Hydrology: Sources of Water and Nutrients

Study results indicate that Silver Lake is colimited by both phosphorus and nitrogen, at the time when the bioassay was conducted. The average N:P ratio was found to be 22:1; however, it varied seasonally as phosphorus and nitrogen concentrations in the lake changed (fig. 8). As a result, both phosphorus and nitrogen are deemed critical nutrients in the development of algal blooms and lake eutrophication in Silver Lake. While this colimitation indicates that both nitrogen and phosphorus are needed to produce excessive algal growth during the summer months, it does not indicate that both nutrients need to be reduced to control algal blooms. Based on the bioassay study, management practices that reduce either nitrogen or phosphorus should be enough to limit excessive primary production in the summer months, and a reduction in both nutrients would likely impact magnitude (Harpole and others, 2011; Conley and others, 2009). To determine the sources of nutrients to Silver Lake, contributions from surface water (tributary inputs, including septic contribution to tributaries), groundwater (including septic), atmospheric deposition (wet and dry), waterfowl, lawn runoff, and internal loading from lake sediments were evaluated as described in the following sections.

Sources of Water–Water Budget

The water budget for Silver Lake can be visualized as a pie graph with individual components represented as a slice of the overall budget. Figure 12 illustrates the various components of the water budget by percentage of outflow and inflow over the 2-year study period. Water loss from Silver Lake is primarily the outflow of water from Silver Lake through Silver Creek which accounts for 91.9 percent of all water leaving Silver Lake. The remaining 8.1 percent is removed through evaporation. The primary contribution of water to Silver Lake is from Hunter Creek at 52.2 percent. Groundwater sources contribute 30.6 percent of inflow, precipitation contributes 10.3 percent, the tributary at the State Park contributes 4.1 percent, and the tributary at North Shore Drive contributes 2.8 percent. Runoff of precipitation from the land directly to the lake is assumed to be small and is considered as part of the groundwater input to the lake.

Further refining the water budget by season for the 2-year study period provides insight on the relative contribution of the various components at different times of year (fig. 13). The three largest components of the water budget remain the outflow of water from Silver Lake, the inflow of water from Hunter Creek, and inflow of water from groundwater sources. However, the relative amounts of each component vary by

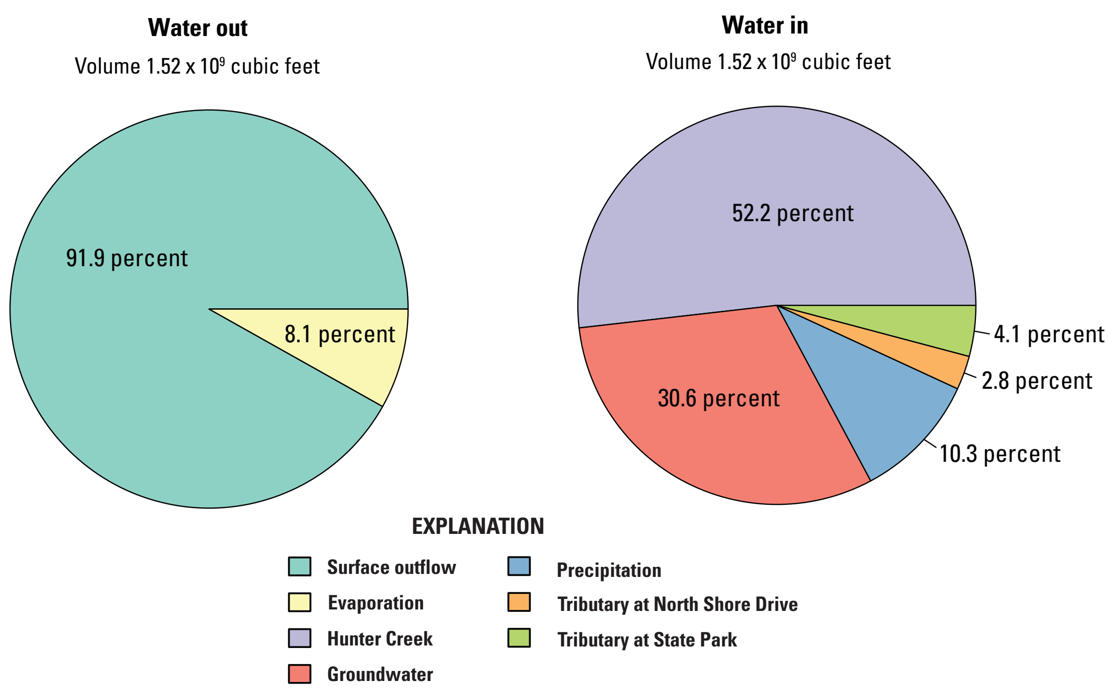

Figure 12. Annual water budget for Silver Lake, Oceana County, Michigan.

