 1978 to about 1990, near-surface chlorophyll *a* concentrations have declined; however, since 1990, no consistent long-term change was apparent. The overall average summer concentration from 1986 to 2005 was 28 µg/L, and the average August concentration was 45 µg/L.

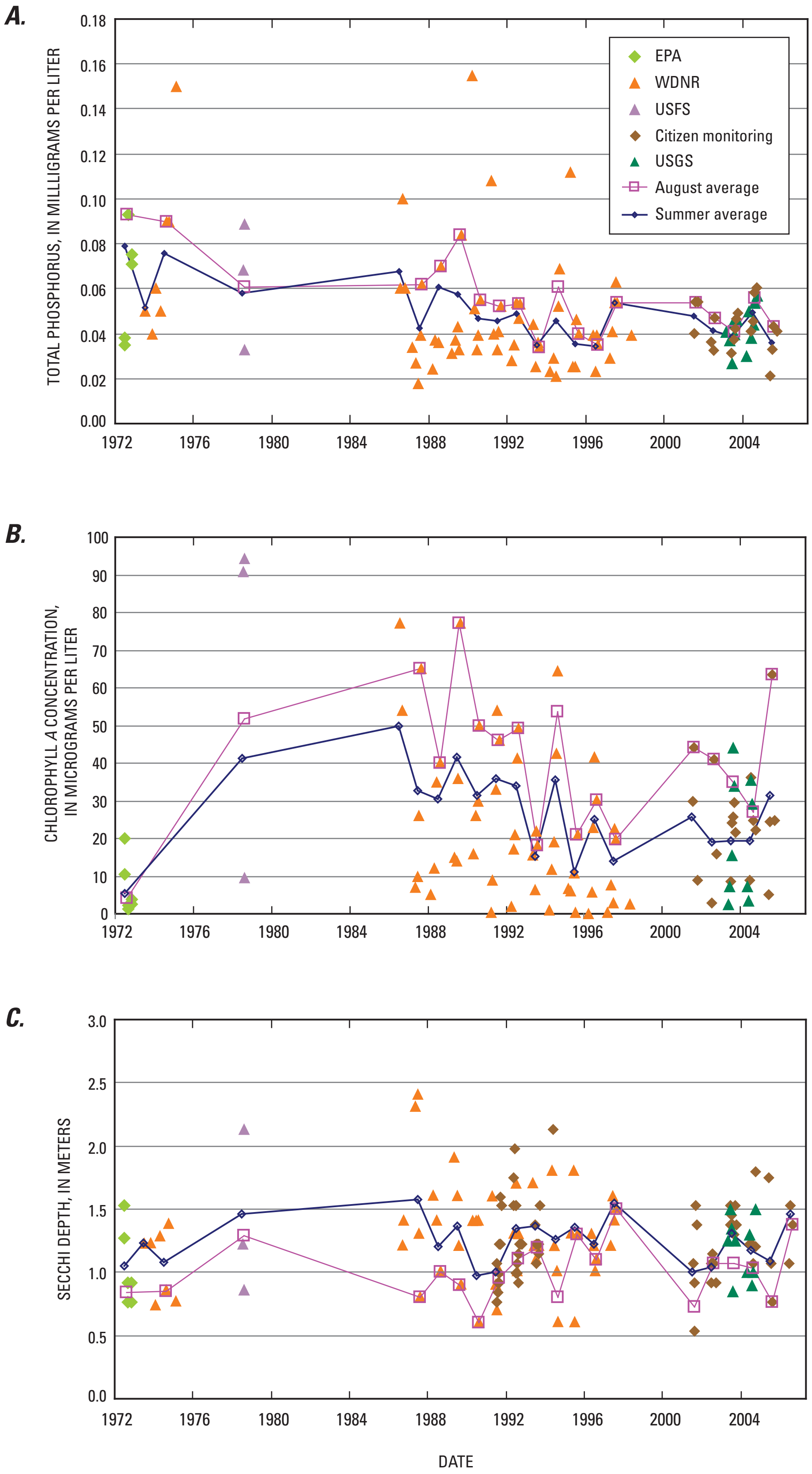


Figure 6. Near-surface ***A***, total phosphorus concentrations, ***B***, chlorophyll *a* concentrations, and ***C***, Secchi depths at the Deep-hole Site in Butternut Lake, Wis., from 1972 to 2006 (EPA, U.S. Environmental Protection Agency; WDNR, Wisconsin Department of Natural Resources; USFS, United States Forest Service; USGS, U.S. Geological Survey).

Table 6. Near-surface, summer-average (May–August) and August water quality and trophic state index (TSI) values for the Deep-hole Site in Butternut Lake, Wis. Data were collected by the U.S. Geological Survey, U.S. Environmental Protection Agency, U.S. Forest Service, Wisconsin Department of Natural Resources, and citizen monitoring.

[mg/L, milligram per liter; µg/L, microgram per liter; m, meter; --, no data]

Year	May–August			August			Trophic state index values (August)		
	Total phosphorus (mg/L)	Chlorophyll *a* (µg/L)	Secchi depth (m)	Total phosphorus (mg/L)	Chlorophyll *a* (µg/L)	Secchi depth (m)	Phosphorus	Chlorophyll *a*	Secchi depth
1972	0.079	5.5	1.05	0.093	4.1	0.8	69.5	44.3	62.5
1973	.052	--	1.24	.057	--	1.0	62.4	--	59.3
1974	.076	--	1.08	.090	--	.9	69.0	--	62.3
1975–77	--	--	--	--	--	--	--	--	--
1978	.058	41.4	1.46	.061	51.8	1.3	63.4	69.3	56.4
1979–85	--	--	--	--	--	--	--	--	--
1986	.067	49.9	--	.068	85.1	--	65.0	74.2	--
1987	.042	32.7	1.58	.062	65.0	.8	63.7	71.6	63.2
1988	.061	30.3	1.20	.070	40.0	1.0	65.4	66.8	60.0
1989	.057	41.5	1.37	.084	77.0	.9	68.0	73.2	61.5
1990	.047	31.3	.97	.055	50.0	.6	61.9	69.0	67.4
1991	.046	35.9	1.00	.052	46.0	1.0	61.1	68.2	60.7
1992	.049	34.0	1.34	.053	49.1	1.1	61.4	68.8	58.5
1993	.035	15.4	1.36	.034	18.0	1.2	55.0	58.9	57.4
1994	.046	35.7	1.26	.061	53.5	.8	63.3	69.6	63.2
1995	.036	11.1	1.36	.040	20.8	1.3	57.3	60.4	56.2
1996	.035	25.2	1.22	.035	30.1	1.1	55.4	64.0	58.6
1997	.054	13.9	1.55	.054	19.8	1.5	61.7	59.9	54.2
1998	--	--	--	--	--	--	--	--	--
2001	.048	25.7	1.00	.054	44.0	.7	61.7	67.7	64.7
2002	.041	19.0	1.05	.047	41.0	1.1	59.7	67.0	59.1
2003	.039	19.4	1.31	.041	34.8	1.1	57.7	65.4	59.0
2004	.049	19.5	1.17	.056	27.0	1.0	62.2	62.9	59.5
2005	.036	31.4	1.09	.043	63.5	.8	58.4	71.3	63.9
2006	--	--	1.46	--	--	1.4	--	--	55.4
Average: All years	.050	27.3	1.24	.058	43.2	1.01	62.1	65.9	60.1
Average: 1986–2006	.046	27.8	1.25	.053	45.0	1.02	61.1	67.0	60.2
Average: 2003–04	.044	19.4	1.24	.049	30.9	1.05	59.9	64.2	59.3

During MY 2003 and MY 2004, Secchi depths in Butternut Lake ranged from 0.65 m on August 13, 2003, in the South Basin to about 1.5 m in the fall of 2004 at several locations (fig. 5*C*). Little consistent seasonal or spatial variability was apparent in Secchi depths. During MY 2003–04, the average summer Secchi depth was about 1.2 m (table 5). Since 1972, Secchi depths have changed very little (fig. 6*C*). Secchi depths between 2 and 4 m indicate mesotrophic conditions, from 1 to 2 m indicate eutrophic conditions, and less than 1 indicate hypereutrophic conditions. Therefore, based on Secchi depths, Butternut Lake would typically be classified as eutrophic.

All three TSIs, based on near-surface concentrations of total phosphorus and chlorophyll *a*, and on Secchi depths, indicate that in MY 2003 and MY 2004, Butternut Lake was typically eutrophic to hypereutrophic (fig. 7 and table 6). During late summer, when phosphorus concentrations were higher and water clarity was poorer than in other parts of the year, the lake was typically classified as hypereutrophic. In general, TSI values based on chlorophyll *a* concentrations were a little higher than those based on total phosphorus concentrations or Secchi depths.

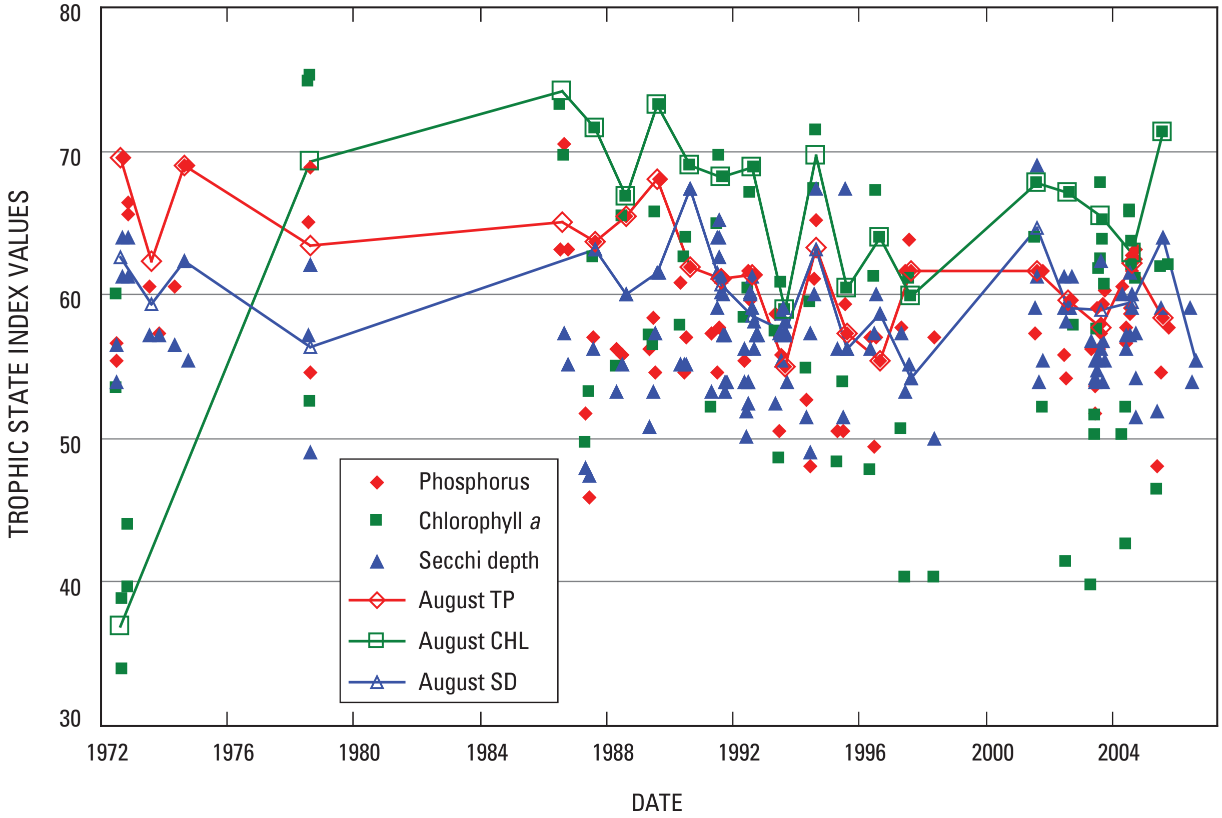


Figure 7. Trophic state index (TSI) values based on surface concentrations of total phosphorus (TP) and chlorophyll *a* (CHL), and Secchi depths (SD), in Butternut Lake, Wis. Data were collected by the U.S. Geological Survey, U.S. Environmental Protection Agency, U.S. Forest Service, Wisconsin Department of Natural Resources, and citizen monitoring.

Inferred Lake Water Quality from Lake-Sediment Analyses

Results of analyses of a sediment core extracted from the deep area of the North Basin in February 2003 were used to quantify changes in sedimentation rates and reconstruct historical changes in the water quality of the lake (Garrison, 2006). The average annual sedimentation rate for Butternut Lake (0.026 g/cm^2) was about average for the lakes that have been studied in Wisconsin. The annual sedimentation rate steadily increased from about 0.01 g/cm^2 in 1840 to about 0.04–0.08 g/cm^2 in 1930–40. Since 1940, there was no discernable trend in sedimentation rates, but the rates fluctuated from about 0.025 to 0.050 g/cm^2.

