Prepared in cooperation with the Little St. Germain Lake Protection and Rehabilitation District

Evaluation of the Effects of Changes in the Timing of Water-Level Drawdowns on the Export of Phosphorus from Little St. Germain Lake, Wisconsin

Scientific Investigations Report 2018–5078

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

Cover. At the outlet of Little St. Germain Lake, a sluice gate drains water from the lake into Little St. Germain Creek. Photograph by Eric D. Dantoin, U.S. Geological Survey.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
mile (mi)	1.609	kilometer (km)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
pound, avoirdupois (lb)	0.4536	kilogram (kg)

Datum

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

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

Elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

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

Abbreviations

CY	calendar year
GCLAS	Graphical Constituent Loading Analysis System
PY	phosphorus year [from September 1 of the defined year to August 31 of the next year]
USGS	U.S. Geological Survey
WVIC	Wisconsin Valley Improvement Company

Evaluation of the Effects of Changes in the Timing of Water-Level Drawdowns on the Export of Phosphorus from Little St. Germain Lake, Wisconsin

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Abstract

Little St. Germain Lake is a 978-acre, multibasin lake in Vilas County, Wisconsin. In the interest of improving its water quality, the Little St. Germain Lake Protection and Rehabilitation District initiated a cooperative study with the U.S. Geological Survey to describe the current phosphorus input into and export from Little St. Germain Lake and evaluate how water releases at different times of the year could affect the amount of phosphorus being released from the lake, potentially affecting water quality in the lake. Approximately 780 pounds per year of phosphorus are exported out of the lake, which is about 80 percent of that contributed to the lake by Muskellunge Creek. By focusing the release of water to times when phosphorus concentrations near the outlet of the lake are highest, export of phosphorus from the lake could increase by about 60 to 80 pounds annually. This is equivalent to reducing phosphorus contributions from Muskellunge Creek by about 7 to 9 percent. Increasing phosphorus export from the lake should improve the long-term water-quality of the lake, especially in the southern basins of the lake.

Introduction

Little St. Germain Lake, located just northeast of the town of St. Germain in Vilas County, Wisconsin (fig. 1), is one of 21 impoundments operated by Wisconsin Valley Improvement Company (WVIC). Little St. Germain Lake is managed as part of the Wisconsin River Reservoir System in compliance with Federal Energy Regulatory Commission (FERC) license P–2113 to maintain as uniform a flow as practicable in the Wisconsin River and a reasonable balance among the benefits the water resource provides, including water conservation, flood control, low flow augmentation, hydroelectric generation, water quality, wildlife, and recreation. The level of the lake, which was originally dammed in 1882, has been maintained by WVIC at about 2.25 feet (ft) above its natural level (also referred to as natural run) since 1908 using a manually regulated sluice gate; this maximum level was established in 1908 and never changed (Stewart, 1911). The lake is annually drawn down by about 1.5 ft from December through March.

In the interest of protecting and improving the water quality of the lake, the Little St. Germain Lake Protection and Rehabilitation District has collaborated with the Wisconsin Department of Natural Resources and the U.S. Geological Survey (USGS) to study the water quality of the lake. Results of these studies indicated that relatively high loading (material transported per unit of time) of phosphorus into the lake from the relatively pristine surrounding watershed has caused most of Little St. Germain Lake to become eutrophic, with the possible exception of the West Bay. In an attempt to find management strategies to improve the water quality of Little St. Germain Lake, the USGS, in cooperation with the Little St. Germain Lake Protection and Rehabilitation District, investigated how changes in the timing of winter drawdown could increase the release of phosphorus from Little St. Germain Lake. In this report, we describe the current load of phosphorus input into and exported from Little St. Germain Lake during 2014 to 2016, the effects of water being released at different times of the year on the amount of phosphorus leaving Little St. Germain Lake, and the potential effects of changing the timing of water releases on water quality in Little St. Germain Lake.

Description of the Study Area

Little St. Germain Lake (fig. 1) is a multibasin lake with a total surface area of 978 acres and a volume of 11,500 acre-feet. Little St. Germain Lake has six basins: Upper East Bay (119 acres), East Bay (336 acres), No Fish Bay (69 acres), West Bay (213 acres), South Bay (122 acres), and Second South Bay (119 acres). The major tributary to the lake is Muskellunge Creek, which flows about 3 miles (mi) from shallow, relatively pristine but eutrophic Muskellunge Lake into the northern end of the East Bay. Muskellunge Lake was extensively studied by the USGS during 2000 to 2001 as part of a cooperative study with the Muskellunge Lake Association (Robertson and others, 2003). Results from that study were used to demonstrate that groundwater and other natural sources were the dominant sources of phosphorus to