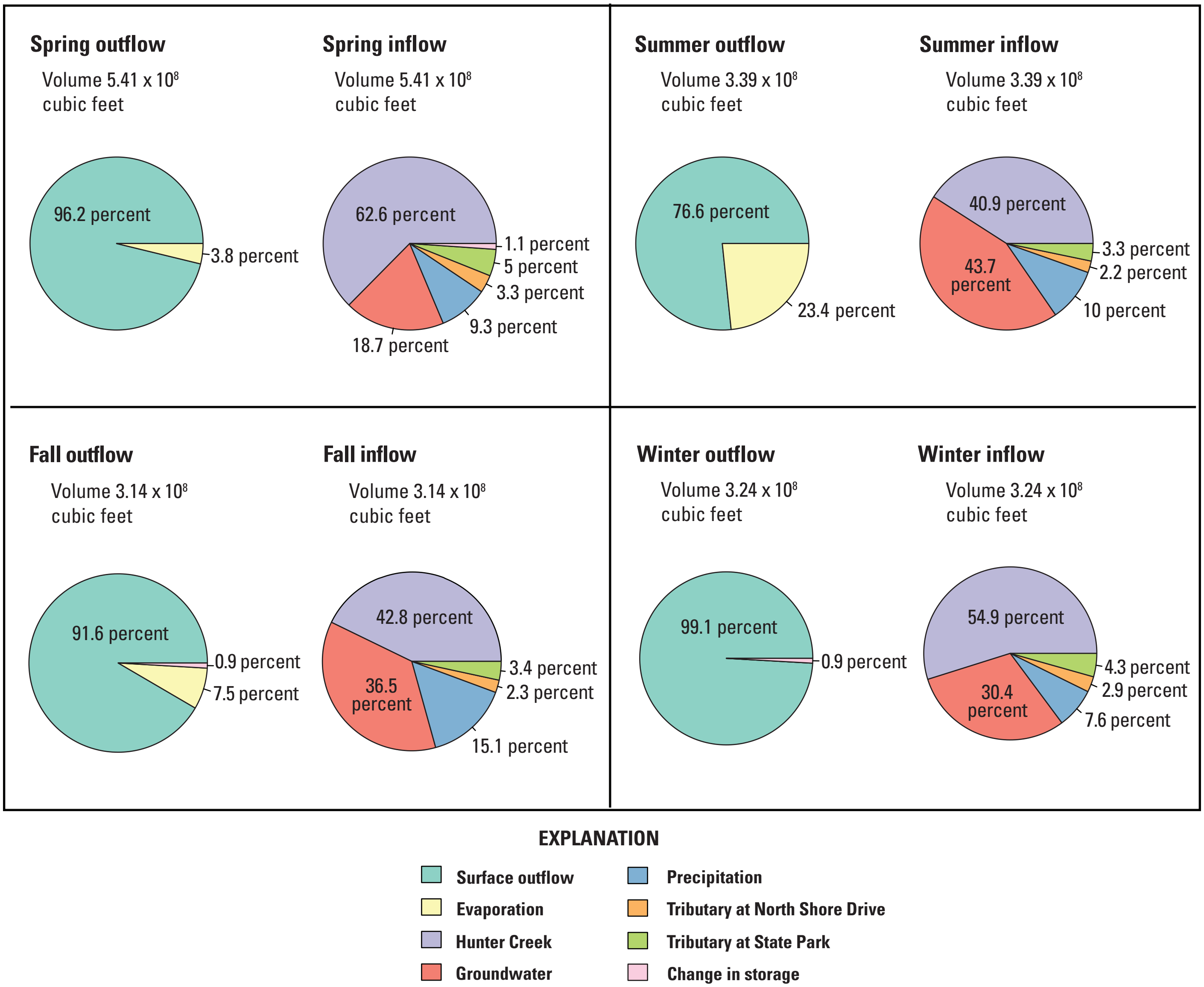

Figure 13. Water budget, by season, for Sliver Lake, Oceana County, Michigan.

season. During the spring season (March—May), Hunter Creek is the dominant source (62.6 percent) of water to the lake. In summer (June—August), the primary contributor of water to the lake becomes groundwater (43.7 percent). The fall season (September—November) shows both Hunter Creek and groundwater contributing similar proportions of the overall water budget (42.8 and 36.5 percent, respectively), with Hunter Creek being slightly more. During winter (December through February), Hunter Creek becomes the dominant source (54.9 percent) of water to the lake again. It should be noted that there is a very small change in storage for the lake by season. During the fall and winter, the lake level drops so there is a loss of water in storage of about 0.9 percent of the outflow volume in each season. In the spring there is a gain in storage of 1.1 percent of the inflow volume, which over the 2-year study balances to no net change in storage.

Sources of Nutrients—Nutrient Budget

A nutrient budget was calculated to (1) determine the sources of phosphorus and nitrogen to Silver Lake and to identify the contribution from each of these sources, and (2) calculate the nutrient output. The annual and seasonal nutrient budgets were computed using the BATHTUB model (Walker, 1996) based on 2 years of data collection. The BATHTUB model was used to simulate the current-conditions in the lake based on the data collected. The model is used to predict eutrophication-related water-quality conditions in a lake using empirical relationships that have been previously developed for lake applications (Walker, 1985). Loads estimated using the BATHTUB model are discussed in this section; details of the model data requirements, limitations, and calibration are given in the Nutrient Load Modeling section.

Nutrient Concentrations

Nutrient data collected from Hunter Creek, the tributary at the State Park, and the tributary at North Shore Drive were analyzed and compared to the EPA ambient water-quality criteria recommendations (EPA nutrient criteria) for rivers and streams for Ecoregion VII (table 5). The seasonal nutrient loading during the winter months was not modeled due to minimal data collection during the winter season.

Surface-Water Inflow and Outflow

Hunter Creek is the largest tributary entering Silver Lake and contributes the highest inputs of nutrients compared to the other surface water inflows to the lake. Average total phosphorus concentrations fell below the EPA nutrient criteria recommendation of 0.033 mg/L (tables 5 and 6). The highest total phosphorus concentrations were typically measured during storm events (except for the April 15, 2013 event) and total phosphorus concentrations peaked during late summer and early fall months with lower concentrations recorded during the April sampling events in 2013 and 2014. Orthophosphate concentrations for Hunter Creek were typically at or below the NWQL detection limit of 0.004 mg/L and, therefore, orthophosphate is a minimal component of the phosphorus contribution from Hunter Creek. The average total nitrogen concentrations in Hunter Creek exceeded the EPA nutrient criterion recommendation of 0.54 mg/L (table 6). The highest total nitrogen concentrations were measured during the spring storm events in 2013–14, with the lowest concentrations measured in mid to late summer. Nitrate typically accounted for half of the total nitrogen in Hunter Creek, averaging 0.63 mg/L during the study.

The tributaries at the State Park and at North Shore Drive also were monitored to assess the remaining surface water inputs to Silver Lake. The average total phosphorus and total nitrogen concentrations are presented in table 6. Total phosphorus concentrations were below or slightly above the EPA nutrient criteria for both small tributaries (tables 5 and 6). There was no correlation between total phosphorus and storm events at the tributary at the State Park; however, it appears there is a seasonal distribution where total phosphorus concentrations are lowest in late winter/early spring and increase through the summer and peak in late summer/early fall. Almost all samples collected at the tributary at North Shore Drive were collected during storm event conditions due to the low flows and minimal input during base-flow periods. Orthophosphate concentrations for both small tributaries were at or below the minimum detection limit of 0.004 mg/L.

The average total nitrogen concentrations were consistent for both tributaries (table 6). At both sites, total nitrogen concentrations exceeded the EPA nutrient criterion of 0.54 mg/L (table 5, table 6). Nitrate and organic nitrogen made up the bulk of the total nitrogen at both tributaries. At the tributary at the State Park, nitrate accounted for 71 percent of total nitrogen, and organic nitrogen accounted for about 28 percent. At the tributary at North Shore Drive, nitrate made up approximately 27 percent of total nitrogen, while organic nitrogen accounted for 69 percent.

***Hunter Creek** upstream from the Upper Silver Lake outlet and the Upper Silver Lake outlet at West Taylor Road (fig. 2, table 2) were monitored on three occasions in August and September 2014; twice during storm events and once during base-flow conditions. Nutrient loads at these two sites represent approximately 1 month (29 days) of the year and were calculated from the date the first sample was collected until the last sample was collected. Upstream Hunter Creek total phosphorus concentrations ranged from 0.02 to 0.07 mg/L, with an average concentration of 0.04 mg/L. The Upper Silver Lake outlet total phosphorus concentrations ranged from 0.02 to 0.03 mg/L, with an average concentration of 0.02 mg/L. Total phosphorus concentrations either slightly exceeded or fell below the EPA nutrient criterion recommendation of 0.033 mg/L (table 5). Total nitrogen concentrations at the upstream Hunter Creek tributary ranged from 1.08 to 1.45 mg/L and averaged 1.22 mg/L, and total nitrogen concentrations at Upper Silver lake outlet ranged from 0.67 to 0.77 mg/L and averaged 0.72 mg/L. Both sites exceeded the EPA nutrient criterion for total nitrogen (table 5). From August 19, 2014 through September 17, 2014, approximately 53 lb of phosphorus and 1,331 lb of nitrogen were delivered from Upper Hunter Creek and approximately 13 lb of phosphorus and 439 lb of nitrogen from the Upper Silver Lake outlet.*

Additional monitoring and discharge measurements will be necessary to determine the annual nutrient loading from Upper Silver Lake and upstream Hunter Creek and to determine if nutrient contributions vary seasonally from each of these tributaries. Some potential sources contributing to elevated nitrogen concentrations in these tributaries include agricultural fertilizers and manure, illicit wastewater discharge, septic system input (including septic systems further than 200 ft from Hunter Creek), precipitation and dry atmospheric deposition, and natural organic decomposition. E. coli concentrations at upper Hunter Creek exceeded the recreational criteria during two of the three sampling events (340, 1,700, and 140 MPN/100 mL). Upper Silver Lake outlet E. coli concentrations exceeded the recreational criteria once (58, 440, and 6 MPN/100mL).