Changes in the diatom assemblages in the lake sediments were used to infer changes in the nutrient concentrations in the water column of Butternut Lake. On the basis of changes in the diatom assemblages, the average in-lake phosphorus concentrations increased steadily from about 0.015–0.020 mg/L in 1850 to about 0.040 mg/L in 1970 (fig. 8). Since 1970, the inferred total phosphorus concentrations fluctuated from about 0.030 to 0.040 mg/L and appeared to have stabilized. The increases in concentrations from 1840 to 1970 are consistent with the increase in phosphorus inputs caused by logging and agricultural activities in the watershed, sewage effluent from the Village of Butternut, discharges from a creamery and cheese factories, and seepage from leaking septic systems. Based on the inferences from analysis of the sediment core, all of the efforts in the watershed to reduce phosphorus inputs from these sources have stopped the increase in total phosphorus concentrations. Given the fluctuations in the inferred total phosphorus concentrations from 1980 to the present, however, it is not possible to determine if the concentrations have decreased in recent years.

Hydrology and Water Budget

Because the productivity in Butternut Lake is limited or colimited by phosphorus (based on N:P ratios) and because reductions in phosphorus concentrations should favor production of green algae over blue-green algae, further reductions in the input of phosphorus to the lake should reduce phosphorus concentrations in the lake and thus improve water quality. Most of the phosphorus entering the lake is transported by water inputs; therefore, to

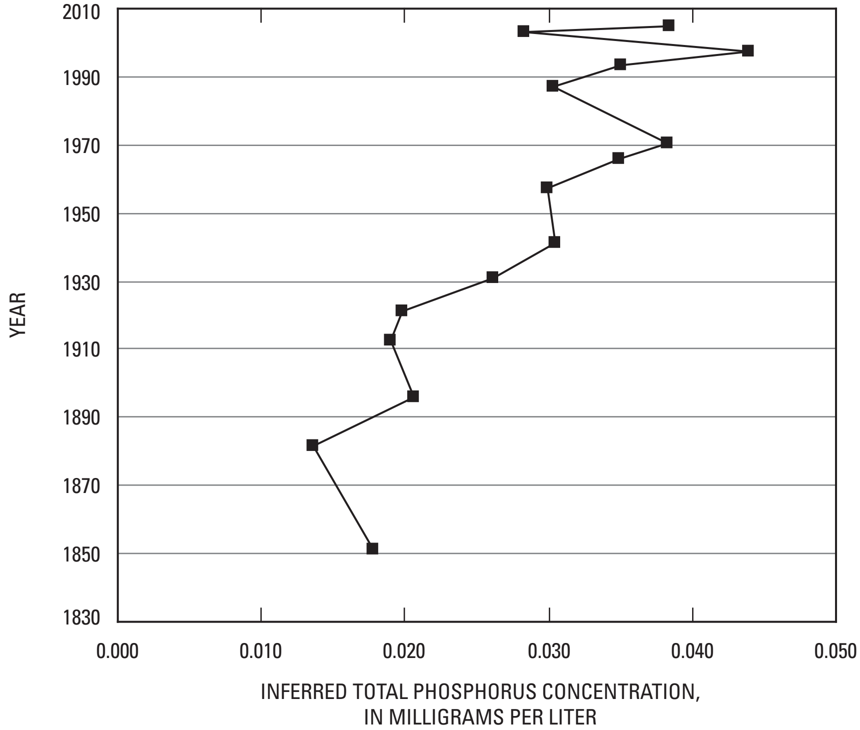


Figure 8. Estimated changes in summer total phosphorus concentrations based on changes in the diatom community in the sediment cores from Butternut Lake, Wis. (from Garrison, 2006).

quantify phosphorus inputs, it is necessary to first quantify the water inputs. Water budgets for the lake were quantified for each of the two monitoring years.

The hydrology of Butternut Lake can be described in terms of components of its water budget. The water budget for a period of interest may be represented by:

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

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 ground-water inflow (GW_{In}). Water leaves the lake through evaporation (E), surface-water outflow (SW_{Out}), and ground-water outflow (GW_{Out}). Each term of the water budget was estimated on a daily basis.

Change in Storage

Changes in the volume of the lake were determined from water elevations measured continuously at the lake-stage gage on the northwestern side of the lake (fig. 2). Lake stage fluctuated from a minimum of 1.46 m (relative to an arbitrary datum) to a maximum of 2.25 m in MY 2003, and from a minimum of 1.49 m to a maximum of 2.19 m in MY 2004 (fig. 9). To simplify computations, the area of the lake was assumed to be constant (393 ha) during the study. The change in storage from beginning to end of the period for MY 2003 was +112,000 m^3, and for MY 2004, it was +422,000 m^3.

Precipitation

During the 2-year study period, total daily precipitation was measured at Butternut Creek at Cutoff Road near the northern end of the lake and at Butternut Creek at Highway B near the southern end of the lake during nonfreezing periods. During winter, precipitation was estimated by averaging the daily data from the National Weather Service stations (National Climatic Data Center, 2002–2004) at Butternut (about 2 km north of the lake) and at Park Falls (about 5 km southeast of the lake). Precipitation on the lake surface during MY 2003 was 63.9 cm (2,510,000 m^3) and during MY 2004, it was 89.9 cm (3,530,000 m^3; table 7). Precipitation was 78 percent of the long-term average (1971–2000) in 2003 and it was 110 percent of the long-term average in 2004.

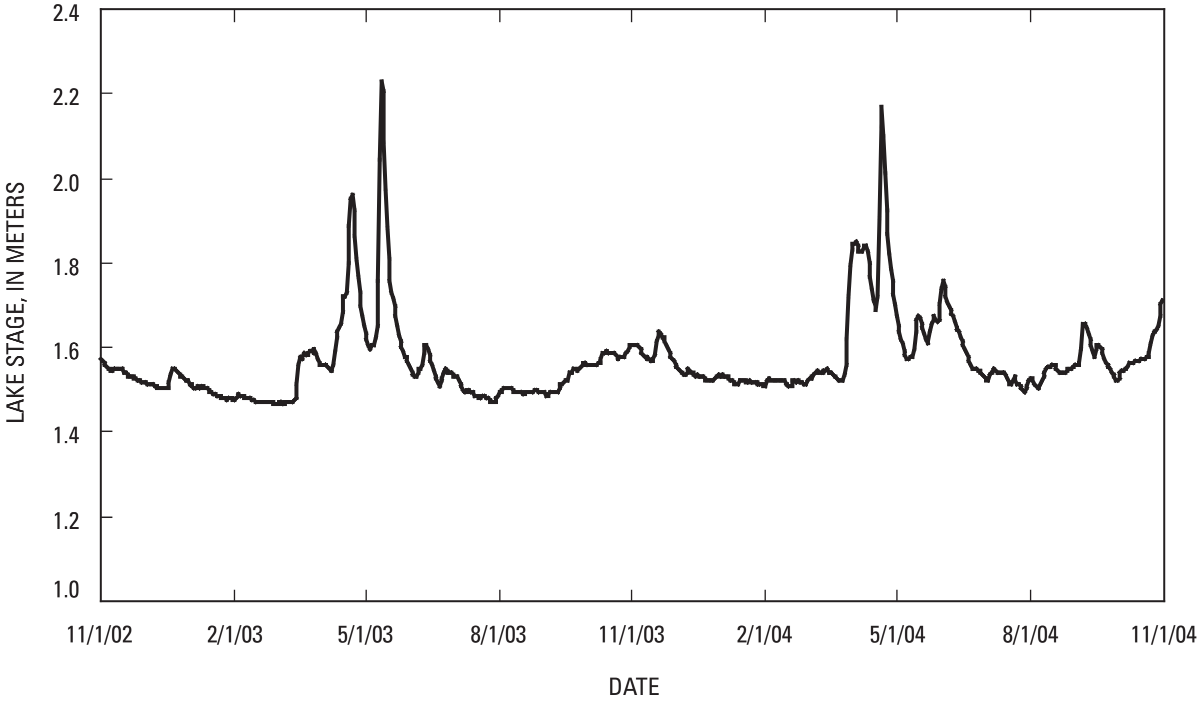


Figure 9. Measured daily water levels of Butternut Lake, Wis.

Table 7. Water budgets for Butternut Lake, Wis., for monitoring years 2003 and 2004, and average for the two years.

[MY, monitoring year (November–October); m^3, cubic meter; Cty., county; Hwy., highway]

Budget component	MY 2003 (thousands of m^3)	MY 2003 (percent)	MY 2004 (thousands of m^3)	MY 2004 (percent)
Inputs to lake				
Precipitation	**2,510**	**7.1**	**3,530**	**8.7**
North Basin	1,170	3.3	1,650	4.1
Middle Basin	803	2.3	1,130	2.8
South Basin	534	1.5	752	1.9
Tributaries	**31,300**	**89.2**	**35,600**	**88.0**
Butternut Creek inlet	22,100	63.0	24,400	60.2
Spiller Creek	6,830	19.5	8,500	21.0
Sum of small tributaries	2,390	6.8	2,740	6.8
Tributary at Cty. Hwy. B	105	.3	62	.2
Schnur Lake Outlet	665	1.9	665	1.6
Southwest Tributary #1	142	.4	291	.7
Southwest Tributary #2	173	.5	252	.6
Southeast Tributary	75	.2	72	.2
Mud Lake Outlet	549	1.6	614	1.5
Ungaged near-lake areas	681	1.9	780	1.9
Tributary input by basin	31,300	89.2	35,600	88.0
North Basin	30,100	85.8	34,100	84.3
Middle Basin	482	1.4	721	1.8
South Basin	710	2.0	799	2.0
Ground water	**1,280**	**3.6**	**1,320**	**3.3**
North Basin	640	1.8	659	1.6
Middle Basin	384	1.1	395	1.0
South Basin	256	.7	264	.7
TOTAL INPUT	**35,100**	**100.0**	**40,400**	**100.0**
Outputs from lake				
Evaporation	**2,650**	**7.6**	**2,520**	**6.2**
North Basin	1,240	3.6	1,180	2.9
Middle Basin	849	2.4	809	2.0
South Basin	565	1.6	538	1.3
Outlet (Butternut Creek)	**32,100**	**92.4**	**37,900**	**93.8**
Ground water	**0**	**.0**	**0**	**.0**
TOTAL OUTPUT	**34,700**	**100.0**	**40,400**	**100.0**

Table 7. Water budgets for Butternut Lake, Wis., for monitoring years 2003 and 2004, and average for the two years—Continued.

[MY, monitoring year (November–October); m^3, cubic meter; Cty., county; Hwy., highway]

Budget component	2-year average (thousands of m^3)	2-year average (percent)
Inputs to lake		
Precipitation	**3,020**	**8.0**
North Basin	1,410	3.7
Middle Basin	967	2.6
South Basin	643	1.7
Tributaries	**33,400**	**88.6**
Butternut Creek inlet	23,200	61.5
Spiller Creek	7,660	20.3
Sum of small tributaries	2,560	6.8
Tributary at Cty. Hwy. B	84	.2
Schnur Lake Outlet	665	1.8
Southwest Tributary #1	216	.6
Southwest Tributary #2	212	.6
Southeast Tributary	74	.2
Mud Lake Outlet	581	1.5
Ungaged near-lake areas	731	1.9
Tributary input by basin	33,400	88.6
North Basin	32,100	85.0
Middle Basin	601	1.6
South Basin	755	2.0
Ground water	**1,300**	**3.4**
North Basin	650	1.7
Middle Basin	390	1.0
South Basin	260	.7
TOTAL INPUT	**37,800**	**100.0**
Outputs from lake		
Evaporation	**2,590**	**6.9**
North Basin	1,210	3.2
Middle Basin	829	2.2
South Basin	552	1.5
Outlet (Butternut Creek)	**35,000**	**93.1**
Ground water	**0**	**.0**
TOTAL OUTPUT	**37,600**	**100.0**

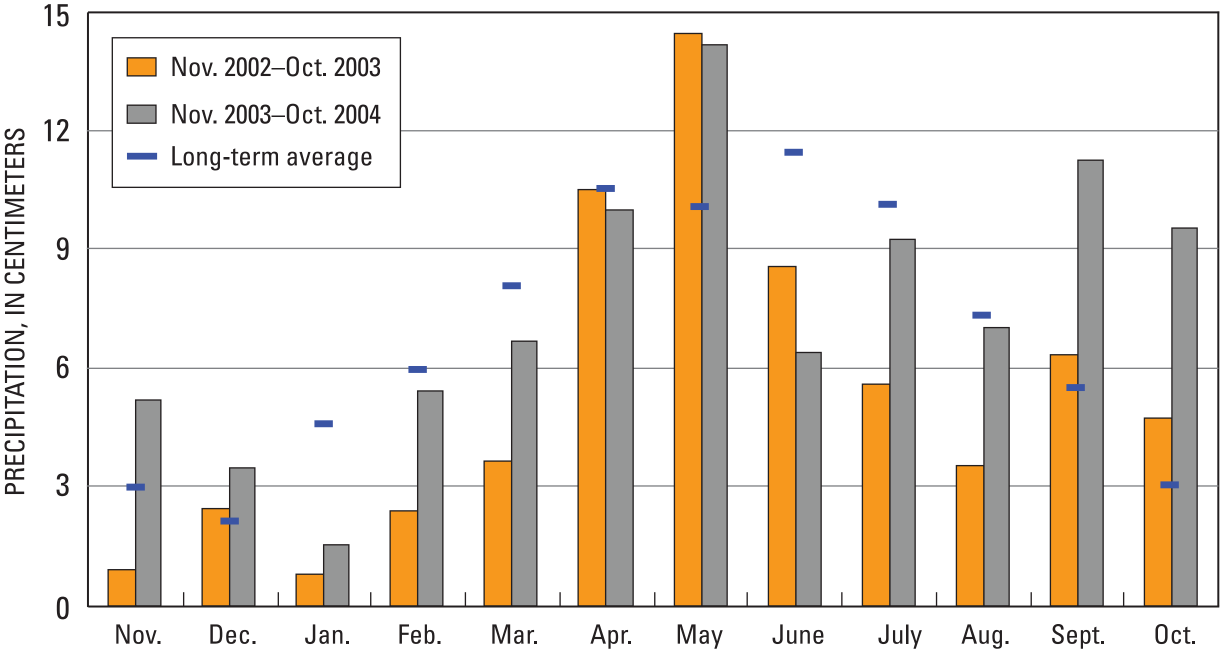


Figure 10. Precipitation at Butternut Lake, Wis., during November 2002 to October 2004, relative to long-term average precipitation at Park Falls, Wis.