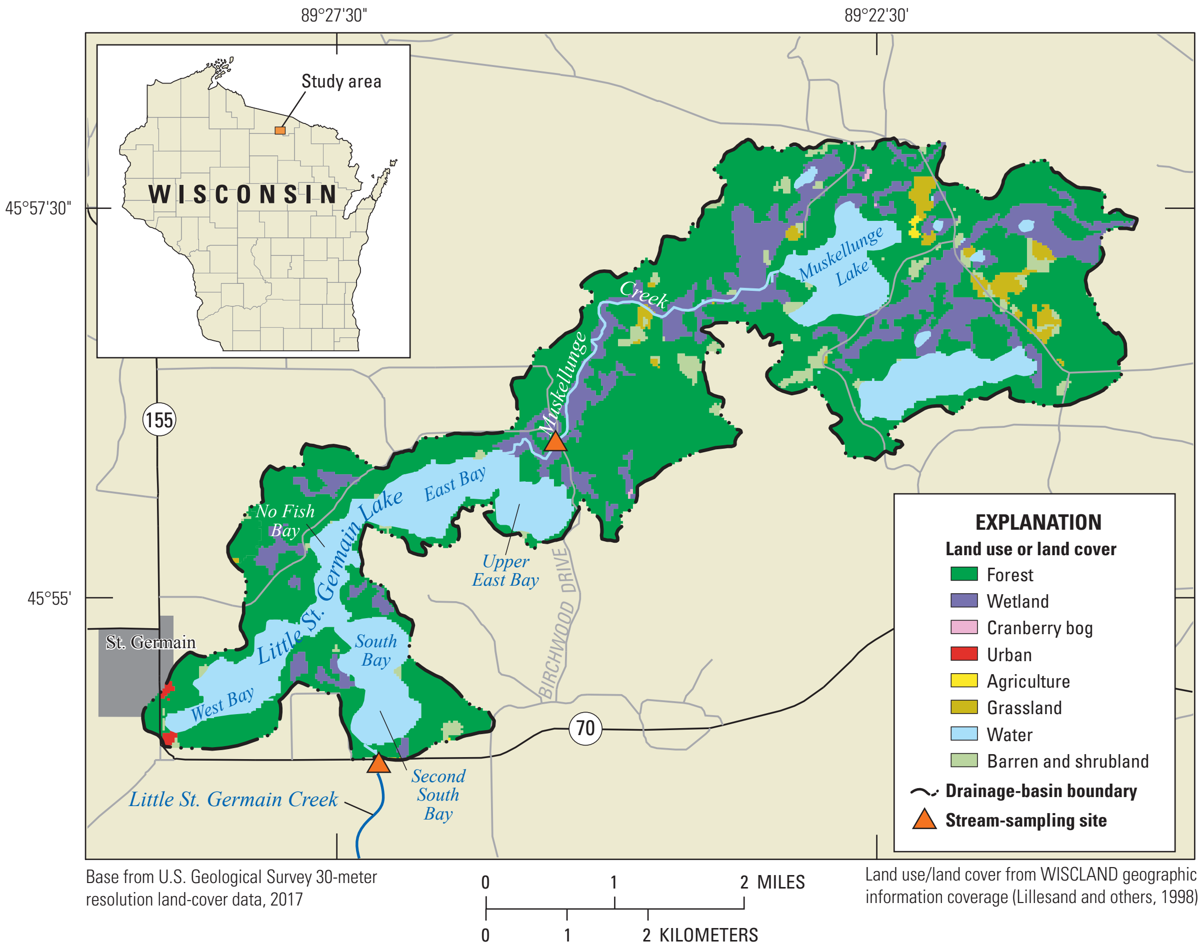

Figure 1. The watershed of Little St. Germain Lake, Wisconsin; water-quality sampling locations are also identified.

Muskellunge Lake. Outflow from Little St. Germain Lake is to Little St. Germain Creek, which leaves the southern side of the Second South Bay and flows about 1 mi before draining into the Rainbow Flowage of the Wisconsin River.

The total area of the Little St. Germain Lake watershed is 10 square miles (mi^2), not including the area of the lake itself. The watershed is predominantly forest (68 percent), wetland (17 percent), and water (8 percent), although areas of low-density residential development exist immediately around the lake (fig. 1). The soils in the watershed consist mainly of well-drained sand and sandy loams. These soils are thought to be naturally high in phosphorus content (Wisconsin Department of Natural Resources, 1985), which may lead to more phosphorus entering lakes in this area than entering lakes in other areas.

Previous Studies

In 1983, the Wisconsin Department of Natural Resources and the Little St. Germain Lake Protection and Rehabilitation District studied the water quality in Little St. Germain Lake and examined management alternatives (Wisconsin Department of Natural Resources, 1985). Results of that study indicated relatively high phosphorus loading to Little St. Germain Lake and proposed that monitoring should continue. Water quality in Little St. Germain Lake was monitored in depth from 1991 to 1994 by the USGS as part of a cooperative study with the Little St. Germain Lake Protection and Rehabilitation District (U.S. Geological Survey, 2017). The study demonstrated variation in water quality among the various basins of the lake and found extensive areas of winter anoxia (absence of oxygen).

Additional studies by the USGS from 1994 to 2000 were conducted to refine the water and phosphorus budgets of Little St. Germain Lake, quantify the effects of annual drawdowns, define the extent of winter anoxia, and provide information needed to develop a comprehensive lake-management plan (Robertson and Rose, 2000). Results of those studies indicated that Muskellunge Creek, which drains a relatively pristine watershed including eutrophic Muskellunge Lake, was the dominant source of phosphorus to Little St. Germain Lake; however, groundwater contributions (based on limited information) appeared to be important and is an area of study that would benefit from further quantification. Results of those studies also indicated extensive areas of anoxia during winter in the Upper East, South, and Second South Bays (fig. 1). Based on results of those studies, aerators were placed in Upper East Bay, northern end of East Bay, and South Bay and operated throughout winter. From 2000 to 2005, the USGS evaluated the success of the aerators at eliminating winter anoxia, developed detailed phosphorus budgets for the lake, and assessed how the water quality in Little St. Germain Lake should respond to changes in phosphorus loading (Robertson and others, 2005). The evaluation demonstrated that the aerators were successful at preventing winter anoxia and that groundwater input was an important driver of the eutrophic condition of Little St. Germain Lake. From 2010 to 2014, the USGS used all the water-quality and phosphorus loading data collected in the lake to describe the interannual and long-term changes in the trophic state of Little St. Germain Lake and examine how morphology, climate, winter aeration, and beaver activity affect the water quality in Little St. Germain Lake (Robertson and others, 2016).

Methods

Purpose and Approach

The purpose of the study detailed in this report was to investigate the potential effects of changing the timing of winter drawdown to coincide with highest total phosphorus concentrations in Little St. Germain Lake and determine a strategy to maximize the release of phosphorus from Little St. Germain Lake. It is believed that increasing the removal of phosphorus from Little St. Germain Lake should improve water quality in the lake, especially in the southern basins. Increasing the removal of phosphorus in this manner is analogous to using hypolimnetic withdrawals to remove phosphorus from a lake to improve its water quality (Cooke and others, 1993). Previous studies have shown that removing deep water (hypolimnetic water) with elevated total phosphorus concentrations can be an efficient and valuable tool in reducing near-surface total phosphorus concentrations in deep reservoirs (Nürnberg, 1987; Nürnberg and others, 1987). Continual removal of phosphorus from a reservoir or lake should gradually reduce the phosphorus stored in the bottom sediments of the lake and reduce the release of phosphorus back into the water column. In the case of Little St. Germain Lake, hypolimnetic withdrawal would not be effective in removing phosphorus because of the morphology of the lake, which results in little stratification in Second South Bay near its outlet.

The hypothesis being examined in this study focuses on maximizing flow releases from the lake during periods of highest total phosphorus concentrations, which generally occur during early fall because of phosphorus being released from the sediments throughout summer and during fall turnover, and during mid to late winter because of phosphorus being released during periods of anoxia near the sediment surface. Phosphorus concentrations and loads in the inflow and outflow from Little St. Germain Lake were determined for the study period (2014–2017; referred to as current conditions) to establish the baseline conditions for water-release operations. Different flow-release scenarios were evaluated to determine the feasibility of increasing the amount of phosphorus released from the lake. In each scenario, daily total phosphorus concentrations leaving the lake were unchanged from the baseline conditions, but the flows were modified. Outflow from the lake when it was not being drawn down was maintained at baseline conditions; however, flows from September through February (associated with winter drawdown) were modified. The magnitude of changes in phosphorus removal were compared with the total baseline phosphorus leaving the lake and compared with the total phosphorus input to the lake from Muskellunge Creek, which is the major tributary to the lake (fig. 1).