The Silver Lake outlet (Silver Creek) also was monitored to determine the nutrient concentrations leaving Silver Lake. Those data are presented in table 6.

Precipitation and Dry Deposition

Phosphorus and nitrogen were measured in dry deposition and wet deposition on four occasions from February 2014 to September 2014, and the average concentrations are presented in table 6. Concentrations of nutrients in wet and dry deposition displayed seasonal variability with the highest concentrations of nitrogen being observed in wet deposition in the winter, while the highest concentrations of phosphorus were observed in dry deposition in the summer. Total nitrogen concentrations were always higher in wet deposition when compared to dry deposition, while total phosphorus concentrations were higher in wet deposition in winter and fall, but higher in dry deposition in spring and summer. Spring and summer peaks in phosphorus are typically related to increased pollen deposition that occurs during these seasons (Lewis and others, 1985).

Groundwater Influence

Nutrient loading from groundwater to Silver Lake was monitored as described in the Water Quality Data Collection-Groundwater Monitoring and Flow section of this report. The influence of groundwater on Silver Lake was unknown prior to this study as previous studies never accounted for that component in the nutrient and water budgets.

To accurately determine the nutrient loading from groundwater, phosphorus and nitrogen concentrations were analyzed at the four wells installed on the east, west, north, and south sides of Silver Lake. Groundwater nutrient concentrations varied amongst the four wells (table 6) and both total phosphorus and total nitrogen concentrations were consistently highest at the south well. Orthophosphate accounted for the majority of phosphorus found in groundwater with orthophosphate concentrations ranging from 83 percent (south well) to 100 percent (west well). In addition, nutrient data from a subset of five drain tiles at the north end of Silver Lake are presented in table 6. Orthophosphate concentrations accounted for approximately 81 percent of the total phosphorus concentrations in the drain tile discharge.

Other Sources of Nutrients

This study describes 2 years of water-quality monitoring in Silver Lake (including internal loading), as well as monitoring of nutrients contributed by groundwater, tributaries, and atmospheric deposition. Other potential sources of nutrients are not individually identified in this report, as the nutrient inputs from these other sources are ultimately captured in the overall water-quality monitoring design of the study. For example, the human impacts on water quality as a result of the recreational use of the sand dunes and Silver Lake were not independently measured; however, the lake and groundwater monitoring in this study accounted for these specific inputs.

Nutrient Loads

Continuous flow data and discrete water-quality data were used to estimate nutrient loads of total phosphorus and total nitrogen from Hunter Creek using the BATHTUB model (Walker, 1996). The BATHTUB model also was used to calculate a nutrient budget for Silver Lake using water-quality data from this study.

Surface-Water Inflow and Outflow

Based on 2 years of monitoring, the mean annual load of phosphorus from Hunter Creek was 384.5 lb, and the mean annual load of nitrogen was 29,277 lb. Of the estimated loads from Hunter Creek, the septic loading model (septic systems as sources of nutrients) indicated that septic systems likely contributed 22.3 percent of phosphorus (85.9 lb) and 0.95 percent of nitrogen (279.3 lb). The seasonal contributions of phosphorus and nitrogen from Hunter Creek are presented in figure 14. Based on the BATHTUB model output, Hunter Creek accounted for approximately 25 percent of the phosphorus load to Silver Lake in the fall (73 lb), 33 percent in the spring (149 lb), and 20 percent in the summer (65 lb). Hunter Creek was the largest contributing source of nitrogen during the fall (51 percent, 8,280 lb) and spring seasons (80 percent, or 27,825 lb), respectively. During the summer, Hunter Creek accounted for 38 percent (7,895 lb) of the nitrogen budget to Silver Lake (fig. 14).

Discharge was measured concurrently with sample collection at the two small tributaries and the data were entered into the BATHTUB model, along with nutrient concentrations, to calculate phosphorus and nitrogen loading. Based on 2 years of monitoring, the mean annual load of phosphorus from the tributary at the State Park was 37 lb, and the mean annual load of nitrogen was 2,111 lb. The mean annual load of phosphorus from the tributary at North Shore Drive was 29.6 lb, and the mean annual load of nitrogen was 1,032 lb. The small tributaries collectively accounted for about 5 percent of the phosphorus load during the fall and 4 percent of the phosphorus load to Silver Lake during the spring and summer. The nitrogen loading from the two small tributaries collectively made up approximately 6 percent of the nitrogen budget in the fall, 7 percent in the spring, and 5 percent in the summer (fig. 14).

The total annual output of phosphorus and nitrogen leaving the lake was approximately 1,340 lb (99.8 percent of total phosphorus load to the lake) and 30,071 lb (57.8 percent of total nitrogen load to the lake), respectively. Even though the majority of phosphorus leaves Silver Lake, the phosphorus remains in the lake for the duration of the lake residence time (223 days), contributing to algal blooms and eutrophication.