Monthly precipitation during each study year is compared to the 1971–2000 average monthly precipitation in figure 10. In MY 2003, precipitation totals for December, April, May, September, and October were above or near the long-term average; all other monthly totals were much below average. In MY 2004, totals for all months except January and June were near or above average.

Evaporation

Evaporation from the lake surface was estimated from June–September pan evaporation measured at Marshfield, Wis., and published long-term monthly estimates of pan evaporation at Green Bay, Wis. Pan evaporation at Marshfield was available only for June, July, August, and September (National Climatic Data Center, 2003; and 2004). Estimates of long-term monthly average pan evaporation for Green Bay were available for the nonsummer months (Farnsworth and Thompson, 1982). Measured pan data from Marshfield and long-term monthly pan data from Green Bay were adjusted for the difference in location to Butternut Lake. Monthly lake/pan coefficients computed as part of a study on Vandercook Lake, Vilas County (Wentz and Rose, 1991) were then used to adjust the pan evaporation rates to obtain total lake evaporation. These coefficients ranged from 0.75 in May to 1.17 in October. It was assumed that evaporation from the lake was zero during periods of ice cover, and that the lake was ice covered from December through March. Annual evaporation in MY 2003 and MY 2004 was estimated to be 67.5 cm (2,650,000 m^3) and 64.3 cm (2,520,000 m^3), respectively (table 7).

Surface-Water Inflow

Daily inflow from Butternut Creek, the main tributary to the lake, was measured at the gaging station at Cutoff Road (fig. 2). The drainage area above this location is 74.7 km^2 (table 3). The annual average streamflow at this site was 0.70 m^3/s (22,100,000 m^3) in MY 2003 and 0.77 m^3/s (24,400,000 m^3) in MY 2004 (table 7; fig. 11). For comparison, the flow measured at the long-term USGS gaging station on the Chippewa River at Bishops Bridge near Winter, Wis. (about 25 km southwest of the lake) was 96 percent of the 94-year average for MY 2003 and 100 percent of the average for MY 2004 (Waschbusch and others, 2004; 2005).

Inflow to the lake from Spiller Creek was monitored at the gaging station at County Highway B, about 0.5 km west of the lake (fig. 2). The drainage area upstream from the gaging station is 22.8 km^2. The annual average streamflow at this site was 0.22 m^3/s (6,830,000 m^3) in

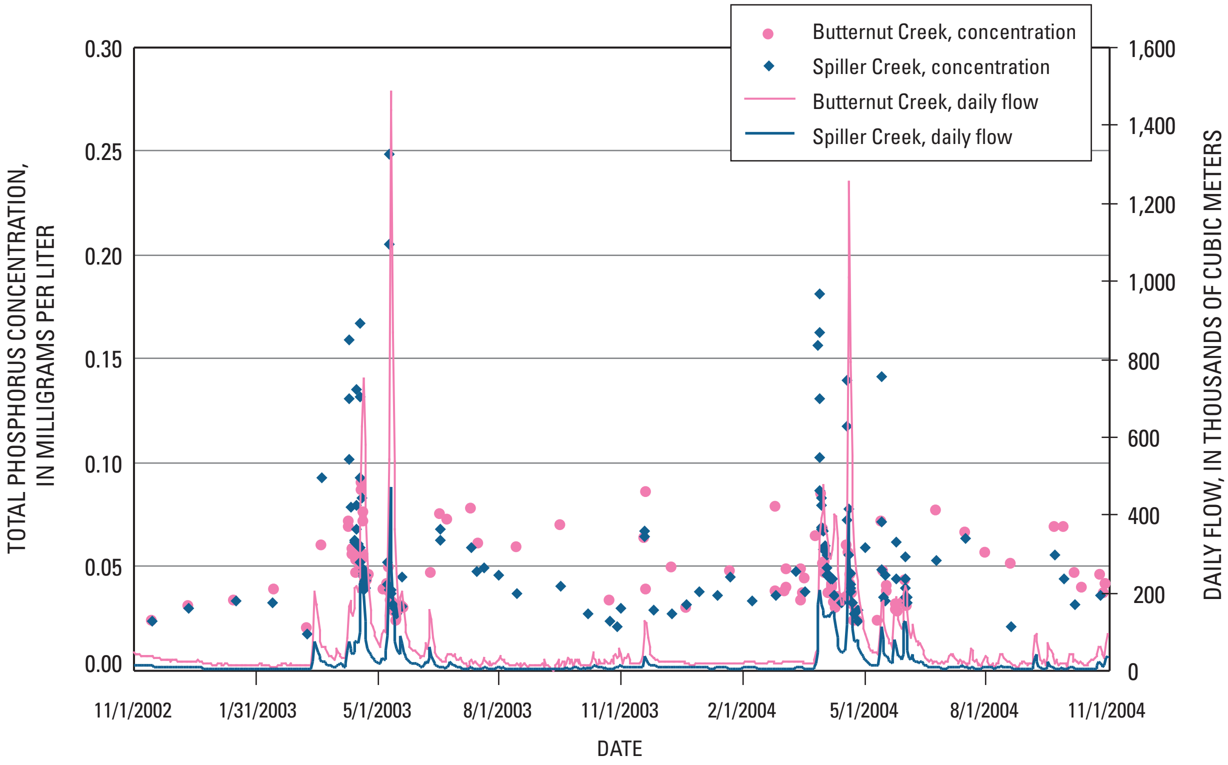


Figure 11. Daily-average flow and total phosphorus concentrations in Butternut Creek at Cutoff Road and Spiller Creek at Highway B, tributaries to Butternut Lake, Wis., November 1, 2002, through October 31, 2004.

MY 2003 and 0.27 m^3/s (8,500,000 m^3) in MY 2004 (table 7; fig. 11).

Of the six small tributaries that were monitored (fig. 2), Schnur Lake outlet and Mud Lake outlet yielded the most flow. The 2-year average flow volumes were 665,000 m^3 and 581,000 m^3 at Schnur Lake and Mud Lake outlets, respectively (table 7). The average annual flow volume from the remaining ungaged near-lake area was 731,000 m^3 during the 2-year period. The sum of flow from the six tributaries and the ungaged near-lake area was 2,390,000 m^3 and 2,740,000 m^3 in MY 2003 and MY 2004, respectively.

Surface-Water Outflow

Total annual surface-water outflow from the lake to Butternut Creek at the southern end of the lake (figs. 1 and 2) was 32,100,000 m^3 in MY 2003 and 37,900,000 m^3 in MY 2004 (table 7; fig. 12). Most of the outflow occurred during May and June.

Ground-Water Inflow and Outflow

Ground-water inflow to the lake was calculated on the basis of base-flow estimates for the area contributing ground water to Spiller Creek and hydraulic-head data from the near-lake piezometers (fig. 2). The hydraulic gradient in the eight near-lake piezometers indicated that the flow of ground water was from the aquifer to the lake along most of the lake's shoreline. The head differences relative to the lake surface ranged from near 0.0 m at piezometer 3 to greater than 0.5 m at piezometer 8.

Several assumptions were necessary to estimate the amount of ground-water inflow to the lake because the data needed to do a rigorous analysis were not available. Base flow in Spiller Creek was assumed to be mostly ground-water discharge. The ground-water contributing area for Spiller Creek was assumed to coincide with its surface watershed. Ground-water discharge to the lake was assumed to be proportional to the ground-water discharge to Spiller Creek by the ratio of the ground-water contributing area of Butternut Lake to the contributing area to Spiller Creek. The ground-water contributing area to the lake was coarsely determined by an analysis of topography

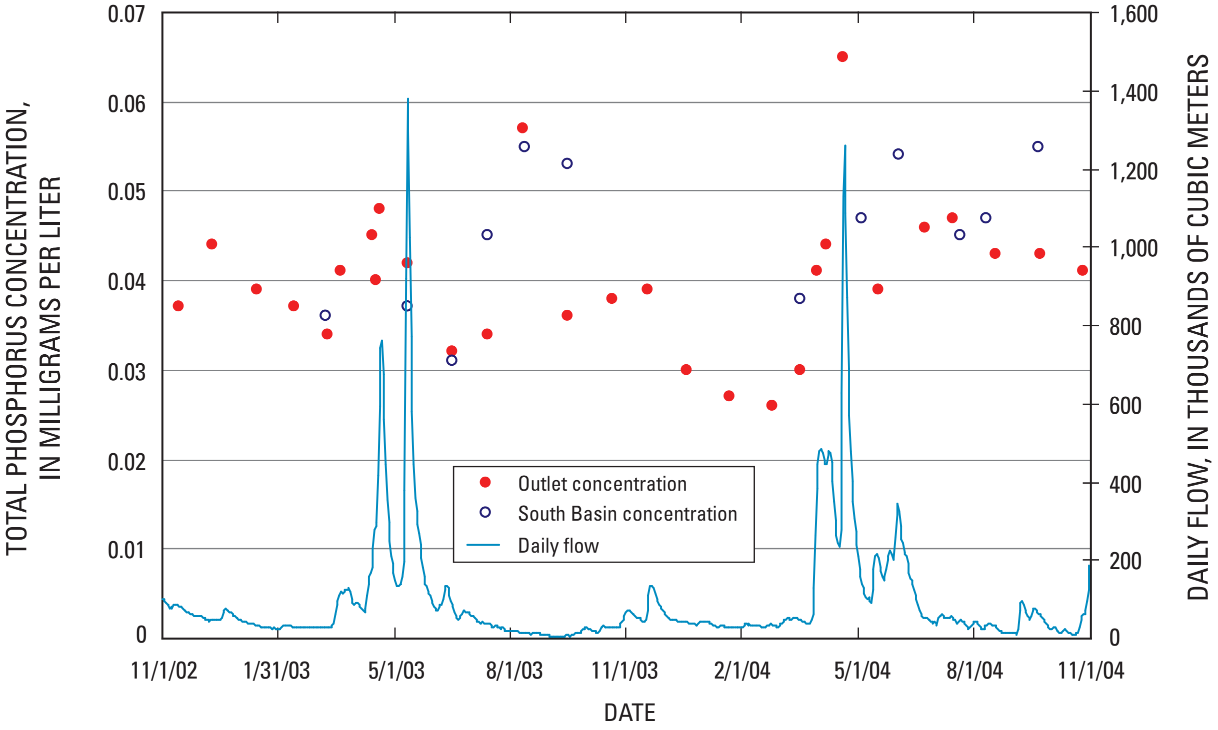


Figure 12. Daily-average flow and total phosphorus concentrations in Butternut Creek at Highway B, outlet from Butternut Lake, Wis., November 1, 2002, through October 31, 2004.

and the altitudes of nearby water features. The estimated ground-water contributing area is shown in figure 13.