Data Collection

Daily loads of phosphorus entering and leaving Little St. Germain Lake from November 2014 to December 2016 were determined from flow measurements and water sample concentrations collected in Muskellunge Creek at Birchwood Drive (USGS streamgage 05390685, Muskellunge Creek near St. Germain, WI) and Little St. Germain Creek at State Highway 70 (USGS streamgage 05390701, Little Saint Germain Creek near Eagle River, WI), respectively (fig. 1). Continuous (15-minute-interval) water elevations were measured at Muskellunge Creek, from which continuous flow was calculated using standard USGS measurement and computation procedures (Rantz and others, 1982). Daily outflows into Little St. Germain Creek, which were calculated from lake elevations and gate-opening settings, were provided by WVIC. Discharge measurements were also made by the USGS at Little St. Germain Creek using a midsection method at approximately monthly intervals. These measurements were used to validate the WVIC flow calculations and make adjustments to WVIC-estimated flow if needed.

Biweekly water samples were collected by the USGS and a local observer at the two USGS streamgages from October 2014 to December 2016. In general, USGS researchers collected water samples near the middle of each month, and a local observer collected water samples early in the month. Water samples were collected using simple grab sampling techniques with a 250-milliliter bottle. The well-mixed, shallow sampling locations allowed a single grab to be an acceptable collection method at both sites (U.S. Geological Survey, 2012). All water samples were preserved and shipped on ice to the Wisconsin State Laboratory of Hygiene for total phosphorus analysis in accordance with standard analytical procedures described in the “Manual of Analytical Methods, Inorganic Chemistry Unit” (Wisconsin State Laboratory of Hygiene, 1993).

Load and Daily Average Concentration Computations

Daily phosphorus loads in Muskellunge Creek and Little St. Germain Creek were calculated using the Graphical Constituent Loading Analysis System (GCLAS) computer program developed by Koltun and others (2006) that is used to estimate loads of water-quality constituents from continuous streamflow data and instantaneous constituent concentrations. To estimate total phosphorus concentrations during unsampled periods, phosphorus concentrations were linearly interpolated between measurements except at the beginning and end of each large change in flow (referred to as an event). Estimated concentrations were added to the time series to better describe concentrations just prior to an event and just following an event or to describe concentrations during events that lacked measured concentrations. Concentrations at the beginning of each large change in flow (event) were estimated based on measured sample concentrations during preceding base-flow periods. Concentrations at the end of the events were estimated from concentrations measured shortly after the end of an event. GCLAS was also used to estimate concentrations during unsampled high-flow events using relations of individual water sample concentrations with associated discharges. These additional estimated concentrations increase the confidence in calculated loads by accounting for the effects of changing flows between known sampled concentrations. From the daily loads, daily average total phosphorus concentrations for September 2014 to December 2016 in Little St. Germain Creek were calculated by dividing the daily total load by the total daily flow. All streamflow and daily estimated total phosphorus concentrations and loads from September 2014 to December 2016 are available from the National Water Information System (U.S. Geological Survey, 2017). Daily flows and concentrations were not measured for January and February 2017; therefore, the flows and concentrations for this period were assumed to be the same as in January to February 2016.

Quantifying Effects of Changes in the Timing of Water Releases

The effects of changing the timing of the water release were quantified by comparing phosphorus loading exported from Little St. Germain Lake during the study period (Scenario 1; baseline) with loadings for eight additional release scenarios. It was thought that phosphorus export from the lake could be increased if the flows leaving the lake were concentrated when total phosphorus concentrations were highest (late summer near September and middle to late winter near February). To develop the scenarios for flow and total phosphorus concentrations, the measured baseline daily loads were first separated into daily flows and daily total phosphorus concentrations. Daily flows for September through February were then adjusted to reflect the flow for each of the eight nonbaseline release scenarios.

The flows from the actual dam operation from September 1, 2014, to December 31, 2016 were extrapolated to February 28, 2017 (the full study period). This full period is referred to as the current release in Scenario 1 and provided a baseline to compare the effects of drawing down water levels in three distinct drawdown periods (September through February in 3 consecutive years). Flow and phosphorus releases were simulated for eight nonbaseline scenarios. In the first six scenarios, total winter drawdown was simulated to occur during specific one-month periods (Scenario 2, September; Scenario 3, October; Scenario 4, November; Scenario 5, December; Scenario 6, January; and Scenario 7, February). In two additional scenarios, drawdown occurred over the 2 months of January and February (Scenario 8) or was split between September and February (Scenario 9).

Daily flows for each scenario were constructed by first calculating the total flow during September through February for each year from 2014 through 2017. For each year, the total minimum flow rate for the months without simulated drawdown during the September through February period was set to 5.6 ft^3/s (minimum allowable flow; Wisconsin Valley Improvement Company, 2017). The flow rates for the simulated drawdown month(s) were then computed from the differences in the total flow for September through February and the total flow during the remaining months at minimum flow divided into the number of days for the specific month(s). The flows for the remaining part of the year (March through August) remained at the gaged daily discharge. Daily total phosphorus loads for each scenario were then calculated by multiplying simulated daily flows by the total phosphorus concentrations determined for the baseline period.

Results

Streamflow

Daily average streamflows at the outlet and inlet to Little St. Germain Lake are shown in figure 2. WVIC-computed discharges were compared to USGS discharge measurements to evaluate the accuracy of the WVIC-computed discharges. In general, the USGS discharge measurements matched the data provided by WVIC reasonably well, except for flows less than 8 ft^3/s. WVIC-computed flows less than 8 ft^3/s, on average, were 9 percent higher than the USGS discharge measurements. Therefore, all supplied flows less than 8 ft^3/s were decreased by 9 percent.

The average daily flow rate in Little St. Germain Creek from September 2014 through February 2017 was 14.7 ft^3/s. The minimum and maximum daily average flow rates were 5.11 ft^3/s (February 27, 2016) and 84.5 ft^3/s (June 10, 2015), respectively. Flow out of the lake was typically highest during late fall and early winter because of the lake being drawn