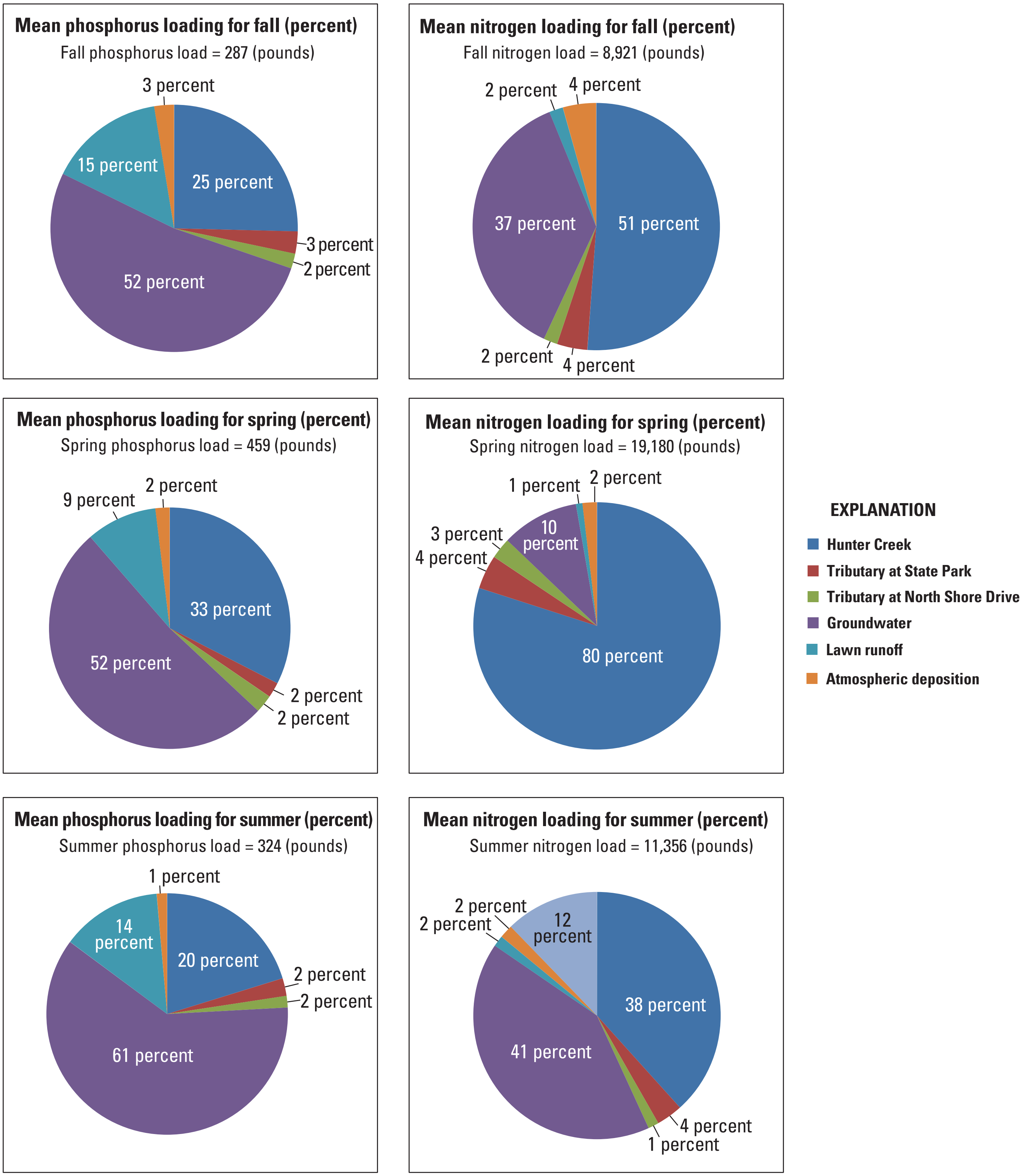

Figure 14. Mean nutrient loading, by season, to Silver Lake, Oceana County, Michigan. (Internal load of phosphorus and nitrogen was measured only during the summer and assumed to be negligible during the remainder of the year. Internal phosphorus loading during the summer was less than 1 percent of the total phosphorus load.).

Precipitation and Dry Deposition

The mean annual atmospheric load of phosphorus to Silver Lake was 87 lbs, and the mean annual load of nitrogen was 4,586 lb. The seasonal phosphorus loading from atmospheric deposition was approximately 3 percent of the phosphorus budget in the fall (7 lb), 2 percent in the spring (9 lb), and 1 percent in the summer (4.5 lb). Nitrogen loading from atmospheric deposition was highest in the fall (4 percent), and made up 2 percent of the nitrogen budget during the spring and summer (fig. 14). Loads of both phosphorus and nitrogen from dry deposition were 10 to 100 times smaller than measured wet deposition loads.

The nutrient load of phosphorus and nitrogen contributed from waterfowl represents a solid mass (not a mass delivered in water) and was included in the BATHTUB model as an addition to the atmospheric deposition value. Loads attributed to waterfowl account for 0.99 percent of total phosphorus deposition and 0.11 percent of total nitrogen deposition to Silver Lake. In total, atmospheric and waterfowl loads were computed to be approximately 6 percent of the total phosphorus annual load and 9 percent of the total nitrogen annual load to Silver Lake.

Table 8. Nutrient loading from groundwater to Silver Lake, Oceana County, Michigan.

[lb/yr; pounds per year]

Groundwater contribution	Total phosphorus (lb/yr)	Total nitrogen (lb/yr)
North quadrant	12.4	39.7
South quadrant	403	8,811
East quadrant	14.8	108
West quadrant	132	3,653
North drain tiles	67.6	340
Total groundwater nutrient load	**630**	**12,951**

Groundwater Influence

The groundwater component of the nutrient budget was calculated by dividing Silver Lake into four quadrants as described in appendix 3. The drain tiles at the north end of Silver Lake were evaluated separately and are included in the groundwater nutrient budget. Based on 2 years of monitoring, the mean annual load of phosphorus and nitrogen from the four groundwater quadrants and the drain tiles are described in table 8. The mean annual load of phosphorus and nitrogen from the north end drain tiles is 68 and 340 lb, respectively.

Results from the BATHTUB model showed the estimated contribution of phosphorus via groundwater to Silver Lake was highest in the summer and made up approximately 61 percent of the summer phosphorus budget (198 lb). The phosphorus loading from groundwater accounted for approximately 52 percent of the phosphorus budget during both the fall and spring (149 and 237 lb, respectively). Study findings indicate that much of the phosphorus contribution to Silver Lake via groundwater is orthophosphate; a form of phosphorus that can readily stimulate algae growth. Based on the BATHTUB model output, groundwater accounted for 80 percent of the nitrogen budget during the spring (1,945 lb), 51 percent during the fall (3,290 lb), and 38 percent during the summer (4,702 lb) (fig. 14). The mean annual load from all monitored groundwater sources was 630 lb of phosphorus and 12,951 lb of nitrogen (table 8).

The septic model (Garn and others, 1996; Reckhow and others, 1980) estimated that septic systems likely contributed 47.8 percent (300.9 lb) of phosphorus and 1.1 percent (136.1 lb) of nitrogen to groundwater annually (fig. 15). This septic model is designed to calculate both phosphorus and nitrogen loading, however has mostly been used for the estimation of phosphorus from septic sources as phosphorus is often times the nutrient of concern. The soil retention coefficient (SR), which represents the fraction of phosphorus or nitrogen retained between the septic system and the lake, was held constant for both phosphorus and nitrogen. The modeled septic and nonseptic (plus septic input greater than 200 ft from shoreline) contributions to the Silver Lake nutrient budget are illustrated in figure 15.

Internal Nutrient Loading

The results of the sediment core incubations experiments showed that internal loading is not a significant source of phosphorus in Silver Lake. Concentrations of total phosphorus in the water column overlying sediment cores tended to remain stable or slightly decline over time, and were generally less than 0.02 mg/L during the core incubations regardless of site, sampling date, or redox treatment (fig. 16). Ninety-seven to 100 percent of SRP concentrations were below the detection limit, so those data are not shown. Mean total phosphorus flux was negative and similar between redox treatments, ranging from −0.23 to −0.02 milligrams per square meter per day ($mg/m^2/d$) (table 9). In lakes where internal phosphorus loading is problematic, release rates are usually much higher in anoxic than oxic conditions because a lack of dissolved oxygen leads to the reduction of ferric oxyhydroxides, thereby resulting in the dissociation of phosphorus from its bound form to iron, and a diffusion of phosphorus into the water column (Boström and others, 1982). This was not observed in the Silver Lake sediment incubations in this study, indicating that sediment release is not a significant source of phosphorus; indeed, the data indicate that sediments may actually be a minor sink for phosphorus in Silver Lake, given the negative release rates.