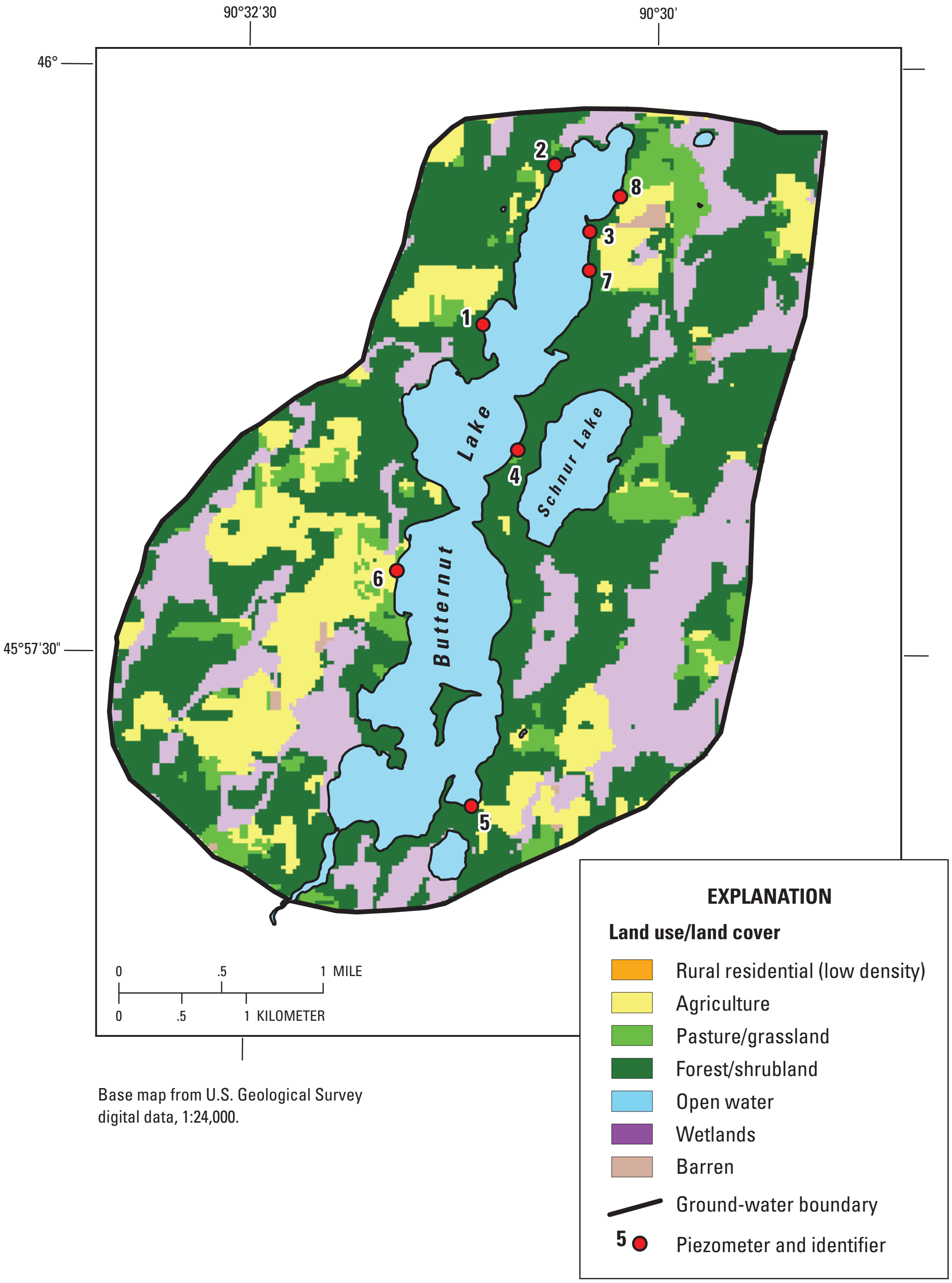
The estimated ground-water discharge to Butternut Lake was 1,280,000 m^3 in MY 2003 and 1,320,000 m^3 in MY 2004 (table 7). Ground-water discharge from the lake, or leakage, was assumed to be zero, because the near-lake piezometer data showed no areas where flow was coming from the lake. It is possible that there is some, but insignificant, leakage in a small area near the outlet at the southern end of the lake.

Water-Budget Summary

Butternut Creek is the largest source of water to the lake, supplying 61.5 percent of the total input during the 2-year study period (table 7; fig. 14). Other sources were Spiller Creek (20.3 percent), precipitation (8.0 percent), small tributaries and the ungaged near-lake drainage (6.8 percent), and ground water (3.4 percent). The total input of water in MY 2003 (35,100,000 m^3) was less than in MY 2004 (40,400,000 m^3), because of the below-normal precipitation during MY 2003 and above normal precipitation in MY 2004. 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 0.45 and 0.39 years on the basis of the total inflows for MY 2003 and MY 2004, respectively, or 0.42 years on the basis of the 2 years of data averaged.

The total annual outputs of water from the lake were slightly less than the total inputs and resulted in a small increase in storage from the beginning to the end of each study year. This amounted to an increase in lake stage of 0.13 m or about 534,000 m^3 of storage in the lake during the 2-year study period. On average, 93.1 percent of the total water leaving the lake left through the Butternut Creek outlet, and evaporation accounted for the remaining 6.9 percent (table 7; fig 14).

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 as meters on the surface of the lake (fig. 15). The differences between the calculated inputs and outputs reflect the cumulative errors in the estimates of all of the components in the water budget. The largest monthly differences were in May 2003 and April 2004,



Base map from U.S. Geological Survey
digital data, 1:24,000.

Figure 13. Estimated ground-water contributing area to Butternut Lake, Wis. Land use/land cover from the WISCLAND geographic information system coverage (Wisconsin Department of Natural Resources, 1998).

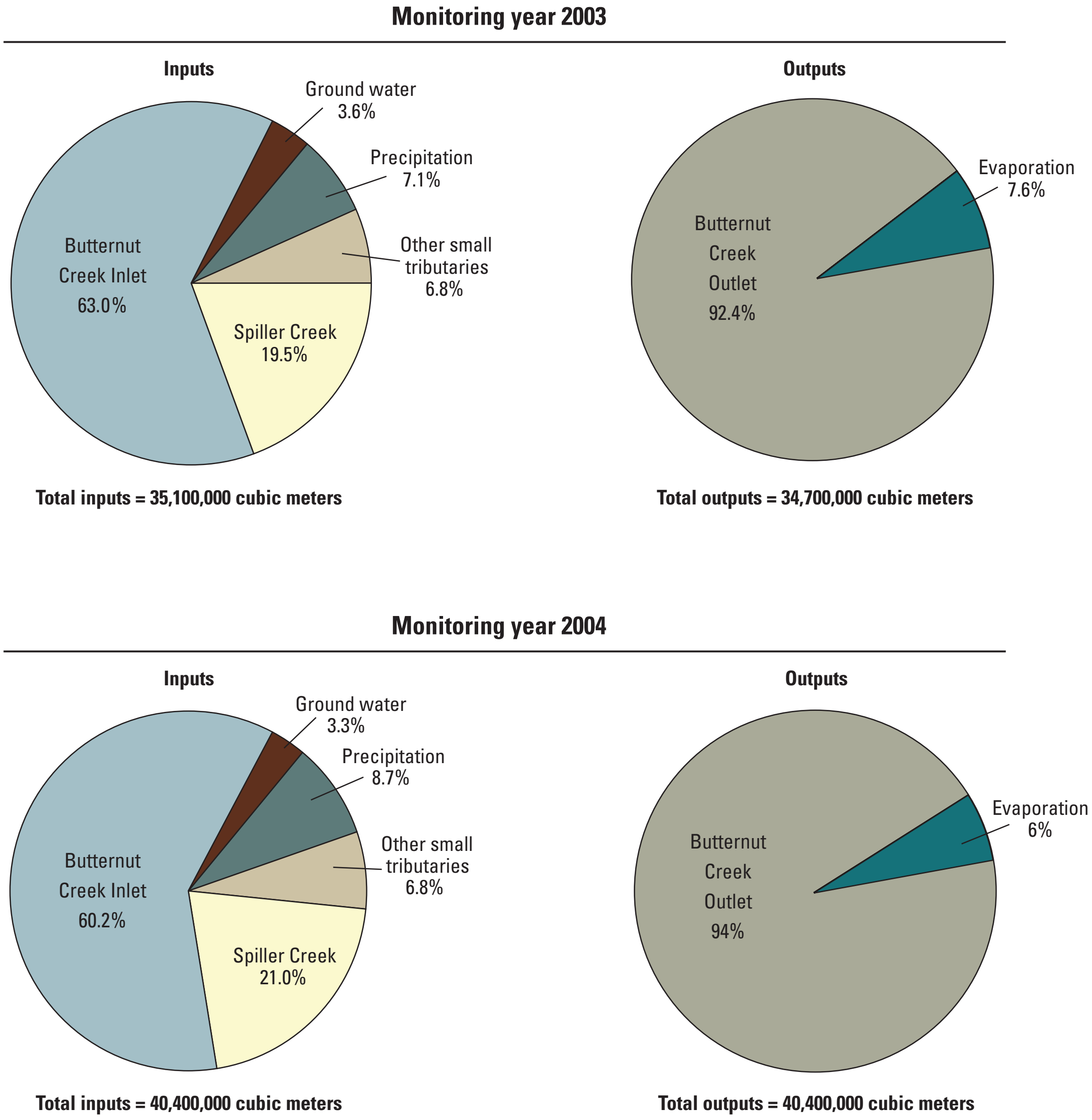


Figure 14. Water budgets for Butternut Lake, Wis., for monitoring years 2003 and 2004. [%, percent]

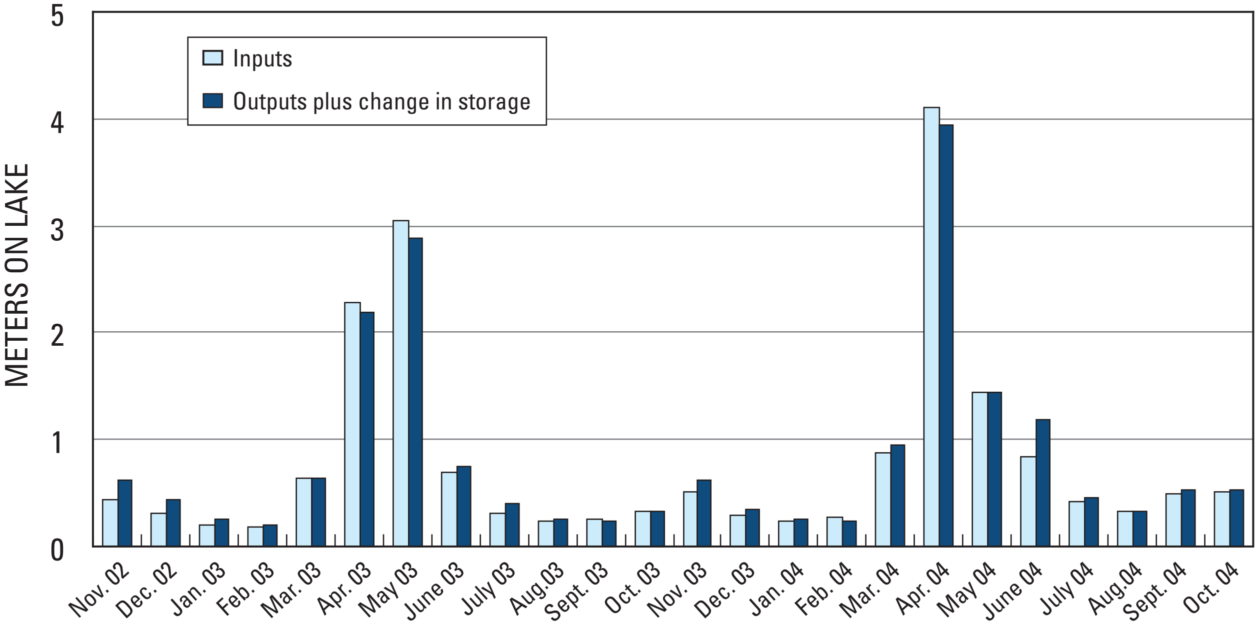


Figure 15. Monthly accuracy of the water budget based on monthly total water inputs and outputs plus storage change for Butternut Lake, Wis.

which when expressed as percentages were only about 10 and 8 percent, respectively. The largest errors occurred during spring when overland flow from the ungaged area was highest. On an annual basis, the percentage error was about 1 percent.

Sources of Phosphorus

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

Precipitation

Phosphorus input to the lake from direct precipitation was estimated by multiplying the daily precipitation volumes by a constant concentration of 0.007 mg/L, a value suggested by Rose (1993) for northern Wisconsin. Phosphorus inputs to the lake from precipitation were 18 kg in MY 2003 and 25 kg in MY 2004 (table 8).

Surface-Water Inflow

Phosphorus loads were estimated for the continuously monitored sites at the Butternut Creek inlet to the lake, Spiller Creek, and the Butternut Creek outlet, as well as for the six small tributaries to the lake and the ungaged near-lake area.

Butternut Creek Inlet

Phosphorus in Butternut Creek inlet at Cutoff Road (fig. 2) originates from the upper watershed, including the Village of Butternut. Total phosphorus concentrations for 114 samples collected during the 2-year study ranged from 0.020 to 0.090 mg/L (fig. 11). The median concentration and flow-weighted-average concentrations were 0.044 and 0.043 mg/L, respectively. On average, about 61 percent of the phosphorus was in the dissolved form. The total quantity of phosphorus delivered from Butternut Creek was 921 kg in MY 2003 and 1,080 kg in MY 2004 (table 8). Yields from the Butternut Creek watershed were 12.3 kg/km^2 in MY 2003 and 14.4 kg/km^2 in MY 2004. These yields are lower than 49 of the 52 rural watersheds that were monitored in Wisconsin and among the lowest

Table 8. Phosphorus budgets for Butternut Lake, Wis., for monitoring years 2003 and 2004, and average for the two years.