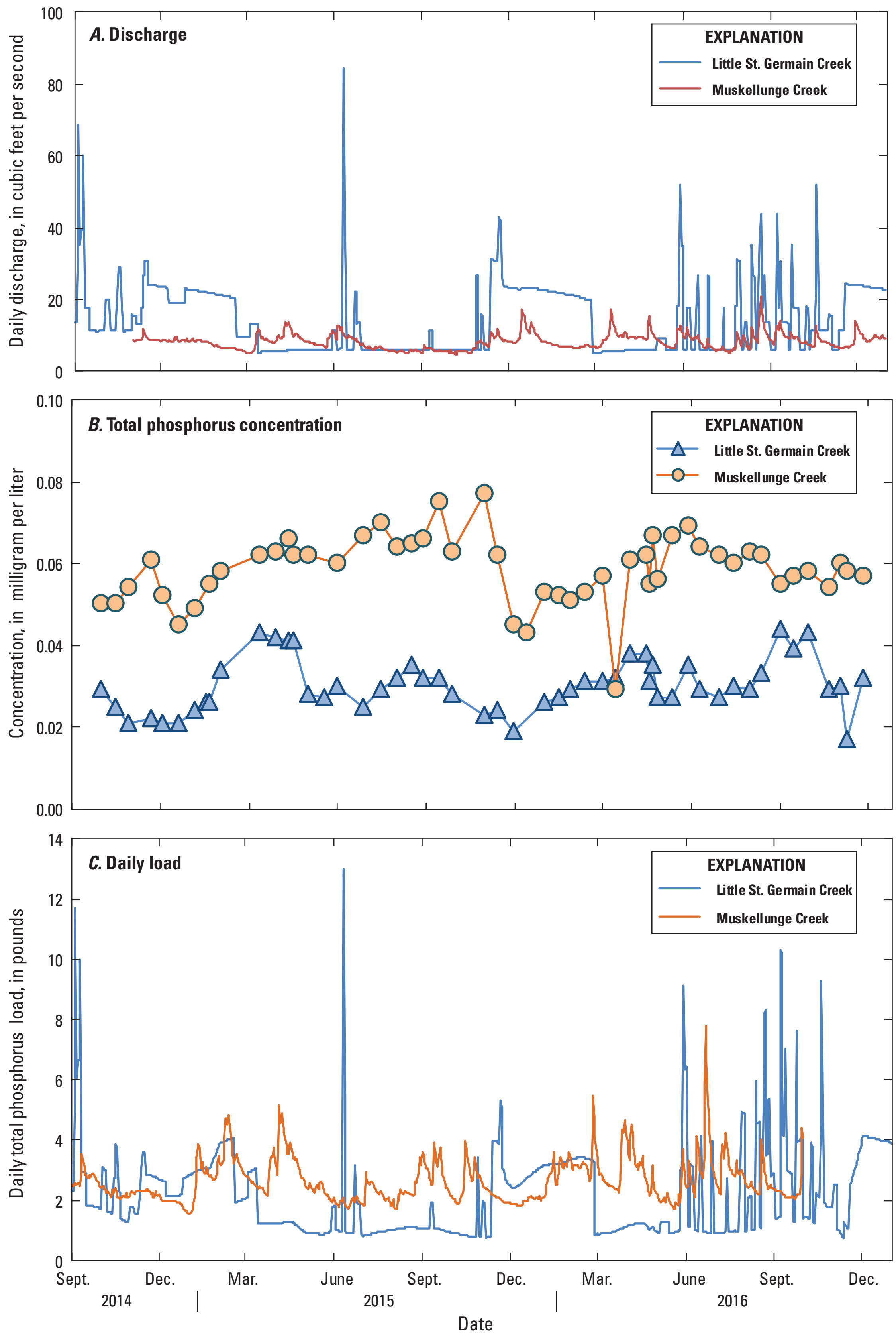

Figure 2. *A*, streamflow, *B*, total phosphorus concentrations, and *C*, daily phosphorus loads in Muskellunge Creek and Little St. Germain Creek into and out from Little St. Germain Lake, Wisconsin.

down and lowest when the lake was being refilled in early spring. An anomaly in flow at the outlet occurred during June 10–11, 2015, when flow rates exceeded 80 ft^3/s. This high-flow event was caused by extensive rain during the preceding weeks, which caused lake elevation to be greater than the FERC authorized maximum water elevation. Increased outflows from the lake were needed to reduce the water level and comply with the FERC license requirements.

The average daily flow rate into the lake from Muskellunge Creek from November 2014 through December 2016 was 8.3 ft^3/s. The minimum and maximum daily average flow rates were 4.9 ft^3/s (March 3, 2014) and 20.7 ft^3/s (August 21, 2015), respectively. In general, flow rates were highest in Muskellunge Creek during spring and summer and lowest in midsummer. There were more high-flow events during April through October 2016 than during other periods of this study.

Stream Water Quality

During October 2014 through December 2016, total phosphorus concentrations in Little St. Germain Creek ranged from 0.017 to 0.043 milligram per liter (mg/L), with an average concentration of 0.03 mg/L (fig. 2). All total phosphorus concentrations were below 0.075 mg/L, which is the Wisconsin total phosphorus water-quality criterion for wadeable streams (Wisconsin Department of Natural Resources, 2017). Concentrations remained relatively constant (0.02 to 0.03 mg/L) for most of the study period; however, concentrations increased in early fall and late winter in each of the 3 years of the study period. The average total phosphorus concentration in Little St. Germain Creek was similar to average concentrations measured in previous studies (Robertson and Rose, 2000, Robertson and others, 2005).

Total phosphorus concentrations in Muskellunge Creek during the study period ranged from 0.03 mg/L in spring 2016 to 0.08 mg/L in fall 2015 (fig. 2), with an overall average concentration of 0.06 mg/L. Except for a few outliers, total phosphorus concentrations remained around 0.05 to 0.07 mg/L regardless of flow or seasonality. The average total phosphorus concentration was similar to average concentrations measured in previous studies (Robertson and Rose 2000, Robertson and others, 2005). Total phosphorus concentrations in the outflow at Little St. Germain Creek were about 50 percent of those entering the lake from Muskellunge Creek.

Output of Phosphorus from Little St. Germain Lake

The total output of phosphorus (load) from Little St. Germain Lake to Little St. Germain Creek during September 2014 to December 2016 is shown in figure 2. The average daily load for this entire period was 2.3 pounds per day (lb/d), but ranged from 0.8 lb/d to the highest daily loads of 13.0 lb/d on June 10–11, 2015. The increased flow on these days magnified the loads of phosphorus during this period even with relatively low total phosphorus concentrations in the discharge water. Monthly loads are summarized in table 1.

To determine how important the phosphorus load exported from the lake during winter drawdown was to the total annual load leaving the lake, annual phosphorus loads were computed from September 1 through August 31 using the actual flows and concentrations. This 12-month period is referred to as a phosphorus year (PY) for the year in which the period ends. During the 2015 phosphorus year (PY2015) and the 2016 phosphorus year (PY2016), the total loads of phosphorus leaving the lake were 756 pounds (lb) and 758 lb, respectively. During the drawdown period of these years (September through February), the total loads of phosphorus leaving the lake were 503 lb and 420 lb, respectively. Therefore, the drawdown periods represented 67 and 55 percent, respectively, of the total phosphorus loads leaving the lake, which demonstrates that the export of phosphorus during the drawdown period is a substantial part of the total annual phosphorus load exported from the lake.

Input of Phosphorus from Muskellunge Creek to Little St. Germain Lake

The total phosphorus input into Little St. Germain Lake from Muskellunge Creek was measured from November 1, 2014, to November 30, 2016 and amounted to 1,920 lb. Daily loadings into Little St. Germain Lake were more constant than those leaving the lake because concentrations of total phosphorus and streamflows at the inlet were more constant than at the outlet. The daily phosphorus loads ranged from 1.5 lb/d on March 3, 2015, to 7.8 lb/d on August 21, 2016. The lowest daily load on March 3, 2015, resulted from a low winter concentration of total phosphorus and a decreased late-winter flow. The highest daily load on August 21, 2016, resulted from a relatively high late summer concentration of total phosphorus and increased flow following substantial rainfall. Monthly phosphorus loads from Muskellunge Creek are listed in table 1. These results indicate that there is less seasonal variation in the loading at the inlet than at the outlet from Little St. Germain Lake.