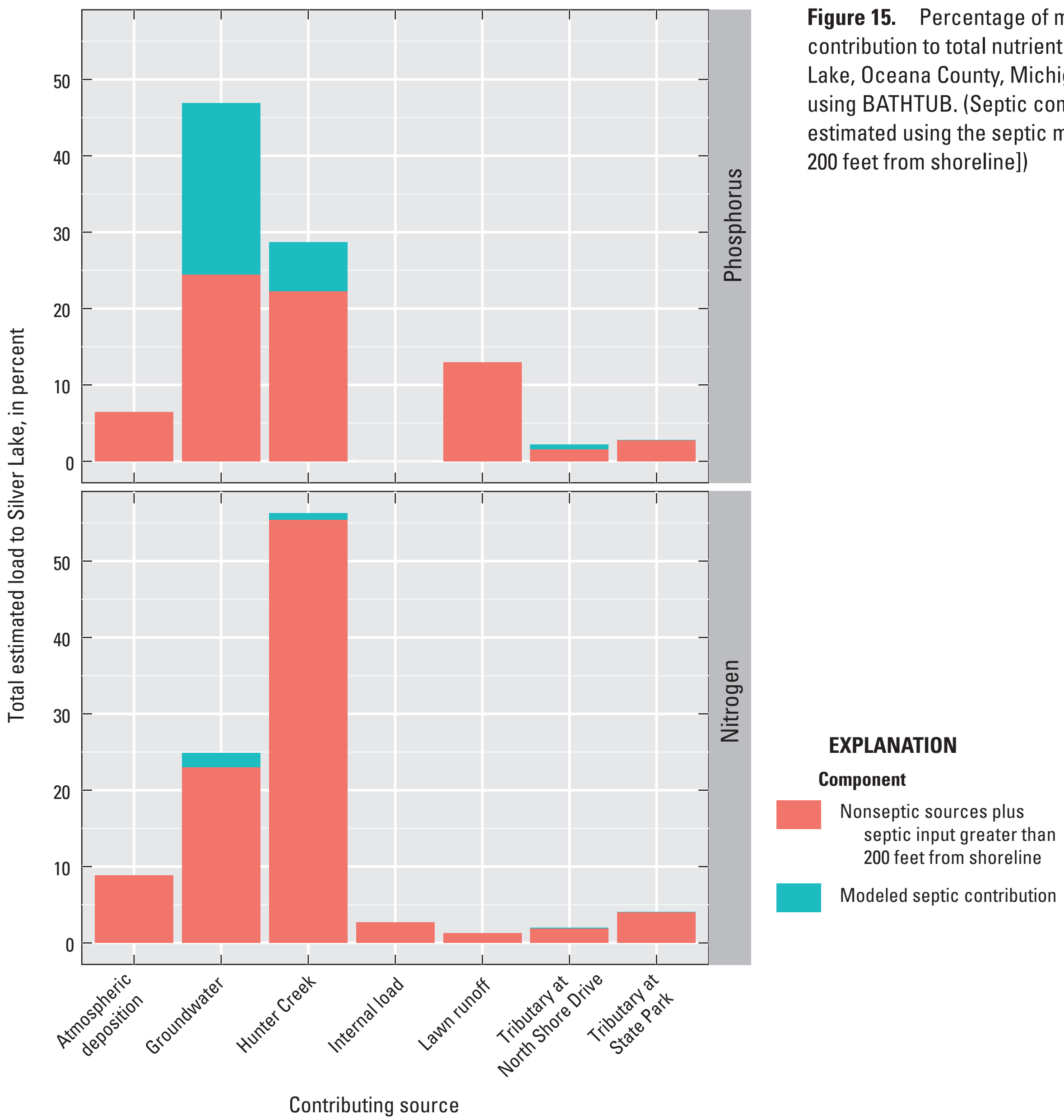

Figure 15. Percentage of modeled septic contribution to total nutrient load in Silver Lake, Oceana County, Michigan, estimated using BATHTUB. (Septic component estimated using the septic model [modeled 200 feet from shoreline])

To place these results in a regional context, total phosphorus sediment release rates in Silver Lake were compared to that of Spring Lake, a west Michigan Lake that was experiencing significant internal phosphorus loading. This lake has undergone an alum treatment to control internal phosphorus release. In anoxic treatments, mean total phosphorus flux in Spring Lake was 18 mg/m^2/d prior to the alum treatment, but after treatment that rate was reduced to only 0.4 mg/m^2/d (1 year after alum) and 2 mg/m^2/d (5 years after alum) (table 9) (Steinman and others, 2004; Steinman and Ogdahl, 2008, 2012). Even in oxic treatments, when phosphorus is expected to be bound to iron, and therefore not prone to diffusion into the water column, total phosphorus flux from Spring Lake sediments was positive, albeit much lower than in anoxic treatments (table 9). Phosphorus release from sediments in Silver Lake is much lower than that in Spring Lake, irrespective of oxic or anoxic conditions.

Unlike phosphorus, the sediment core experiments revealed that internal loading is contributing nitrogen to the water column of Silver Lake. There was a distinct difference in ammonium concentrations between the redox treatments throughout the core incubation period. Initial ammonium concentrations were approximately 0.1 mg/L and increased to as much as 1.5 mg/L in anoxic treatments by day 28 (fig. 17, illustrates data from middle site only, L2).