[MY, monitoring year (November–October); kg, kilogram; Cty., county; Hwy., highway]

Budget component	MY 2003 (kg)	MY 2003 (percent)	MY 2004 (kg)	MY 2004 (percent)
Inputs to lake				
Precipitation	**18**	**1.2**	**25**	**1.4**
North Basin	8	0.6	12	0.7
Middle Basin	6	.4	8	.5
South Basin	4	.3	5	.3
Tributaries	**1,370**	**94.5**	**1,650**	**94.9**
Butternut Creek inlet	921	63.6	1,080	62.1
Spiller Creek	330	22.8	405	23.4
Sum of small tributaries	117	8.1	164	9.5
Tributary at Cty. Hwy. B	4	0.3	2	0.1
Schnur Lake Outlet	15	1.0	13	.7
Southwest Tributary #1	16	1.1	42	2.5
Southwest Tributary #2	18	1.2	25	1.5
Southeast Tributary	4	.3	4	.2
Mud Lake Outlet	27	1.9	30	1.7
Ungaged near-lake areas	33	2.3	47	2.7
Tributary input by basin	1,370	94.5	1,650	94.9
North Basin	1,290	89.1	1,530	88.0
Middle Basin	42	2.9	78	4.5
South Basin	35	2.4	41	2.4
Ground water	**22**	**1.5**	**22**	**1.3**
North Basin	11	.8	11	.6
Middle Basin	7	.5	7	.4
South Basin	4	.3	4	.3
Septic systems	**41**	**2.8**	**41**	**2.3**
North Basin	17	1.2	17	1.0
Middle Basin	11	.8	11	.7
South Basin	13	.9	13	.7
Total external input	**1,450**	**100.0**	**1,730**	**100.0**
Sediment release				
North Basin	467	49.4	467	49.4
Middle Basin	306	32.4	306	32.4
South Basin	172	18.2	172	18.2
Total internal input	**945**	**100.0**	**945**	**100.0**
TOTAL INPUT	**2,390**		**2,680**	
Outputs from lake				
Evaporation	**0**	**.0**	**0**	**.0**
Outlet (Butternut Creek)	**1,320**	**100.0**	**1,670**	**100.0**
Ground water	**0**	**.0**	**0**	**.0**
TOTAL OUTPUT	**1,320**	**100.0**	**1,670**	**100.0**
Stored in lake				
STORED IN LAKE	**1,070**		**1,010**	

Table 8. Phosphorus budgets for Butternut Lake, Wis., for monitoring years 2003 and 2004, and average for the two years—Continued.

[MY, monitoring year (November–October); kg, kilogram; Cty., county; Hwy., highway]

Budget component	2-year average (kg)	2-year average (percent)
	Inputs to lake	
Precipitation	**21**	**1.3**
North Basin	10	0.6
Middle Basin	7	.4
South Basin	5	.3
Tributaries	**1,510**	**94.7**
Butternut Creek inlet	999	62.8
Spiller Creek	368	23.1
Sum of small tributaries	140	8.8
Tributary at Cty. Hwy. B	3	0.2
Schnur Lake Outlet	14	.9
Southwest Tributary #1	29	1.8
Southwest Tributary #2	22	1.4
Southeast Tributary	4	.3
Mud Lake Outlet	29	1.8
Ungaged near-lake areas	40	2.5
Tributary input by basin	1,510	94.7
North Basin	1,410	88.5
Middle Basin	60	3.8
South Basin	38	2.4
Ground water	**22**	**1.4**
North Basin	11	.7
Middle Basin	7	.4
South Basin	4	.3
Septic systems	**41**	**2.6**
North Basin	17	1.1
Middle Basin	11	.7
South Basin	13	.8
Total external input	**1,590**	**100.0**
Sediment release	**945**	**100.0**
North Basin	467	49.4
Middle Basin	306	32.4
South Basin	172	18.2
Total internal input	**945**	**100.0**
TOTAL INPUT	**2,540**	
	Outputs from lake	
Evaporation	**0**	**.0**
Outlet (Butternut Creek)	**1,490**	**100.0**
Ground water	**0**	**.0**
TOTAL OUTPUT	**1,490**	**100.0**
	Stored in lake	
STORED IN LAKE	**1,050**	

for the Northern Lakes and Forests ecoregion (Corsi and others, 1997).

Spiller Creek

Total phosphorus concentrations for 132 samples collected at Spiller Creek during the 2-year study ranged from 0.018 to 0.249 mg/L (fig. 11). The median and flow-weighted-average concentrations were 0.046 and 0.048 mg/L, respectively. On average, about 67 percent of the phosphorus was in the dissolved form. The total quantity of phosphorus delivered to the lake by Spiller Creek was 330 kg in MY 2003 and 405 kg in MY 2004 (table 8). Yields from the Spiller Creek watershed were 14.5 kg/km^2 in MY 2003 and 17.8 kg/km^2 in MY 2004. These yields are slightly higher than the yields from the Butternut Creek watershed, but they are much lower than yields for most of the monitored rural watersheds in Wisconsin (Corsi and others, 1997).

Small Tributaries and Ungaged Near-Lake Area

In all, 109 runoff samples were collected from the six small tributaries to the lake. Total phosphorus concentrations ranged from 0.015 to 0.665 mg/L. The median and flow-weighted-average concentrations were 0.053 and 0.055 mg/L, respectively. The combined total quantity of phosphorus delivered to the lake by these tributaries and the other ungaged near-lake area was 117 kg in MY 2003 and 164 kg in MY 2004 (table 8). Yields from the combined tributary and ungaged area were 5.7 kg/km^2 in MY 2003 and 8.0 kg/km^2 in MY 2004, which are even lower than the yields from the Butternut Creek and Spiller Creek watersheds. The Mud and Schnur Lake watersheds represent 51.1 percent of the total area of the six small tributaries and ungaged near-lake area. The relatively low yields, in part, may be attributed to the lakes trapping some of the phosphorus contributed by their watersheds.

Ground Water

Dissolved phosphorus concentrations in water collected from the eight near-lake piezometers (fig. 2) were used to estimate the phosphorus concentration in the ground water entering the lake. Average concentrations ranged from 0.009 mg/L in piezometer 1 to 0.348 mg/L in piezometer 3, and the median concentration of all of the samples was 0.017 mg/L. The phosphorus concentration in piezometer 3 was about 14 times greater than the average concentration from the other seven piezometers. Hence, it was assumed that the concentration in piezometer 3 was not typical of ground water entering the lake, and it may have been influenced by a local factor such as a septic system. In order to estimate the phosphorus input to the lake by ground water, it was assumed that the concentration of water entering the lake was equal to the median concentration measured in the piezometers (0.017 mg/L). Thus, ground water delivered about 22 kg of phosphorus to the lake annually (table 8).

Septic Systems

The input of phosphorus from septic systems (M) was estimated by use of equation 5 (Reckhow and others, 1980):

$$M = E_s * (\textit{number of capita years}) * (1\text{-}S_R), \qquad (5)$$

where M is a function of a phosphorus export coefficient, E_s, a soil retention coefficient, S_R, and the number of people using the septic systems annually (*capita years*). In applying equation 5, it was assumed that the most likely value for E_s was 0.68 kg of phosphorus per capita per year. Typical export coefficients range from 0.5 kg per capita per year (Reckhow and others, 1980; Panuska and Kreider, 2002) to 0.82 kg per capita per year (Garn and others, 1996). The *number of capita years* was estimated to be 200, based on 150 year-round residents and 198 3-month residents. The number of residents was estimated from the number of parcels of land around the lake with houses, assuming that the parcels with nonlocal ownership were occupied only 3 months of the year. All houses occupied year round were assumed to have two residents, and houses occupied for 3 months were assumed to have three residents. A value of 0.7 (70 percent retention by the soil) was used for S_R. Based on the above assumptions, the annual input of phosphorus from septic systems was 41 kg (table 8). Because inputs from septic systems were not directly measured, low and high estimates for septic inputs were obtained by applying high and low estimates for S_R (0.9 and 0.5) in equation 5. The low and high estimates for phosphorus inputs from septic systems were 14 and 68 kg, respectively.

Release of Phosphorus from Lake Sediments

Rates of phosphorus release from the aerobic and anaerobic sediments in Butternut Lake were estimated from 18 sediment cores collected from the lake (fig. 2) and

Table 9. Summary of estimated rates of phosphorus release from the sediments of Butternut Lake, Wis., in August 2004.

[ID, identification number; mg/m^2/d, milligram per square meter per day; *r*, correlation coefficient; --, not applicable]

Sample description/ core ID	Aerobic or anaerobic	Release rate (mg/m^2/d)	Regression fit from laboratory results (*r*)	Average release at site (mg/m^2/d)
Lake water blank	Aerobic	-0.08	NA	--
		North Basin		
1A	Aerobic	0.30	0.83	0.34
1B	Aerobic	.39	.90	--
2A	Aerobic	1.24	.92	1.53
2B	Aerobic	1.82	.98	--
2C	Anaerobic	5.23	.97	5.56
2D	Anaerobic	5.88	.98	
3A	Aerobic	.67	.93	.63
3B	Aerobic	.59	.97	--
Average	**Aerobic**	**.83**	**--**	**--**
Average	**Anaerobic**	**5.56**	**--**	**--**
		Middle Basin		
4A	Aerobic	1.02	0.88	0.77
4B	Aerobic	.52	.92	--
4C	Anaerobic	7.51	.98	6.32
4D	Anaerobic	5.13	.97	--
5A	Aerobic	.71	.97	.55
5B	Aerobic	.39	.93	--
5C	Anaerobic	4.78	.96	5.49
5D	Anaerobic	6.21	.97	
Average	**Aerobic**	**.66**	**--**	**--**
Average	**Anaerobic**	**5.91**	**--**	**--**
		South Basin		
6A	Aerobic	1.02	0.98	0.78
6B	Aerobic	.53	.97	--
Average	**Aerobic**	**.78**	**--**	**--**
Average	**Anaerobic**	**5.91**[a]	**--**	**--**

[a] Value not computed; therefore, the release rates were obtained from the Middle Basin.

analyzed in the laboratory. Average aerobic-release rates at 22ºC ranged from 0.66 mg/m^2/d in the Middle Basin to 0.83 mg/m^2/d in the North Basin (table 9). Average anaerobic-release rates at 22ºC ranged from 5.56 mg/m^2/d in the North Basin to 5.91 mg/m^2/d in the Middle Basin. No sediment cores from the South Basin were analyzed under anaerobic conditions; therefore, it was assumed that its anaerobic-release rate was similar to that of the Middle Basin.

For each basin, the amount of phosphorus released from the sediment was computed on a daily basis by summing the amount of phosphorus released from the aerobic and anaerobic areas. The daily aerobic and anaerobic areas were obtained by linear interpolating between the dates for which these areas were estimated (table 4); the sediment release was assumed to be similar for both years. The daily sediment release was computed as the product of the temperature-adjusted release rates (rates in table 9 multiplied by the values from fig. 3 corresponding to the estimated daily water temperature for that day) and the respective aerobic and anaerobic areas. The estimated phosphorus released from the sediments of the North Basin was 467 kg (table 8; 216 kg from aerobic sediments and 251 kg from anaerobic sediments), from the Middle Basin was 306 kg (117 kg from aerobic sediments and 189 kg from anaerobic sediments), and from the South Basin was 172 kg (94 kg from aerobic sediments and 77 kg from anaerobic sediments). Therefore, on an annual basis, the sediments released an estimated total of 945 kg (427 kg from aerobic sediments and 518 kg from anaerobic sediments). Approximately 90 percent of the phosphorus was released during May through September.

Surface-Water Outflow

Phosphorus is discharged from the lake into Butternut Creek through its outlet. Total phosphorus concentrations in the 29 samples collected near the outlet during the 2-year study period ranged from 0.026 to 0.065 mg/L (fig. 12), and the flow-weighted-average concentration was 0.043 mg/L. The total phosphorus output from the lake to Butternut Creek was 1,320 kg in MY 2003 and 1,670 kg in MY 2004 (table 8).

Phosphorus Budget Summary

The average annual load of phosphorus to the lake was 2,540 kg, of which 1,590 kg came from external sources (63 percent) and 945 kg came from the sediments in the lake (37 percent). Internal loading of phosphorus ranged from 38.5 percent of the total phosphorus load to the lake in MY 2003 to 35.3 percent in MY 2004 (fig. 16). During wet years, this internal release represents a smaller percentage of the total phosphorus delivered to the lake and during dry years, it represents a higher percentage.

The total external input of phosphorus to Butternut Lake was 1,450 kg in MY 2003 and 1,730 kg in MY 2004, for an average annual input of 1,590 kg (table 8). The largest external source of phosphorus entering the lake is from Butternut Creek, which delivered about 63 percent of the external phosphorus entering the lake (table 8; about 39 percent of the total phosphorus load to the lake, fig. 16) compared with about 61 percent of the water input (table 7; fig. 14). The next largest external contribution was from Spiller Creek, which delivered about 23 percent of the external phosphorus entering the lake (about 14 percent of the total load to the lake). The six small tributaries and ungaged near-lake area contributed about 9 percent of the total external load to the lake (about 6 percent of the total load to the lake). Minor contributions were from precipitation, ground water, and septic systems, which accounted for 1.3, 1.4, and 2.2 percent of the external load, respectively (about 0.8, 0.9, and 1.6 percent, respectively, of the total load). If the high estimates for phosphorus contributions from septic systems (68 kg) were used in the budget, septic systems would increase to about 4 percent of the total external phosphorus load (about 3 percent of the total load to the lake). External phosphorus loading in MY 2004 was about 1.2 times that in MY 2003 because of the greater precipitation and accompanying runoff during MY 2004.