Effects Of Changes in the Timing of the Water Releases from Little St. Germain Lake

To quantify the effects of focusing the release of water during winter drawdown to specific months on the total phosphorus load exported from Little St. Germain Lake, eight different scenarios were simulated and compared to the actual current baseline loading (Scenario 1). The experimental flow rates during specified drawdowns months (Scenarios 2–7) ranged between 71.1 and 86.9 ft^3/s. The daily flows for three of the scenarios (Scenarios 1, 2, and 7) are shown in figure 3. By drawing down the water levels in the lake over 2 months under Scenarios 8 and 9, flow rates for the specified monthly

Table 1. Measured phosphorus loads entering and leaving Little St. Germain Lake, Wisconsin, and phosphorus loads leaving the lake under various release scenarios.

[Phosphorus loads enter Little St. Germain Lake from Muskellunge Creek. lb, pound; NA, not available; CY, calendar year; PY, phosphorus year (period from September 1 to August 31, ending in the year specified)]

Year	Month	Phosphorus load entering lake, in lb	Phosphorus load leaving lake, in lb, under scenario								
			1	2	3	4	5	6	7	8	9
			Baseline Release	September Release	October Release	November Release	December Release	January Release	February Release	January and February Release	September and February Release
2014	September	NA	104	442	28	28	28	28	28	28	242
	October	NA	65	23	361	23	23	23	23	23	23
	November	82	75	20	20	313	20	20	20	20	20
	December	69	74	20	20	20	310	20	20	20	20
2015	January	70	96	24	24	24	24	380	24	211	24
	February	54	89	31	31	31	31	31	528	267	271
	March	82	57	57	57	57	57	57	57	57	57
	April	107	36	36	36	36	36	36	36	36	36
	May	83	30	30	30	30	30	30	30	30	30
	June	109	67	67	67	67	67	67	67	67	67
	July	72	29	29	29	29	29	29	29	29	29
	August	60	34	34	34	34	34	34	34	34	34
	September	68	34	369	28	28	28	28	28	28	204
	October	73	32	24	305	24	24	24	24	24	24
	November	90	81	21	21	269	21	21	21	21	21
	December	83	83	20	20	20	257	20	20	20	20
2016	January	67	99	25	25	25	25	319	25	180	25
	February	57	91	27	27	27	27	27	360	185	187
	March	87	30	30	30	30	30	30	30	30	30
	April	101	35	35	35	35	35	35	35	35	35
	May	91	64	64	64	64	64	64	64	64	64
	June	92	60	60	60	60	60	60	60	60	60
	July	66	51	51	51	51	51	51	51	51	51
	August	108	99	99	99	99	99	99	99	99	99
	September	92	111	562	38	38	38	38	38	38	309
	October	80	78	33	484	33	33	33	33	33	33
	November	70	65	22	22	335	22	22	22	22	22
	December	NA	125	30	30	30	436	30	30	30	30
2017	January	NA	99	25	25	25	25	365	25	204	25
	February	NA	90	26	26	26	26	26	412	209	212
Summary periods (12 months)											
	CY2015	938*	668	742	683	650	638	755	897	823	816
	CY2016	994*	907	1038	963	825	918	756	898	824	817
	PY2015	NA	756	813	736	692	689	754	896	821	853
	PY2016	983	758	823	764	731	719	777	816	795	820

Table 1. Measured phosphorus loads entering and leaving Little St. Germain Lake, Wisconsin, and phosphorus loads leaving the lake under various release scenarios.—Continued

[Phosphorus loads enter Little St. Germain Lake from Muskellunge Creek. lb, pound; NA, not available; CY, calendar year; PY, phosphorus year (period from September 1 to August 31, ending in the year specified)]

Year	Month	Phosphorus load entering lake, in lb	Phosphorus load leaving lake, in lb, under scenario								
			1	2	3	4	5	6	7	8	9
			Baseline Release	September Release	October Release	November Release	December Release	January Release	February Release	January and February Release	September and February Release
Drawdown period (September–February)											
2015 drawdown		NA	503	560	483	439	436	501	643	568	600
2016 drawdown		437	420	485	426	393	381	439	478	457	482
2017 drawdown		NA	568	699	624	487	580	514	560	536	632

*Full year of loading was obtained using loads from December to November of the specified year.

releases were reduced from approximately 75 ft^3/s to 40 ft^3/s, depending on the year.

Daily total phosphorus concentrations for September 2014 to December 2016 in Little St. Germain Creek for all the scenarios were calculated by dividing the daily total loads for Scenario 1 (baseline conditions) by the measured daily average flows (fig. 4). Because the daily concentrations were not measured for the last 2 months of the simulation period (January and February 2017), they were assumed to be the same as those measured in January and February 2016. Daily total phosphorus loads for each scenario were then obtained by multiplying the daily average flows (fig. 3) by the daily average total phosphorus concentrations (fig. 4).

Phosphorus loads exported out of Little St. Germain Lake during winter drawdown (September through February) during each of the nine scenarios are listed in table 2. The effects of focusing flow to a specific time period varied by year, but the scenarios that focused the removal of water in September (Scenario 2), February (Scenario 7), and split between September and February (Scenario 9) on average had the largest increase in phosphorus loads exported from the lake from 63 to 84 lb/yr (table 2). Results for Scenarios 2 and 7 are compared with current (baseline) phosphorus release in figure 5. Scenarios that increased releases during November (Scenario 4) and December (Scenario 5) generally decreased the load of phosphorus exported from the lake by an average of 58 lb/yr and 32 lb/yr, respectively (table 2). Focused releases during October (Scenario 3) and January (Scenario 6) had little effect on the amount of phosphorus exported from the lake. Release spread out during January and February (Scenario 8) resulted in an average increased export of 23 lb/yr of phosphorus. Scenario 9 split the focused release between September and February and resulted in an average increase in export of 84 lb/yr of phosphorus. Focused flow releases resulted in a change in the average annual phosphorus exported from the lake ranging from, on average, an 11 percent decrease (focusing the release in November; Scenario 4) to a 17 percent increase (focusing the release in September; Scenario 2) in phosphorus export compared with the phosphorus load typically exported from the lake for the entire period from September through February (current-release conditions).

Relative Importance of Focused Water Withdrawals

During 2015 to 2016, input of phosphorus from Muskellunge Creek into Little St. Germain Lake was 962 lb/yr (table 1). By focusing the release of water to a specific month or months (September, Scenario 2; February, Scenario 7; and September and February, Scenario 9), it would have been possible to remove an additional 63 to 84 lb/yr, on average, from Little St. Germain Lake (table 2). This is equivalent to reducing the contributions of phosphorus from Muskellunge Creek by 7 to 9 percent, annually.