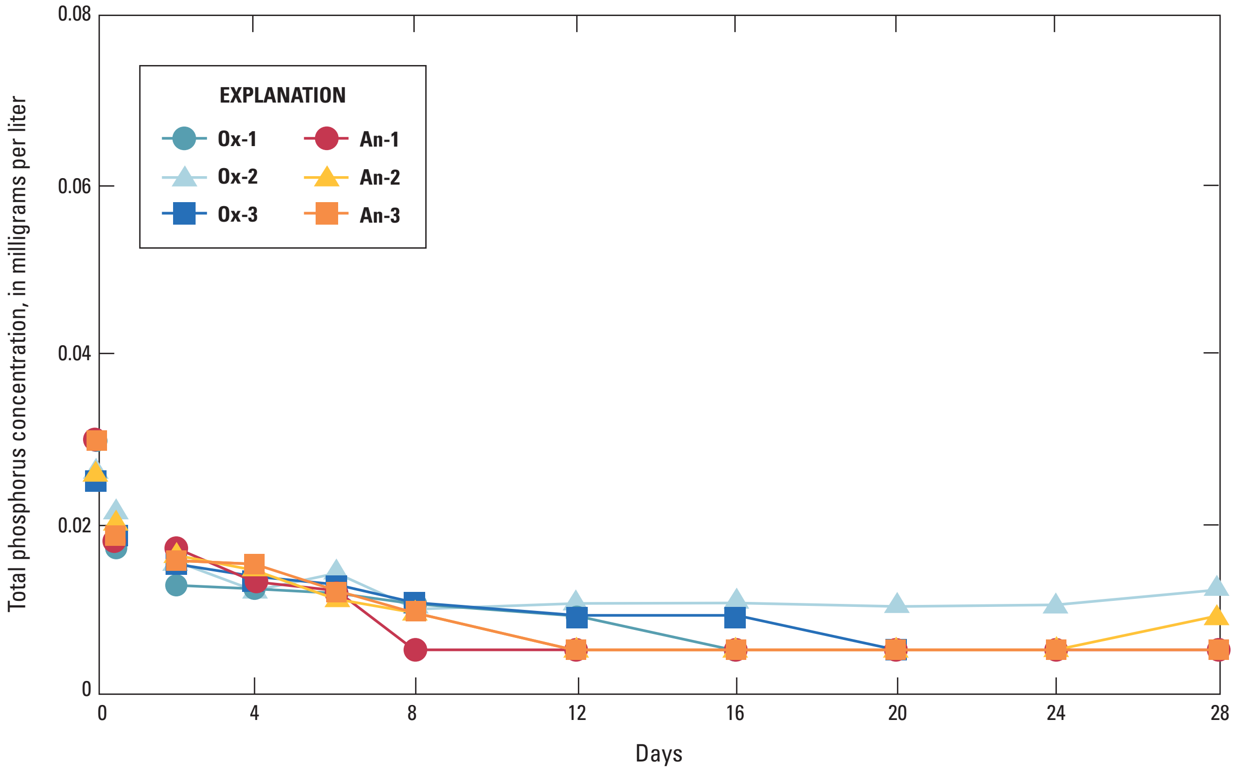

Figure 16. Total phosphorus concentrations released/retained from sediment into the water column for oxic (Ox) and anoxic (An) treatments. (These data are from the middle site [L2], August 2014, and phosphorus release/retention patterns are representative of all release experiments.)

Table 9. Mean and standard deviation (SD) of total phosphorus (TP) and ammonium (NH_4^+) flux, in milligrams per squaremeter per day, from sediment cores collected from Silver Lake, Oceana County, Michigan, and incubated for 28 days.

[Total phosphorus flux measured in cores from Spring Lake, Michigan, are presented for comparison: pre-alum treatment (Steinman and others, 2004), 1 year after alum treatment (Steinman and Ogdahl, 2008), and 5 years after alum treatment (Steinman and Ogdahl, 2012); mg/m²/d, milligrams per square meter per day; SD, standard deviation; —, no data]

		Total phosphorus flux (mg/m²/d)				Ammonium flux (mg/m²/d)			
		Oxic		Anoxic		Oxic		Anoxic	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Silver Lake	May 2013	−0.16	0.12	−0.16	0.06	−1.10	0.00	4.53	1.92
	August 2013	−0.08	0.03	−0.09	0.00	4.33	5.04	9.01	2.72
	June 2014	−0.11	0.07	−0.02	0.07	4.53	5.79	8.91	2.08
	August 2014	−0.23	0.00	−0.23	0.00	2.21	0.08	9.89	2.92
Silver Lake (before alum)	June/July 2003	0.03	0.44	17.97	8.07	—	—	—	—
Silver Lake (1 year after alum)	July 2006	0.20	0.08	0.41	0.38	—	—	—	—
Silver Lake (5 years after alum)	September 2010	1.14	1.24	2.27	0.46	—	—	—	—

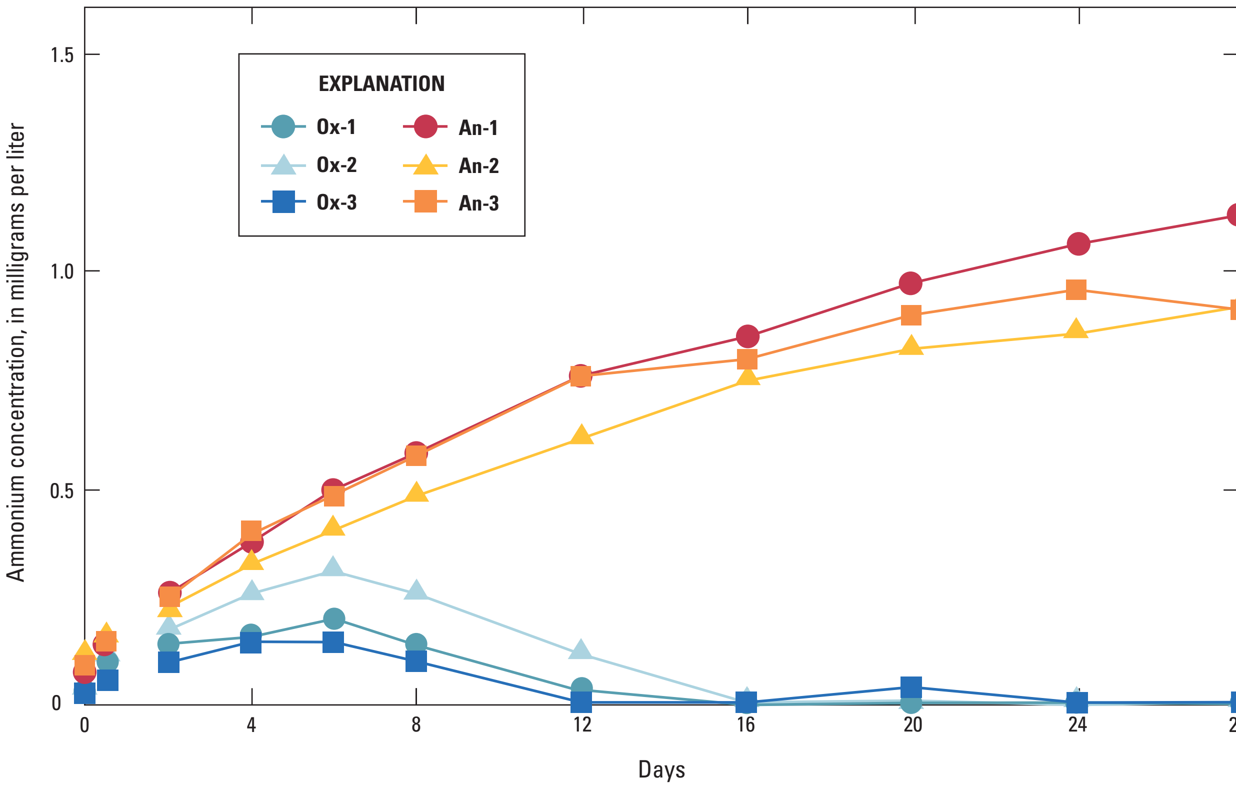

Figure 17. Ammonium concentrations released/retained from sediment into the water column for oxic (Ox) and anoxic (An) treatments. (These data are from the middle site [L2], August 2014, and release/retention patterns are representative of all release experiments.)