The average annual surface-water discharge of phosphorus into Butternut Creek was 1,490 kg; 1,320 kg of phosphorus in MY 2003 and 1,670 kg in MY 2004. Therefore, on average, about 94 percent of the external inputs or 59 percent of the total load to the lake is removed from the lake. An even higher percentage of the phosphorus input to the lake would have been exported if the volume of water leaving the lake would have been equal to that entering the lake during the study period. About 6 percent of the new phosphorus entering the lake is retained in the lake sediments and contribute to the continued release from the sediments.

The total load of phosphorus to the lake in MY 2003 and MY 2004 is expected to be much smaller than it was prior to 1980 when sewage, creamery, and cheese-factory effluents were discharged into Butternut Creek and more intensive agriculture (including dairy or beef farming) and deficient septic systems in the watershed exported more phosphorus to the lake. The USEPA estimated that the total external load of phosphorus during 1972 was about 2,600 kg, with 895 kg contributed by sewage effluent from the Village of Butternut and 73 kg from septic systems (U.S. Environmental Protection Agency, 1974), which is approximately 62 percent greater than in MY 2003–04.

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

Empirical models that relate phosphorus loading to measured water-quality characteristics can be used to determine how further reductions in phosphorus loading could improve the present-day water quality of the lake and how increases in phosphorus loading could degrade water quality. These models were developed on the basis of comparisons of hydrologic and phosphorus loading

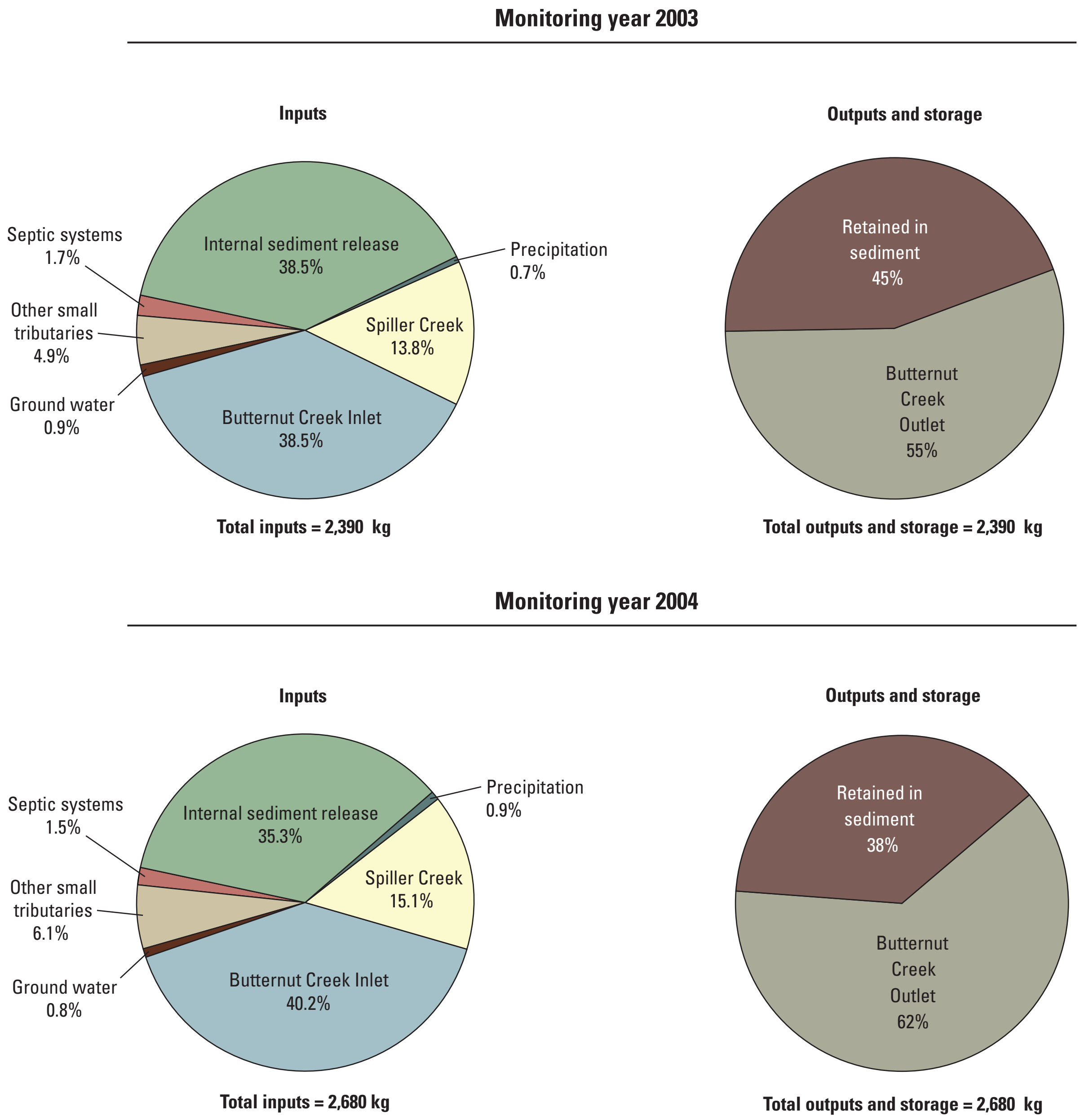


Figure 16. Phosphorus budgets for Butternut Lake, Wis., for monitoring years 2003 and 2004. [%, percent]

estimates determined for many different lake systems, with specific measures for describing lake water quality, such as near-surface phosphorus and chlorophyll *a* concentrations, and Secchi depth. Some of these empirical models are contained within the BATHTUB model (Walker, 1996) and the Wisconsin Lake Modeling Suite (WiLMS; Panuska and Kreider, 2002). The BATHTUB model has hydrologic transport algorithms and is, therefore, capable of simulating changes in water quality in complex lakes (multibasin lakes or lakes connected by short channels), whereas WiLMS is more suited for simulating changes in single-basin lakes or lakes with relatively uniform (horizontally uniform) water quality. To predict changes in the water quality of Butternut Lake that should occur with changes in phosphorus loading, the BATHTUB model was applied to the three basins of Butternut Lake using the most applicable algorithm in the model for each water-quality constituent. Because the water quality was relatively uniform throughout the different basins in Butternut Lake, several of the models within WiLMS also were applied to the entire lake to determine if other water-quality models demonstrated similar relations to the single phosphorus algorithm that was applied with BATHTUB.

Modeling Approach

To estimate the expected changes in water quality in Butternut Lake in response to changes in phosphorus loading, nine scenarios were simulated with the BATHTUB model. The first scenario simulated the average conditions for MY 2003–04 and established a base case to which the other eight simulations were compared. Eight basin-wide strategies simulated decreases in controllable external phosphorus loading by 50 and 25 percent and increases in controllable external phosphorus loading by 25, 50, 75, 100, 200, and 400 percent. Controllable external loading includes phosphorus from septic systems and all of the tributaries and nearshore areas of the lake. In addition, the base case, the 50-percent decrease, and the 400-percent increase in controllable external loading were simulated with no additional internal phosphorus loading added in the model to determine how the water quality of the lake could change if internal phosphorus loading from the sediments could be eliminated. Nine of the models within WiLMS were then used to simulate the average conditions in MY 2003–04.

Data Requirements

Four types of data are required as input into these models: morphometric data (table 2), water-quality data (table 5), hydrologic data (table 7), and nutrient-loading data (table 8). For the BATHTUB model, all of this information is needed for each basin, whereas for the models in WiLMS, this information is needed only for the lake as a whole. For the BATHTUB model, in addition to total phosphorus concentrations, dissolved ortho-phosphorus concentrations are needed. Dissolved ortho-phosphorus concentrations were obtained by multiplying the flow-weighted-average total phosphorus concentration for each stream by the fraction of phosphorus that was in the dissolved form in samples collected in that stream. The time period for the hydrologic and nutrient loading used in the BATHTUB model is dependent on the phosphorus-turnover ratio (number of times the phosphorus mass in the lake is replaced in a specific time period). The model should be run for a period that results in a phosphorus-turnover ratio greater than 2. Annual simulations resulted in a phosphorus turnover ratio of 5.4 for the lake as a whole; therefore, the average annual loadings in tables 7 and 8 were used in the model. Even though loading data are summarized for the entire year, the model simulates water quality only for the growing season (May through September). All of the models within WiLMS use annual hydrologic and phosphorus loadings, but they simulate the water quality for different discrete seasons (described later). Phosphorus from internal loading (sediment release) is not typically included as a phosphorus source for BATHTUB and WiLMS, because most empirical models already incorporate this source; therefore, this source should be added only when a lake/reservoir has abnormally high internal loading (Walker, 1996). It was believed that Butternut Lake, being polymictic, has abnormally high internal loading; therefore, an average internal loading of 1.0 mg/m^2/d was applied in BATHTUB simulations; a value of 1.0 mg/m^2/d equates to about 1,400 kg per year. This value appears reasonable given the release rates obtained from the sediment cores incubated in the laboratory (table 9). The models within WiLMS also were used to estimate the amount of internal phosphorus loading by determining how much additional phosphorus would be required to accurately simulate the water quality measured in MY 2003–04.

Algorithms and Calibration

When applying BATHTUB, the specific algorithms used to simulate each water-quality characteristic must be defined. The algorithms chosen to simulate total phosphorus and chlorophyll *a* concentrations are listed in table 10; all are the default algorithms and have been shown to usually be the best models for most lakes and reservoirs. Nonalgal turbidity factors (or the reduction in clarity caused by factors other than algae) were computed within BATHTUB. Calibration coefficients for each water-quality constituent may be applied for each lake/basin. The calibration coefficients applied in the simulations for Butternut Lake are given in table 11. Only small adjustments were required for estimating chlorophyll *a* concentrations in the North and Middle Basins. No other calibrations were required.

With the average annual loading data from WY 2003–04, BATHTUB was used to simulate the summer-average water quality (May through September) in each basin and the entire lake. The simulated and measured values for

Table 10. Algorithms within the BATHTUB model (Walker, 1996) that were used to simulate water quality in the basins in Butternut Lake, Wis.

Process	Model number	Algorithm description
Phosphorus balance	1	Second order, available phosphorus
Nitrogen balance	0	Not computed
Chlorophyll *a* concentration	2	Phosphorus, light, and temperature
Secchi depth	1	Chlorophyll *a* and turbidity
Dispersion	1	Fisher numeric
Phosphorus calibration	1	Decay rates
Nitrogen calibration	0	None

Table 11. Calibration coefficients used in the BATHTUB model (Walker, 1996) simulations of the water quality in the basins in Butternut Lake, Wis.

Basin	Total phosphorus	Chlorophyll *a*	Secchi depth
North	1.00	1.15	1.00
Middle	1.00	1.25	1.00
South	1.00	1.00	1.00

MY 2003–04 (table 5) are compared in figure 17. For each characteristic, the simulated values are given for the precalibrated and calibrated (simulated) models. The coefficient of variation for each measured value was computed on the basis of all of the summer-average data from 1986 to 2005 from the Deep-hole Site and used to calculate an estimate of the certainty of the measured data (plus and minus one standard error around the average summer value). After model calibration, BATHTUB accurately simulated total phosphorus to within ± 0.001 mg/L, chlorophyll *a* to within ± 2 µg/L, and Secchi depths to within ± 0.01 m in all of the basins and the lake as a whole.

Models within WiLMS also were used to simulate the average conditions in MY 2003–04. Of the 13 empirical models contained in WiLMS, 9 of the models were applicable to the hydrologic system of Butternut Lake. To determine if these nine models were capable of simulating phosphorus concentrations in this polymictic lake, the morphometry of the lake and the average hydrologic and phosphorus loadings for MY 2003–04 were input into these models and near-surface total phosphorus concentration was simulated. All of the models within WiLMS use annual hydrologic and phosphorus loadings, but they simulate water quality for discrete seasons; however, each season had a measured total phosphorus concentration of 0.044 mg/L.

The average simulated total phosphorus concentration for MY 2003–04 from the nine models in WiLMS was 0.024 mg/L (table 12). This value is about one-half of the concentration measured in the lake (0.044 mg/L). All nine models simulated a total phosphorus concentration that was much lower than that measured in the lake, indicating that this polymictic lake behaves much differently than a typical dimictic lake.