Discussion

Factors Causing Focused Drawdowns To Affect Phosphorus Export

External phosphorus input to a lake drives in-lake phosphorus concentrations and lake productivity (plant and algal growth). The phosphorus is then either exported out of the lake or deposited in the lake sediments. The phosphorus that is deposited in the bottom sediments, however, does not all remain there; some of the phosphorus is released back into the water column, referred to as “internal phosphorus loading.” Mortimer (1941) demonstrated that phosphorus release rates increase dramatically when dissolved oxygen near the sediment-water interface is completely depleted (a condition known as anoxia). Typically, in deep dimictic lakes (lakes that

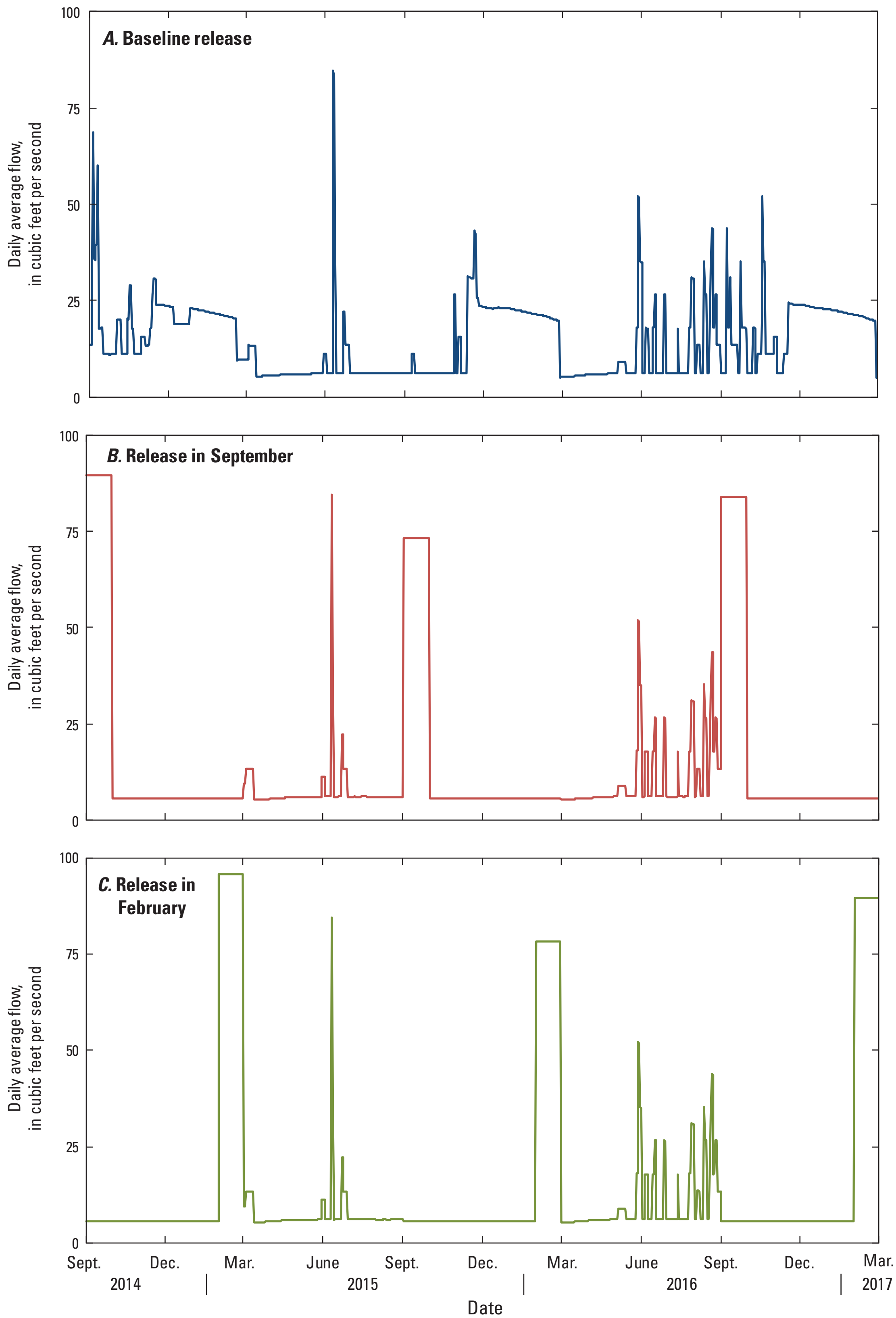

Figure 3. Flow releases from Little St. Germain Lake, Wisconsin, during September 1, 2014 through February 28, 2017, and for concentrated releases in September and February of each year in the study period. Scenario 1 is the baseline scenario for current releases for the period of study and Scenarios 2 and 7 are releases of all excess water from the lake in September and February, respectively.

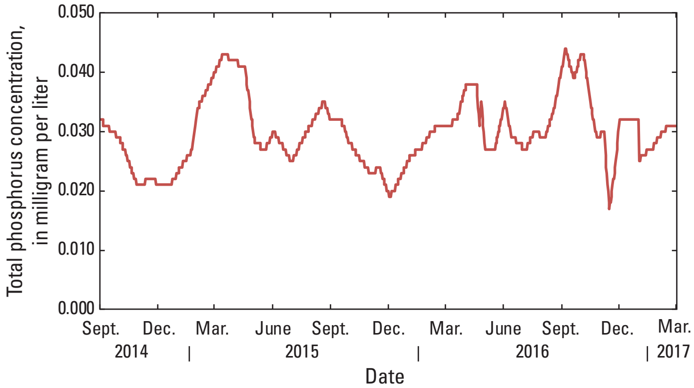

Figure 4. Daily average total phosphorus concentrations in Little St. Germain Creek, Wisconsin, during September 1, 2014, through February 28, 2017.

stratify throughout summer), phosphorus released from the deep sediments is retained in the deep (hypolimnetic) water and primarily released to the near-surface (epilimnetic) water during spring and fall turnover. Therefore, near-surface total phosphorus concentrations in dimictic lakes usually remain stable or decrease as summer progresses (Welch and Cooke, 1995). In shallow lakes, as are most of the basins in Little St. Germain Lake, microzones of anaerobic conditions can develop at the sediment/water interface during short periods of stratification, especially during summer when biological activity is high. Then, the frequent mixing events that occur in shallow lakes transport this phosphorus to the surface waters, which results in near-surface total phosphorus concentrations and productivity increasing throughout summer (Welch and Cooke, 1995; Robertson and others, 2016). In shallow lakes, total phosphorus concentrations usually reach the highest concentrations of the year in fall (September or October). Therefore, increasing the export of water from the lake late in fall may increase the export of phosphorus from shallow lakes, such as observed in Scenarios 2 (September release) and 9 (September and February release).

In shallow lakes, as are most of the basins in Little St. Germain Lake, dissolved oxygen concentrations throughout the water column can drop below critical concentrations during winter and cause increased internal phosphorus loading and a gradual increase in phosphorus concentrations under the ice (Wetzel, 1983; Hudson and Kirschner, 1997; Robertson and Rose, 2000). Therefore, increasing the export of water in late winter may increase the export of phosphorus from shallow lakes, such as observed in Scenarios 7 (February release) and 9 (September and February release).