Ammonium concentrations in oxic treatments tended to have a slight increase for 8–12 days before decreasing to below the detection limit (fig. 17). Mean ammonium flux ranged from −1.1 to 4.5 mg/m²/d in oxic treatments and 4.5 to 9.9 mg/m²/d in anoxic treatments (table 9). There was no clear relation between ammonium flux and site or sampling date. Given that anoxic conditions appear to be rare in Silver Lake, the lower release rates in the oxic treatments are probably more representative of what is occurring in the lake than the rates under anoxic conditions. Nonetheless, if the mean oxic ammonium release rate of 2.54 mg/m²/d is representative of the entire lake, and it is assumed this rate is constant but occurs only during summer months, the overall mass of ammonium potentially released from Silver Lake sediments is 622 kg (2,719,488 m² [672 acres] × 2.54 mg/m²/d × 90 d) or approximately 1,371 lb, or about 2.6 percent of the estimated annual nitrogen mass in Silver Lake (see Nutrient Budget section). Based on the BATHTUB model simulations, the internal loading of nitrogen to Silver Lake makes up 12 percent of the nitrogen load during the summer months (fig. 14). Internal loading of nitrogen from sediments is a modest source in Silver Lake; however, these rates may be overestimates given that they are gross inputs and do not account for potential nitrogen losses such as denitrification.

Sediment total phosphorus concentrations (upper 5 cm) were less than 1,000 milligrams per kilogram (mg/kg) at both sites during all coring events, and less than 500 mg/kg at the middle site with the exception of August 2014 (fig. 18). Compared to other west Michigan lakes, sediment total phosphorus concentrations in Silver Lake are low, particularly at the middle site (fig. 18).

The concentrations of four key sediment metals (calcium, iron, phosphorus, and aluminum) were higher at the south site than at the middle site. Calcium was the most abundant element, followed by iron. Iron:total phosphorus ratios (by weight) were 23 and 12 at the south and middle sites, respectively. Lakes with iron:total phosphorus ratios greater than 15 tend to have low SRP flux under oxic conditions (Jensen and others, 1992), such as those observed in Silver Lake. This is because the ferric oxyhydroxides bind to phosphorus, preventing its diffusion into the water column above (Boström and others, 1982). In general, it appears there is sufficient iron to bind the phosphorus that is present in Silver Lake sediments, and prevent diffusion under oxic conditions. However, the iron:total phosphorus ratio should be applied with care because the ratio uses total phosphorus, which includes forms that may not be available for biotic uptake (Rydin and others, 2000). Phosphorus fractionation would be necessary to determine how much of the total phosphorus is in the bioavailable phosphorus fraction in these sediments.

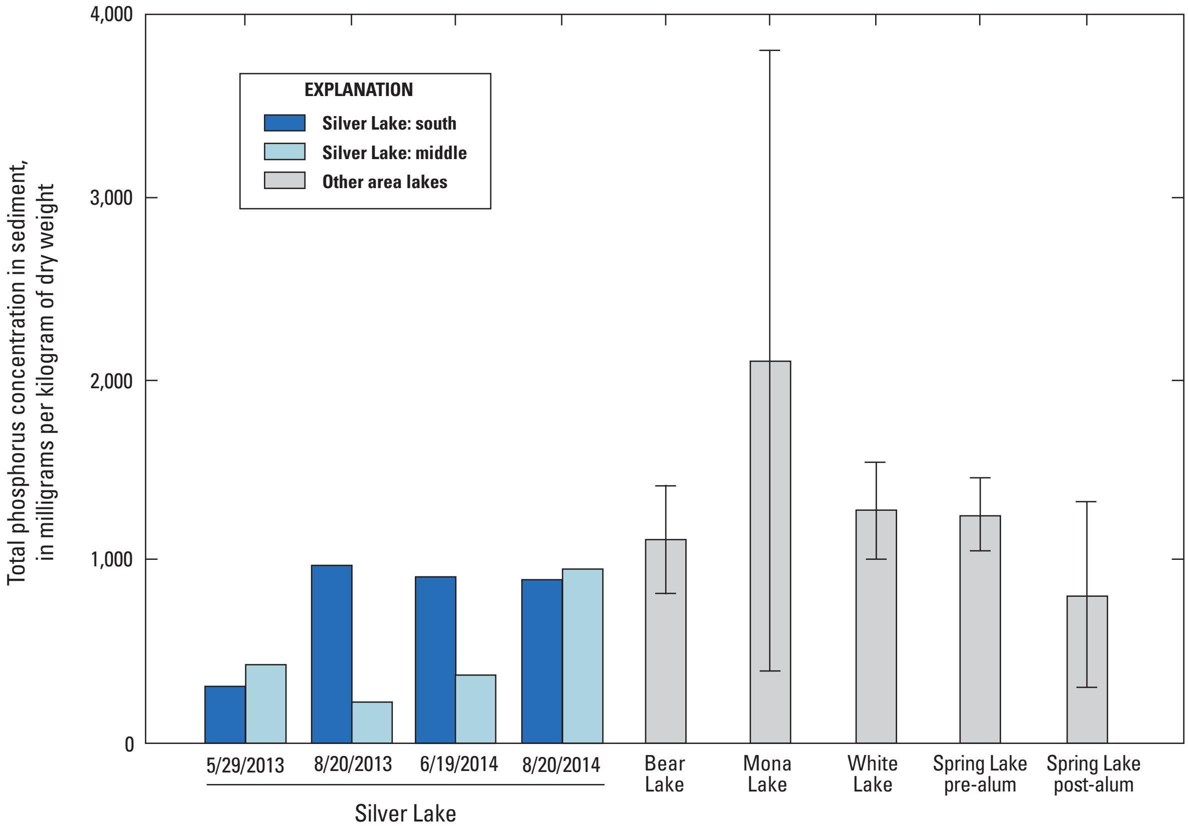

Figure 18. Total phosphorus concentrations in sediment (upper 5 centimeters) at the two internal loading study locations in Silver Lake, Oceana County, Michigan, on each core collection date. (Mean [plus or minus standard error] total phosphorus in sediment for other lakes in west Michigan are provided for comparison [gray bars]. Sources: Bear Lake, Steinman and Ogdahl, 2015; Mona Lake, Steinman and others, 2009; White Lake, Steinman and others, 2008; Spring Lake before alum treatment, Steinman and others, 2004; Spring Lake after alum treatment, Steinman and Ogdahl, 2008)

Lawn Runoff

Based on the BATHTUB model output, the contribution of phosphorus via lawn runoff to Silver Lake was highest in the summer and fall and made up approximately 14 and 15 percent of the summer and fall phosphorus budgets, respectively (estimated 44 lb per season) (fig. 14). The phosphorus loading from lawn runoff accounted for approximately 9 percent of the phosphorus budget during the spring even though the lawn-runoff estimates considered the predominant use of phosphate-free fertilizer. Lawn runoff accounted for a small component of the nitrogen budget during the spring, summer, and fall (1 percent during the spring, and 2 percent during the summer and fall) (163 lb per season) (fig. 14). Overall, lawn runoff accounted for approximately 13 percent of the annual phosphorus budget and 1 percent of the annual nitrogen budget (fig. 19).

Nutrient Budget Summary

The nutrient budget for Silver Lake was calculated using the BATHTUB model based on 2 years of water quality data collection. A mean annual phosphorus and nitrogen budget summary were calculated for Silver Lake and are presented in figure 19. A seasonal breakdown on the phosphorus and nitrogen budgets was also summarized and is presented in figure 14.