The models in WiLMS also can be used to determine how much the phosphorus load would need to be increased for Butternut Lake to respond as a typical lake. The annual phosphorus loads required for each of these models to simulate an in-lake phosphorus concentration of 0.044 mg/L are given in table 12. To properly simulate the measured conditions in Butternut Lake, the annual phosphorus load should be about 3,260 kg. Therefore, results from these models suggest that there should be an additional phosphorus load of 1,660 kg (or 51 percent more than the measured average-annual external phosphorus load to the lake). It was estimated from the core studies that the annual inter-

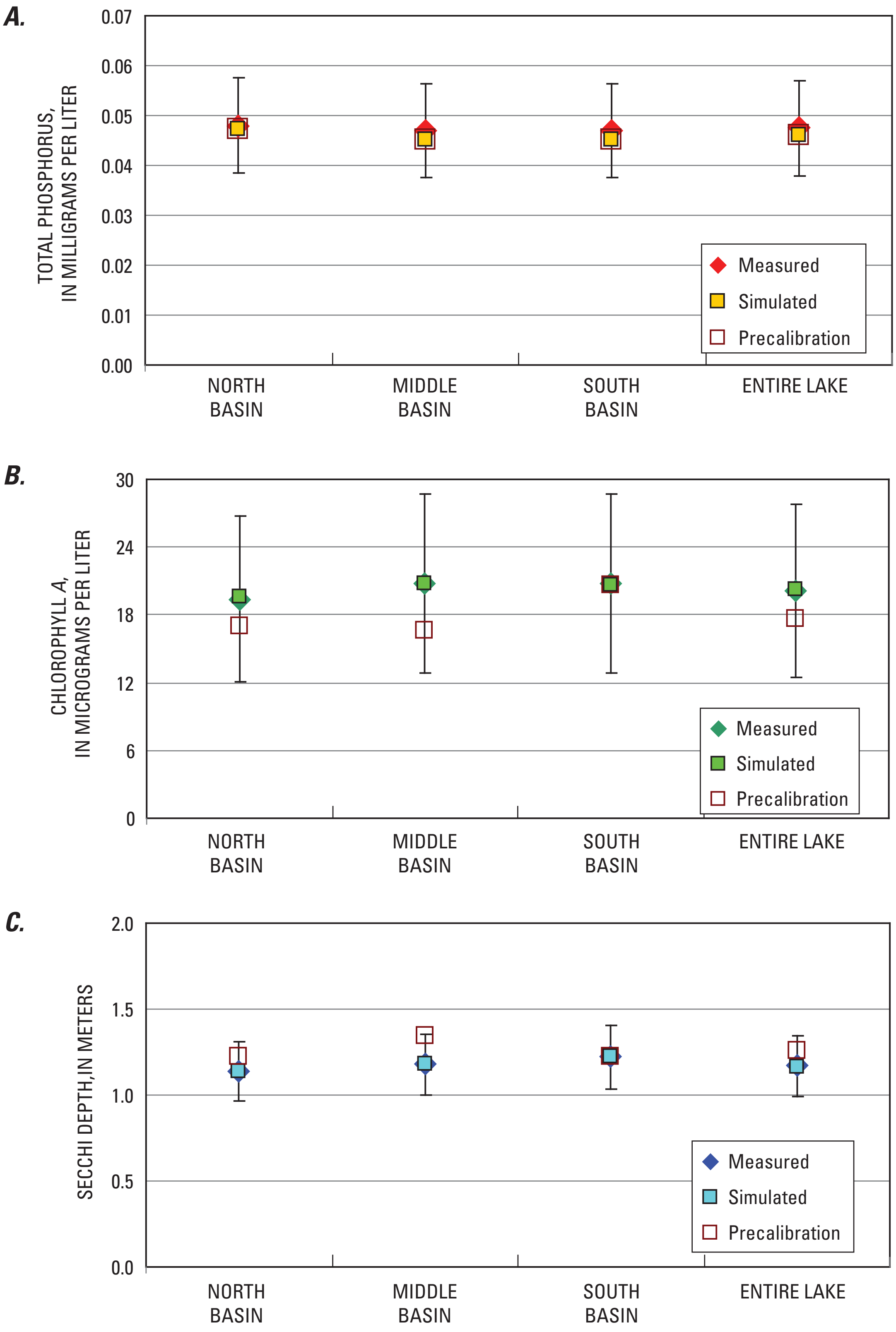


Figure 17. Measured and simulated (prior to and after calibration with the BATHTUB model) average summer (May through September) near-surface ***A***, total phosphorus concentrations, ***B***, chlorophyll *a* concentrations, and ***C***, Secchi depths in the three basins in Butternut Lake, Wis., and the lake as a whole.

Table 12. Estimated near-surface phosphorus concentrations in Butternut Lake, Wis., from various hydrologic and phosphorus loading models contained in the Wisconsin Lakes Modeling Suite (Panuska and Kreider, 2002) and estimated total annual phosphorus load needed to result in a 0.044 mg/L total phosphorus concentration in the lake.

[mg/L, milligram per liter; kg, kilogram]

Lake phosphorus model (description)	Measured		Modeled	
	Prediction season	Seasonal concentration (mg/L)	Base scenario (mg/L)	Total annual phosphorus load required to produce 0.044 mg/L (kg)
Canfield and Bachman, 1981 (natural lakes)	Growing season	0.044	0.029	2,640
Canfield and Bachman, 1981 (artificial lakes)	Growing season	.044	.026	3,290
Reckhow, 1979 (general lakes)	Growing season	.044	.018	3,840
Reckhow, 1977 (anoxic lakes)	Growing season	.044	.038	1,840
Reckhow, 1977 (water load less than 50 m/year)	Growing season	.044	.026	1,680
Kirchner and Dillon, 1975 (general lakes)	Spring	.044	.015	4,570
Walker, 1977 (general lakes)	Spring	.044	.026	2,740
Vollenweider, 1982 (general lakes)	Annual	.044	.023	3,450
Vollenweider, 1982 (shallow lakes)	Annual	.044	.019	4,250
Average of the models		**.044**	**.024**	**3,260**

nal phosphorus load was approximately 945 kg (table 8) and approximately 1,400 kg of internal phosphorus loading was required to accurately simulate the in-lake phosphorus concentration with the BATHTUB model.

Response in Water Quality to Changes in Phosphorus Loading

To predict the expected response in water quality in Butternut Lake to watershed-wide changes in external phosphorus loading, eight scenarios were simulated with the BATHTUB model. The volume-weighted-average total and dissolved ortho-phosphorus concentrations (total nutrient load divided by total water load) for each of the sources were decreased by 50 and 25 percent and increased by 25, 50, 75, 100, 200, and 400 percent. Nitrogen concentrations were not altered in the various phosphorus-loading scenarios. Because the lakes/basins were typically phosphorus limited, altering nitrogen concentrations was shown to have little effect on the simulated results.

Changes in Phosphorus Concentrations

On the basis of BATHTUB model simulations, phosphorus concentrations in each of the basins and the lake as a whole should have a relatively linear response to a linear change in controllable external phosphorus loading (only the changes in the concentrations of the lake as a whole are shown in fig. 18*A*). The changes in in-lake phosphorus concentrations, on a percentage basis, are smaller than the changes in external phosphorus loadings. Changes in in-lake phosphorus concentrations are only about 25–42 percent of the changes in phosphorus loading. In other words, a 50-percent increase in controllable external phosphorus loading causes a 19-percent increase in in-lake phosphorus concentrations and a 50-percent decrease in external loading causes a 21-percent decrease in concentrations. When external loading is increased by 62 percent, which is similar to the loading estimated by the USEPA to have occurred in the early 1970s (U.S. Environmental Protection Agency, 1974), the summer average concentration is estimated to be about 0.057 mg/L. This estimated concentration is less than what was measured for that time period (0.069 mg/L). This difference in the estimated and measured concentrations suggests that the relatively crude load estimate for the early 1970s may be low.

The estimated changes in in-lake phosphorus concentrations, being smaller than the reductions in controllable external phosphorus loadings, are primarily the result of not simulating reductions in internal loading and reductions in the loads from ground water and precipitation; the loadings from these sources represent about 40 percent of the total input of phosphorus to the lake. Short-term changes in external phosphorus loading are not expected

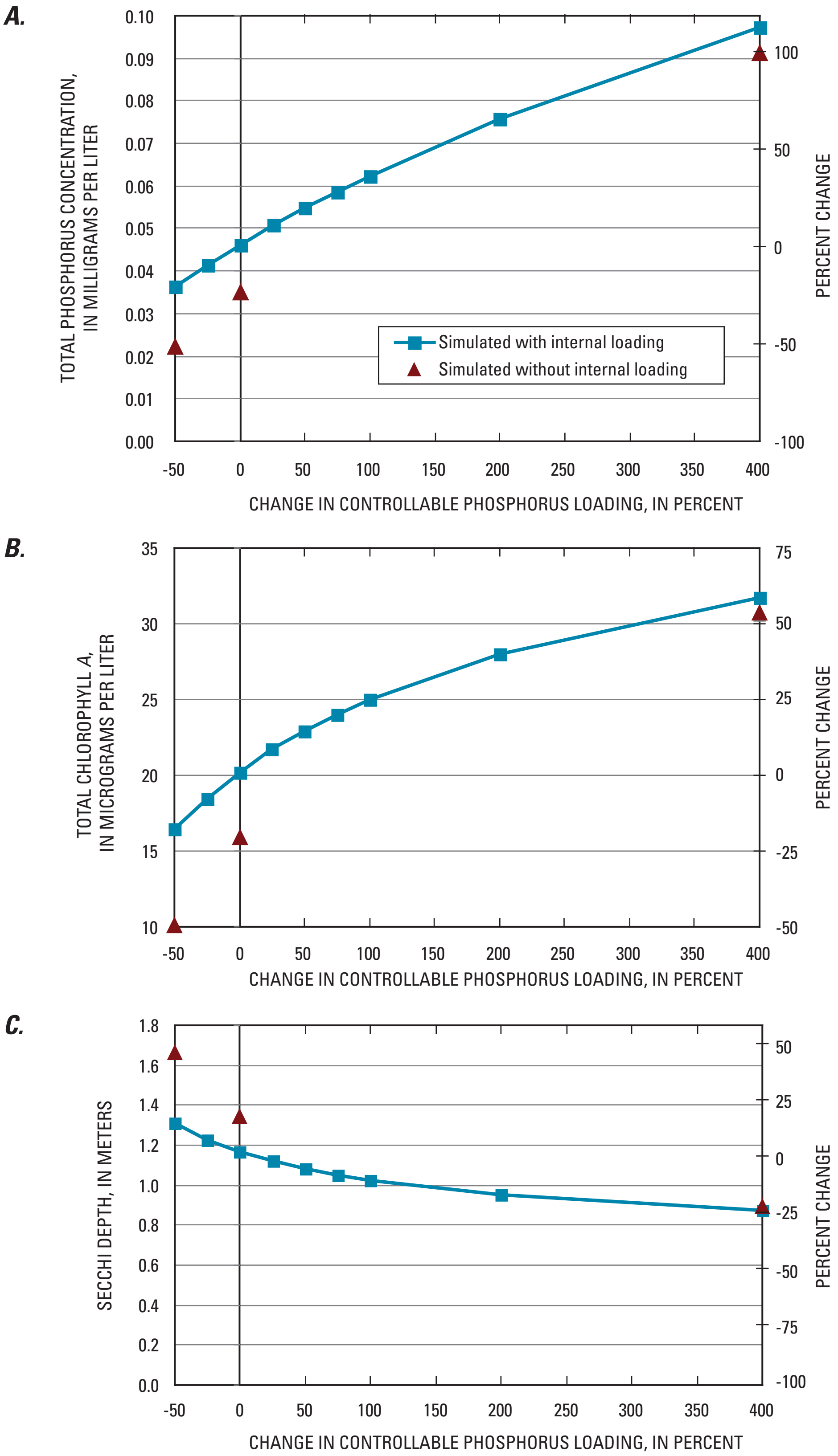


Figure 18. Simulated changes in near-surface ***A***, total phosphorus concentrations, ***B***, chlorophyll *a* concentrations, and ***C***, Secchi depths at the Deep-hole Site in Butternut Lake, Wis., in response to various phosphorus-loading scenarios. Simulated results for changes in these constituents without additional phosphorus from internal loading are also identified.

to affect the rate of internal loading immediately. When internal phosphorus loading is removed from the model, the simulated average summer phosphorus concentration is 0.035 mg/L (a reduction of 24 percent from the base case). When internal phosphorus loading is removed from the 50-percent-decrease scenario, the simulated in-lake phosphorus concentration is 0.022 mg/L (a 52-percent decrease from the base case and a 37-percent decrease from the base case with no internal loading), and when it is removed from the 400-percent-increase scenario, the simulated in-lake phosphorus concentration is 0.091 mg/L (a 98-percent increase from the base case and a 168-percent increase from the base case with no internal loading). Therefore, the high internal phosphorus loading in Butternut Lake greatly reduces the effects of (response to) changes in external phosphorus loading.

Changes in Chlorophyll *a* Concentrations

Simulated average-summer chlorophyll *a* concentrations have a nonlinear response to changes in controllable external phosphorus loading. The response of chlorophyll *a* concentrations is larger (on a percentage basis) for decreases in loading than for similar increases in loading (fig. 18*B*). A 50-percent reduction in controllable external phosphorus loading results in an 18-percent reduction in chlorophyll *a* concentrations, while a 50-percent increase in loading results in an increase by only 13 percent, and a 400-percent increase in loading results in an increase by only 57 percent. When internal phosphorus loading is removed from the model, the changes associated with reductions in external phosphorus loading are much greater than with increases in loading. When internal loading was removed, a 50-percent decrease in external phosphorus loading resulted in a 50-percent decrease in chlorophyll *a* concentrations (a 36-percent decrease from the base case with no internal loading); however, with a 400-percent increase in loading, chlorophyll *a* concentrations increased by only 52 percent (a 93-percent increase from the base case with no internal loading).