Because of the release of phosphorus from the bottom sediments, there is distinct seasonality in total phosphorus concentrations in Little St. Germain Lake. The purpose of focusing water releases during late summer and middle to late winter is to take advantage of this seasonality in inlake total phosphorus concentrations and release water from the lake when the total phosphorus concentrations are greatest.

Effects of Drawdowns on Lake Water Quality

By focusing winter drawdown to a specific month or months, it might be possible to remove an additional 60 to 80 lb/yr of phosphorus from Little St. Germain Lake (table 2). Over several years, this would be equivalent to reducing the contributions of phosphorus from Muskellunge Creek by 6 to 9 percent annually. It is not expected that modifying the timing of winter drawdown will immediately improve the water quality of Little St. Germain Lake, but by continually removing an additional 60 to 80 lb of phosphorus each year through optimizing the timing of the release, total phosphorus concentrations stored in the sediments of Little St. Germain Lake are expected to gradually decline, similar to what occurs with hypolimnetic withdrawal systems (Nurnberg, 1987; Nurnberg and others, 1987), and reduce the release of phosphorus back into the water column, resulting in lower total phosphorus concentrations in the lake. The decreases in total phosphorus concentrations are expected to primarily occur in the most downstream areas of the lake, such as the South and Second South Bays. It was estimated that a 25 percent decrease in phosphorus loading to Little St. Germain Lake should decrease summer average total phosphorus concentrations by about 0.004 to 0.007 mg/L in the East Bay of Little St. Germain Lake (Robertson and others, 2005). If the South and Second South Bays of Little St. Germain Lake respond in a similar way as the East Bay, it is expected that a 7 to 9 percent increase in phosphorus removal from the lake (or about 7/25ths to 9/25ths of the changes simulated for the East Bay) should gradually result in about a 0.001 to 0.003 mg/L reduction in total phosphorus concentrations in the South Bays. Decreases in total phosphorus concentrations should then decrease algae (chlorophyll *a*) concentrations and improve water clarity (Secchi depth) in the downstream bays.

When dissolved oxygen concentrations throughout the water column drop below critical concentrations under the ice during winter, it can cause fish kills (referred to as “winterkill”), increased internal phosphorus loading, and odor problems where water leaves the lake (Wetzel, 1983; Hudson and Kirschner, 1997). To try to eliminate these issues, aeration systems have been installed in Little St. Germain Lake and operated throughout winter. Winter aeration has been shown to have measurable effects on the water quality in Little St. Germain Lake (Robertson and others, 2005) and other lakes (Hudson and Kirschner, 1997) in winter and has eliminated winterkill in Little St. Germain Lake (S. Gilbert, Wisconsin Department of Natural Resources, pers. commun., 2014).

By focusing water withdrawal from the lake to a specific month or months, it may be possible to reduce the extent of winter anoxia in specific areas of Little St. Germain Lake. When water levels are drawndown in late fall or early winter, much of the water that has high dissolved oxygen

Table 2. Phosphorus export from Little St. Germain Lake, Wisconsin, from 2015 to 2017 during the winter drawdown (September through February) and under modified flow-release scenarios.

Year	Scenario								
	1	2	3	4	5	6	7	8	9
	Baseline Release	Sept. Release	Oct. Release	Nov. Release	Dec. Release	Jan. Release	Feb. Release	Jan./Feb. Release	Sept./Feb. Release
	Phosphorus loading into Little St. Germain Creek for September through February, in pounds								
2015	503	560	483	439	436	501	643	568	600
2016	419	484	425	392	381	438	477	456	481
2017	568	699	624	487	580	514	560	536	632
	Increase in phosphorus removed from the lake, in pounds								
2015	0	57	-20	-64	-68	-2	140	65	97
2016	0	66	6	-27	-38	19	58	38	62
2017	0	130	56	-82	11	-54	-9	-33	63
Average		**84**	**14**	**-58**	**-32**	**-12**	**63**	**23**	**74**
	Percent increase in drawdown (September–February) phosphorus removal								
2015	0	11	-4	-13	-13	-0	28	13	19
2016	0	16	2	-6	-9	5	14	9	15
2017	0	23	10	-14	2	-10	-2	-6	11
Average	**0**	**17**	**2**	**-11**	**-7**	**-2**	**13**	**5**	**15**
	Percent increase in the annual phosphorus removal								
2015	0	8	-3	-8	-9	-0	18	9	13
2016	0	9	1	-4	-5	3	8	5	8
2017	0	17	7	-11	1	-7	-1	-4	8
Average	**0**	**11**	**2**	**-8**	**-4**	**-2**	**8**	**3**	**10**
	Percentage of increase in phosphorus removal compared to phosphorus inputs in Muskellunge Creek[1]								
2015	0	6	-2	-7	-7	-0	14	7	10
2016	0	7	1	-3	-4	2	6	4	6
2017	0	13	6	-8	1	-6	-1	-3	7
Average	**0**	**9**	**1**	**-6**	**-3**	**-1**	**6**	**2**	**8**

[1]Average annual load for Muskellunge Creek is based on loads from November, 2015 through October, 2016.

concentrations is released before ice covers the surface of the lake. This results in an increased rate of dissolved oxygen depletion as winter progresses because oxygen in the sediment is consumed in a smaller volume of lake water. However, if water is released later in the winter, in February (Scenarios 7 and 9), much of the oxygen consumption would be from a larger volume of water, and dissolved oxygen concentrations would not be reduced so greatly. However, maintaining higher water levels early in the winter may reduce the effectiveness of a mid- to late-winter (February) withdrawal in terms of phosphorus load reduction because higher water levels should result in increased dissolved oxygen concentrations, decreased phosphorus release from sediments, and decreased total phosphorus concentrations in the lake.

Recognizing and understanding the potential effects of changing the timing of winter drawdown to an optimized period is important. To better evaluate implementation of a specific drawdown strategy, the potential positive and negative effects, whether speculative or known, should also be considered. The most positive effect of Scenarios 2, 7, and 9 is increased removal of phosphorus from Little St. Germain Lake, which could potentially improve its long-term water quality, especially in the most downstream South and Second South Bays of the lake. The anticipated increased phosphorus export out of Little St. Germain Lake is similar for all three of these scenarios; therefore, the potential negative effects of each of these three scenarios were examined.