The mean annual input of phosphorus to Silver Lake was approximately 1,342 lb. The major sources of phosphorus to Silver Lake were groundwater (630 lb, or 46.9 percent) followed by Hunter Creek (385 lb, or 28.7 percent) (fig. 19). A large proportion of the phosphorus load being delivered to the lake by groundwater and Hunter Creek is likely originating from septic systems. Septic model loading scenarios indicate that 19.5 to 73.7 percent of phosphorus in groundwater and 2.1 to 43.6 percent of phosphorus in Hunter Creek is likely derived from septic loading. The most likely septic loading scenario estimates that septic systems contribute 47.8 percent of the phosphorus to groundwater and 22.3 percent of phosphorus to Hunter Creek (table 10). These results indicate that septic systems are a major source of phosphorus loading to Silver Lake. The

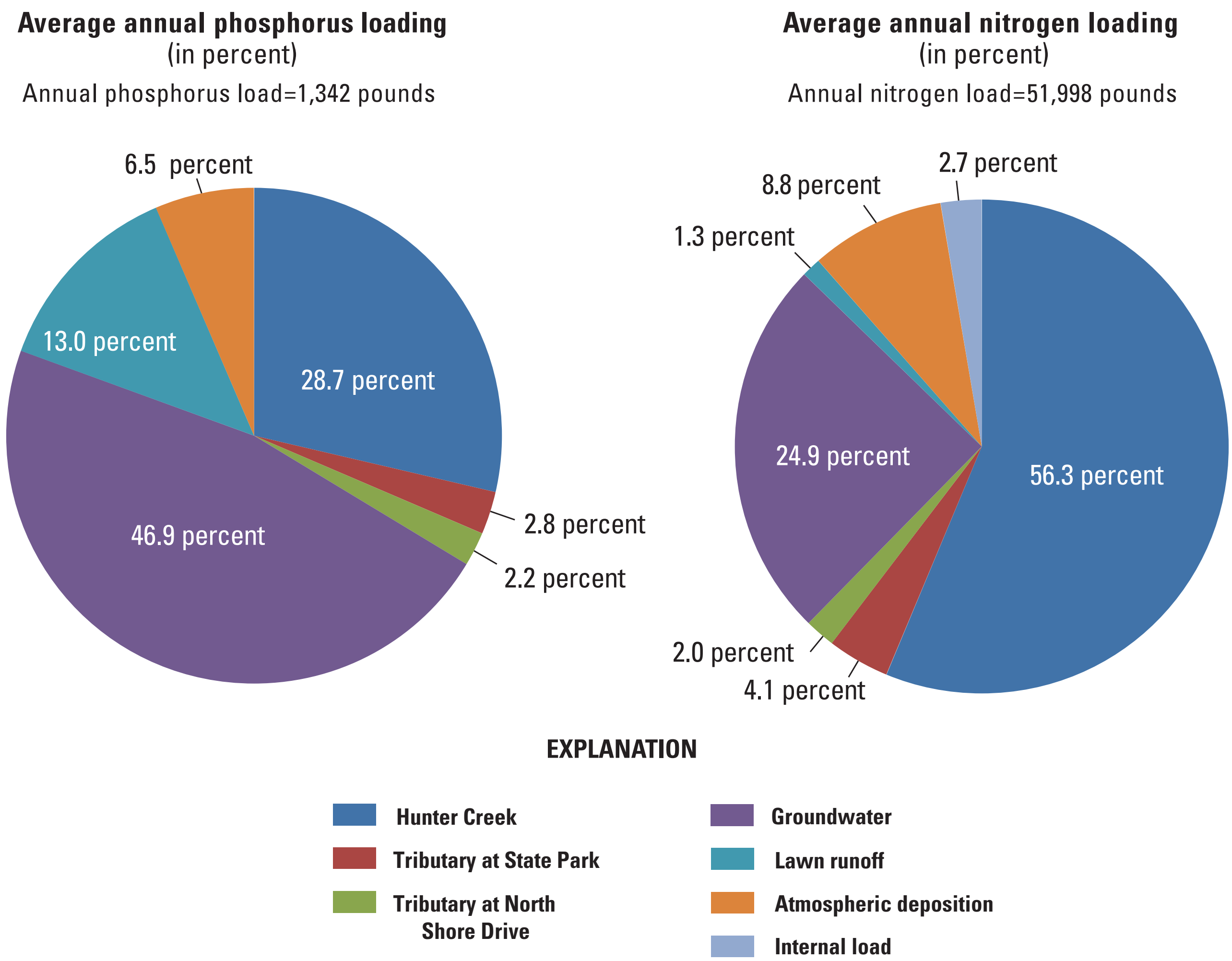

Figure 19. Annual phosphorus and nitrogen budget summaries for Silver Lake, Oceana County, Michigan. (Internal load of phosphorus and nitrogen was measured only during the summer and assumed to be negligible during the remainder of the year. Internal phosphorus loading during the summer was less than 1 percent of the total phosphorous load.)

largest loading of phosphorus to Silver Lake occurred in the spring months, followed by the summer and fall (fig. 14). Of the total 1,342 lb of phosphorus that entered Silver Lake annually (mean), almost all of the phosphorus was exported out of the lake (1,340 lb), with minimal to no phosphorus deposition occurring in the lake-bed sediment, which is consistent with the estimated analysis of internal phosphorus loading from the sediment cores. Although the majority of phosphorus is exported out of the lake with minimal internal loading, the residence time (223 days) is long enough for phosphorus to contribute to algal blooms and lake eutrophication in Silver Lake.

The mean annual input of nitrogen to Silver Lake was approximately 51,998 lb. The major source of nitrogen to Silver Lake was Hunter Creek (29,277 lb, or 56.3 percent of the nitrogen budget). Other major sources of nitrogen to Silver Lake include groundwater (12,951 lb, or 24.9 percent of the nitrogen budget) and atmospheric deposition (4,586 lb or 8.8 percent) (fig. 19). The septic model loading scenarios indicate that septic systems account for 0.05 to 3.1 percent of the load to Hunter Creek, and 0.23 to 2.8 percent of the contribution of nitrogen to groundwater (table 10). The most likely septic loading scenario indicates that septic systems account for 0.95 percent of the nitrogen load to Hunter Creek and 1.1 percent of the contribution of nitrogen to groundwater. Other potential sources of nitrogen to groundwater include animal manure and nitrogen fertilizers used for agriculture, animal pasture, food processing discharge, leaching from fertilizers from private lawns and golf courses, and the ongoing decay of organic matter in the soil (Oregon Department of Environmental Quality, 2011). The largest nitrogen loading to Silver Lake also was observed during the spring, followed by the summer and fall months. About twice as much nitrogen entered Silver Lake during the spring (19,180 lb) compared to the fall months (8,921 lb) (fig. 14). Of the 51,998 lb of nitrogen that entered Silver Lake annually (mean), approximately 42.2 percent (or 21,928 lb) of nitrogen was deposited in the lake bed sediment as simulated by the BATHTUB model.