Changes in Secchi Depths (Water Clarity)

Simulated Secchi depths are more responsive to decreases in controllable external phosphorus loading than to increases in loading (fig. 18*C*). When external phosphorus loading is decreased by 50 percent, Secchi depths increase by 0.14 m (12 percent); however, when loading is increased by 50 percent, Secchi depths decrease by only about 0.09 m (7 percent). Very little change in Secchi depth is estimated with increases in external loading above 100 percent. When internal phosphorus loading is removed from the model, the changes associated with reductions in phosphorus loading are much greater than with increases in phosphorus loading. When internal loading is removed, a 50-percent reduction in external phosphorus loading results in Secchi depth increases of about 0.35 m (42-percent increase and a 24-percent increase from the base case with no internal loading).

Changes in Trophic Status

The TSI values indicate that Butternut Lake is currently borderline between eutrophic and hypereutrophic (fig. 7). On the basis of the simulations with the BATHTUB model, even when controllable external phosphorus loading is reduced by 50 percent from that measured in MY 2003–04, the lake would remain moderately eutrophic (TSI values 56–58) with respect to phosphorus concentration, chlorophyll *a* concentration, and Secchi depth. This minimal response in water quality to reductions in external phosphorus loading is due primarily to the high internal phosphorus loading. However, if the internal phosphorus loading could be eliminated and the external phosphorus loading could be reduced by 50 percent, the trophic state of the lake should become borderline mesotrophic/eutrophic, with TSI values ranging from 49 (for phosphorus) to 53 (for chlorophyll *a* and Secchi depth).

Changes in the Percentage of Days with Algal Blooms

All of the previously described model simulations were based on changes in the average water quality during the growing season (May through September). However, often what are perceived as the biggest problems in lakes are the visible extremes in water quality; for example, algal blooms. The definition of what constitutes the occurrence of an algal bloom can be site-specific and subjective. In what typically is a clear lake, a slight green color in the water is considered an algal bloom, whereas for a typically productive lake, only a very green color or an algal scum is considered an algal bloom. A chlorophyll *a* concentration of 30 µg/L represents what many would consider a moderate algal bloom. Results from BATHTUB model simulations are used to demonstrate how the percentage of days from May through September with a chlorophyll *a* concentration exceeding a certain value (30 µg/L) changes in response to changes in controllable external phosphorus loadings (fig. 19). Changes in the frequency of algal

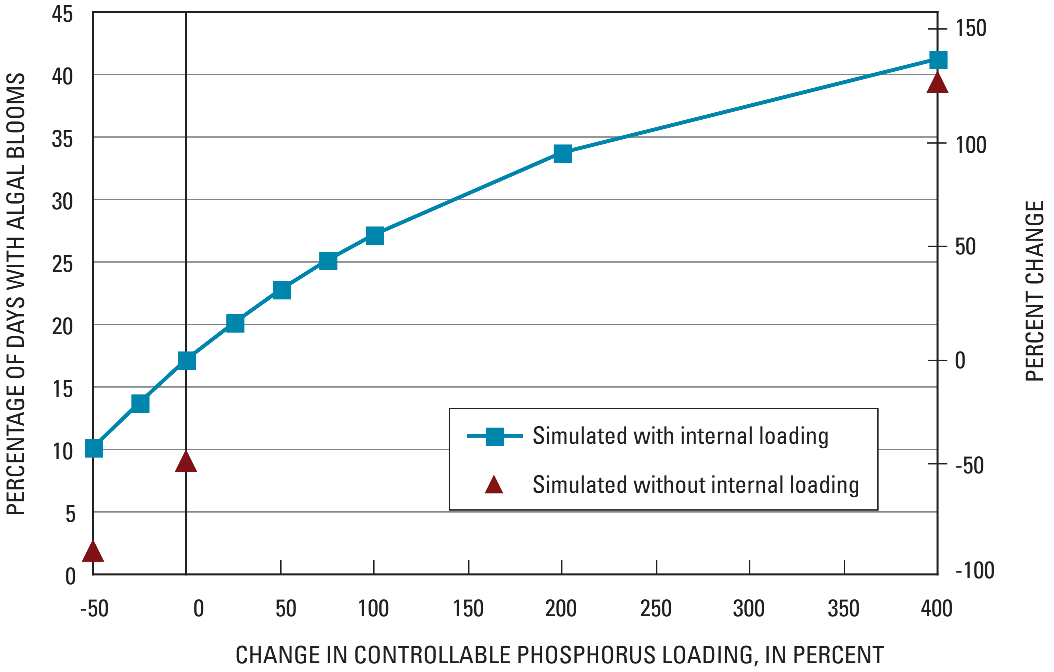


Figure 19. Simulated changes in the percentage of days from May through September with an algal bloom (chlorophyll *a* concentration greater than 30 µg/L) in response to various phosphorus-loading scenarios for Butternut Lake, Wis. Simulated results for changes in these constituents without additional phosphorus from internal loading are also identified.

blooms are larger with decreases in phosphorus loading than with similar increases in loading. When controllable external phosphorus loading is decreased by 50 percent, the number of days with algal blooms decreases by 41 percent, while an increase in loading of 50 percent results in an increase in the days with algal blooms by 33 percent. When internal phosphorus loading is removed from the model, the changes caused by reductions in external phosphorus loading are much larger than those with increases in phosphorus loading. When internal loading is removed, a 50-percent decrease in phosphorus loading results in an 89-percent decrease in the number of days with algal blooms (a 79-percent decrease from the base case with no internal loading).

Importance of Internal Phosphorus Loading

When the deep water of a productive lake, like Butternut Lake, becomes anaerobic, the rate of phosphorus release from the deep sediments is often greatly accelerated. Typically, in deep dimictic lakes, this phosphorus from internal loading is trapped in the hypolimnion during summer and released into the shallow water primarily at fall overturn. In polymictic lakes, however, the phosphorus released from the sediments is not trapped in the bottom of the lake but is intermittently released to the shallow water throughout the summer. These mixing events resulted in increases in the near-surface phosphorus concentrations in Butternut Lake as summer progressed, and a higher overall near-surface, summer-average phosphorus concentration than that of a dimictic lake with a similar internal phosphorus load. This is the primary reason why the additional internal phosphorus load had to be added to the BATHTUB model for accurate simulations and why all of the models in WiLMS underestimated the near-surface phosphorus concentration in Butternut Lake. It was estimated that internal loading added about 37 to 51 percent of the annual phosphorus loading to the lake.

Although the phosphorus load to Butternut Lake has decreased as a result of many efforts in the watershed (table 1), the internal phosphorus load has and probably will continue to limit the response of the lake to reductions in external phosphorus loading. This conclusion is in agreement with the small changes in measured water quality (fig. 6) and the small changes inferred from the paleoecological study (fig. 8) conducted by Garrison (2006). This conclusion also is in agreement with the belief that once a polymictic lake becomes hypereutrophic, it is difficult to alter its trophic state because the high internal phosphorus loading usually does not quickly respond to reductions in external phosphorus loading (Newton and Jarrell, 1999; Nurnberg, 1998; Welch and Cooke, 1995).

If external phosphorus loading to Butternut Lake is further reduced in the future, the results from the BATHTUB model (with internal loading included) should accurately predict the changes in water quality that would occur in the lake. However, if the reduction in external load were to persist for a long period of time, the internal phosphorus release rate should gradually decrease and come to equilibrium with the new external loading. This should ultimately result in a slightly greater improvement in water quality than predicted in figures 18 and 19 (when internal loading was included). If, in addition to reductions in external loading, internal phosphorus loading were able to be reduced, such as with an alum treatment (Robertson and others, 2000), then the predicted in-lake water quality should be similar to the estimates in figures 18 and 19, simulations with internal phosphorus loading removed. Even if internal phosphorus loading were eliminated, a 50-percent reduction in external phosphorus loading would be needed for Butternut Lake to become borderline mesotrophic/eutrophic. When alum is used to reduce or eliminate internal phosphorus loading, short-term changes in water quality are often more dramatic than indicated in figures 18 and 19 because alum also immediately removes most of the phosphorus from the water column. The long-term changes in water quality associated with an alum treatment, however, should be similar to those indicated with no internal loading in figures 18 and 19.

Summary and Conclusions

Butternut Lake is a eutrophic to hypereutrophic, polymictic lake in northcentral Wisconsin. Because water quality improved only slightly after many actions were taken to reduce nutrient loading from the watershed, a study was conducted by the USGS from 2002 to 2007 to better understand how the lake functions. The goals of the study were to describe the water quality and hydrology of the lake, quantify external and internal sources of phosphorus, and evaluate the effects of past and future changes in phosphorus loading on the water quality of the lake. To achieve these goals, water-quality data were collected in the lake during 2002–04 and compared with historical data. Water and phosphorus budgets were quantified to gain a better understanding of the various phosphorus sources. Lake water-quality models were then used to determine why the water quality in the lake had not dramatically changed in response to the reductions in nutrient loading. Results from model simulations will aid in decision-making for future lake-management actions by predicting the changes that may be expected with changes in external phosphorus inputs to the lake.

Seasonal changes in the water quality of polymictic Butternut Lake were different from those in most dimictic lakes: bottom temperatures increased more dramatically throughout the summer than in other lakes, and bottom dissolved oxygen concentrations alternated between being aerobic and anaerobic as a result of frequent mixing during summer. Near-surface phosphorus concentrations in the lake increased as summer progressed as a result of the episodic release of phosphorus from an occasionally anaerobic hypolimnion. On the basis of nitrogen to phosphorus (N:P) ratios, phosphorus typically should be the nutrient limiting algal growth in Butternut Lake and should be the nutrient of concern when considering management efforts to improve the lake's water quality.

Since the early 1970s, the water quality of Butternut Lake has not changed dramatically in response to the nutrient reductions from the watershed. The largest changes were in near-surface total phosphorus concentrations: concentrations during August decreased from about 0.090 mg/L in the early 1970s to about 0.050 mg/L after 2000, whereas average-summer concentrations decreased only from about 0.055–0.060 mg/L to about 0.045 mg/L. Since the early 1970s, only small changes were measured in chlorophyll *a* concentrations and Secchi depths.

Butternut Creek was the largest source of water to Butternut Lake, supplying about 62 percent of its water. Other sources were Spiller Creek (20 percent), precipitation (8 percent), small tributaries and the ungaged near-lake area (7 percent), and ground water (3 percent). Total inputs of water in MY 2003 were less than those in MY 2004 because of the above normal precipitation in MY 2004. The average residence time of water in the lake ranged from 0.39 to 0.45 years. Butternut Creek outlet accounted for 93 percent of the total outflow from the lake and evaporation accounted for 7 percent.

The average annual load of phosphorus to the lake was 2,540 kg, of which 1,590 kg came from external sources (63 percent) and 945 kg came from the sediments in the lake (37 percent). The largest source of external phosphorus was Butternut Creek, which delivered 63 percent of the external phosphorus compared with 61 percent of the water input. The next largest contribution was from Spiller Creek, which delivered 23 percent of the external phosphorus entering the lake. The six small tributaries and ungaged near-lake area collectively contributed 9 percent of the total external phosphorus load. The surface-water outflow into Butternut Creek removed 94 percent of the external phosphorus coming into to the lake, and the remaining 6 percent was stored in the lake sediment.

The BATHTUB model and nine of the water-quality models contained in WiLMS were used to determine if the response in the water quality of Butternut Lake to phosphorus loading was similar to that of most other lakes or if it responded differently because it is a polymictic lake with unusually high internal phosphorus loading. Unless additional phosphorus from internal loading was included in the simulations, the BATHTUB model was unable to simulate the water quality in the lake, and all of the models within WiLMS underestimated the in-lake phosphorus concentration by about 50 percent. After internal loading of phosphorus was added to the BATHTUB model, it accurately simulated the water quality measured in MY 2003–04. With this model, a relatively linear response was found between in-lake total phosphorus concentrations and external phosphorus loading; however, the changes in in-lake concentrations were smaller than the changes in external phosphorus loadings. Changes in in-lake phosphorus concentrations were about 25–42 percent of the changes in phosphorus loading. Changes in chlorophyll *a* concentrations, the percentage of days with algal blooms, and Secchi depths (water clarity) were nonlinear, with a larger response to reductions in external phosphorus loading than to increases in loading. When simulated external phosphorus loading was reduced by 50 percent, chlorophyll *a* concentrations decreased by about 18 percent, the percentage of days with algal blooms decreased by about 41 percent, and Secchi depth increased by about 12 percent. When the additional internal phosphorus loading was removed from the model, there was a much larger response in all of these constituents.

Butternut Lake, being polymictic, was vulnerable to the historically high, non-natural, external phosphorus loading that resulted in high internal phosphorus loading. Once Butternut Lake became hypereutrophic, it became very difficult to alter its trophic state with reductions in external phosphorus loading. The high internal loading rate helps maintain the current state of the lake and does not respond quickly to reductions in external nutrient loading. In order to improve Butternut Lake to a mesotrophic/eutrophic state, a combination of practices will be needed to reduce/eliminate internal phosphorus loading and also reduce the external phosphorus loading by about 50 percent.

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