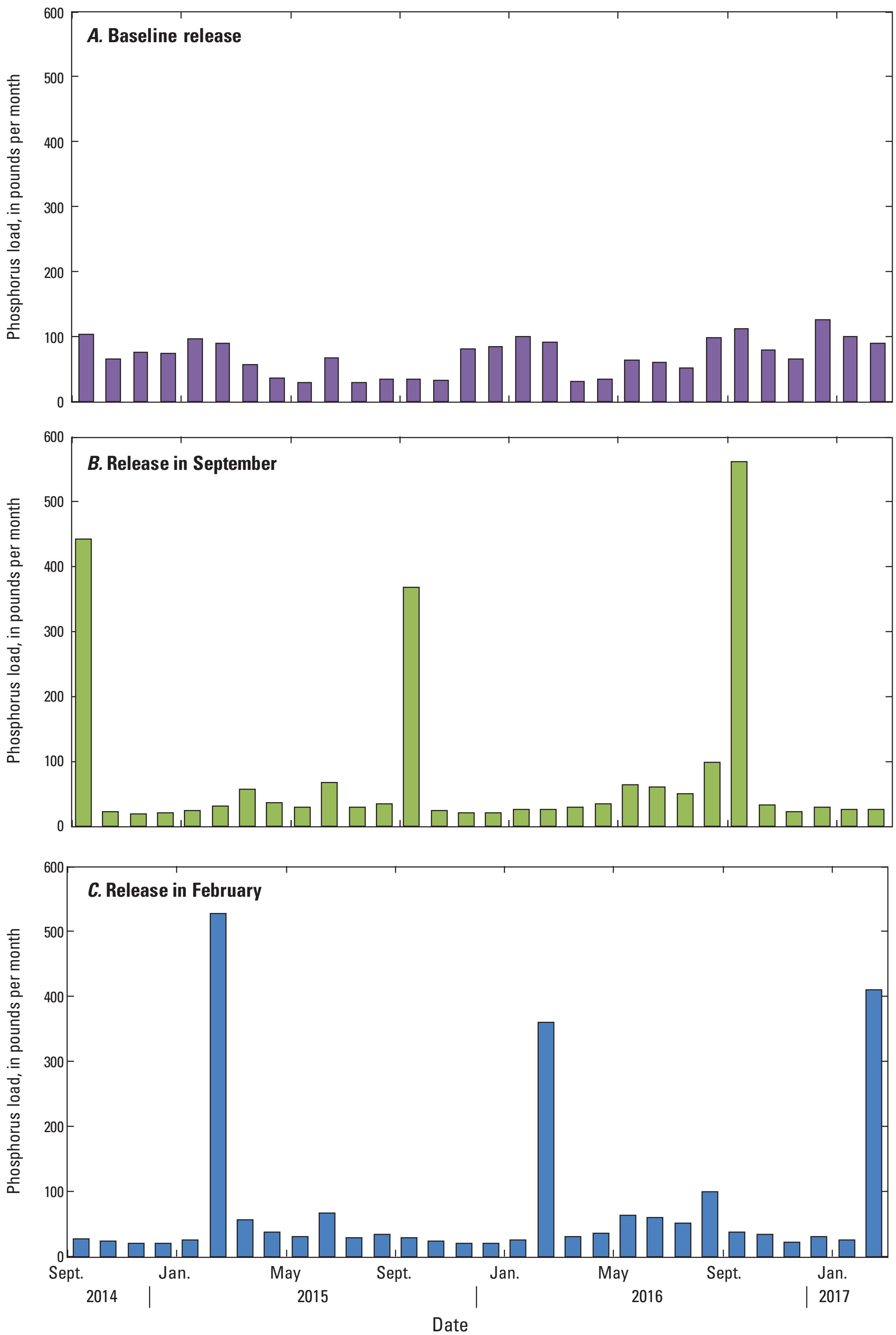

Figure 5. Monthly total phosphorus loads exported out of Little St. Germain Lake, Wisconsin, for baseline-release, September, and February release scenarios.

A concentrated September release appears to have the most potential negative effects of the three scenarios. Drawing down Little St. Germain Lake in September could affect open-water recreation and shoreline structure use, such as access to boat docks. Drawing down Little St. Germain Lake early in fall could also increase the risk of more widespread anoxia issues because of the smaller volume of oxygen-rich water in the lake before the lake freezes. Focusing the release to a 1-month period should be achievable given the design of the dam except during very dry conditions, but could result in flows that may be greater than the morphology of Little St. Germain Lake Creek can handle and cause bank and channel erosion. In addition, fall turnover is often weather dependent and may not have always occurred prior to a September release and possibly result in lower total phosphorus concentrations in the lake. Lowering the lake elevations earlier than current-release operations, such as in September, may increase groundwater flow into the lake by increasing the gradient between the surface of the lake and that of the surrounding groundwater for a longer period of time. Increased flow of groundwater with relatively high phosphorus concentrations into the lake could potentially increase the phosphorus loading to the lake. Further investigation and modeling may be required to determine the significance of these types of groundwater/lake interactions.

With a concentrated February release, Little St. Germain Lake would maintain a greater volume of water during more of the winter months and reduce the anoxic conditions in the lake. Maintaining a higher lake elevation during the winter months may also decrease the groundwater flow by maintaining a weaker gradient between the lake and the groundwater. However, with lake levels remaining higher than current-release conditions, shoreline structures could be damaged by ice. Focused drawdown during the winter months could potentially cause ice jams downstream and affect the two recreational bridges downstream of the lake where Little St. Germain Creek flows into the Rainbow Flowage. In addition, the unnatural flows during midwinter could cause negative ecological effects that should be considered (Wisconsin Department of Natural Resources, 2011).

A split September and February drawdown (Scenario 9) may minimize the negative effects that could occur in Scenarios 2 and 7 by reducing the flow rates compared with focused single-month releases. With the flow rates leaving the lake cut in half during each of the 2 months, the effects on channel morphology and ecological concerns should be reduced. The overall effectiveness of this scenario may be slightly more weather dependent than a full drawdown in February but more effective than only focusing the drawdown to September. A split January and February drawdown would minimize the negative effects of increased flow but would not remove as much phosphorus as Scenarios 2, 7, and 9 because dissolved oxygen concentrations have not yet been depleted in January and phosphorus concentrations in the lake have not yet increased.

Summary

In the interest of improving the water quality of Little St. Germain Lake, the U.S. Geological Survey studied phosphorus loading into and out of the lake and evaluated how focusing winter drawdown to different times of the year should affect the amount of phosphorus being released from the lake, potentially influencing the water quality in the lake. During 2015 and 2016, an average of about 780 pounds per year (lb/yr) of phosphorus was exported out of the lake, which is about 80 percent of that contributed to the lake by Muskellunge Creek. By optimizing the timing of winter drawdown to when concentrations near the outlet of the lake are highest (September and February), there could be an increased export of phosphorus from the lake by about 60 to 80 lb/yr, which is equivalent to reducing the contributions of total phosphorus from Muskellunge Creek by about 7 to 9 percent. Increasing phosphorus export from the lake should gradually improve the water quality of the lake, especially in the South and Second South Bays of the lake. The study focused drawdown to specific months, but in practice, the phosphorus concentrations in the South and Second South Bays of Little St. Germain Lake should drive the withdrawal strategy. To optimize the phosphorus release, the timing of the drawdown would be best served by coinciding with the highest concentrations of phosphorus in the lake, typically in fall and late winter.

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