Table 10. Summary of septic-load estimates to Silver Lake, Oceana County, Michigan, using the septic model.

[lb/yr; pounds per year]

Total phosphorus				
Septic load scenario	**Phosphorus load from septic (lb/yr)**	**Septic percentage of average annual Load (percent)**	**Septic contribution to groundwater (percent)**	**Septic contribution to Hunter Creek (percent)**
Most likely	396	29.5	47.8	22.3
Low	132	9.8	19.5	2.1
High	650	48.4	73.7	43.6
Total nitrogen				
Septic load scenario	**Nitrogen load from septic (lb/yr)**	**Septic percentage of average annual Load (percent)**	**Septic contribution to groundwater (percent)**	**Septic contribution to Hunter Creek (percent)**
Most likely	445	0.86	1.1	0.95
Low	46	0.09	0.23	0.05
High	1,362	2.62	2.8	3.10

Nutrient Load Modeling

Nutrient concentration data and flow data collected from all major potential nutrient pathways were used to estimate the trophic status of Silver Lake. The BATHTUB model (Walker, 1996) was used to simulate the current conditions in the lake based on the data collected. In addition, the BATHTUB model was used to estimate the effect on the trophic status of Silver Lake as a result of changes to various nutrient inputs to the lake.

BATHTUB Data Requirements and Limitations

Multiple datasets were compiled and evaluated to determine the appropriate input data for the BATHTUB model: (1) an annual dataset consisting of data collected October 1, 2013–September 30, 2014 (water year 2014), (2) a complete dataset consisting of all data collected throughout the study period (2 years), and (3) a categorization of seasonal and specified storm events. For this dataset, the nutrient turnover ratio (Nutrient Turnover Ratio = Length of Averaging Period for Mass Balances [years] / Mass Residence Time [years]), which approximates the number of times that the nutrient mass in the lake is displaced during the averaging period, was approximately or greater than 2.0 (turnover ratio for phosphorus and nitrogen, 1.6 and 2.8, respectively) as recommended in the model (Walker, 1996), and therefore was chosen as the final dataset for the model. Note that the seasonal datasets (spring, summer, and fall) were evaluated and used in the calculation of seasonal nutrient loading as described in the Nutrient Budget Summary section.

Even though the loading data are summarized for the entire study, the BATHTUB model predicts the effects of nutrient loading on an annual basis. The idea of partitioning out the storm event datasets in an effort to evaluate these events separately from the annual loading proved to be difficult. The storm event datasets were limited and because of insufficient data from which to accurately describe the different input sources without excessive model calibration, which fell outside the recommended calibration criteria (Walker, 1996). Thus, storm events were not examined separately but were evaluated as a whole with the rest of the nutrient dataset.

The BATHTUB model required specified input data including Silver Lake morphometric data, hydrologic data, and nutrient concentration data for each source. Silver Lake was treated as one segment, and observed nutrient concentrations and flow data were entered in the model based on an annual mean using 2 years of data for each of the tributaries, the outlet, the four groundwater quadrants, and the tile drains. The atmospheric deposition component of the BATHTUB model was based on approximately 1 year of data collection. The internal nutrient loading was calculated based on two sampling events. The model input for lawn runoff was calculated (as described in Study Methods and Sampling Sites, Lawn Runoff section of this report), and identified in the model as a point source.

Algorithms and Calibration

Prior to running the BATHTUB model, the model algorithms must be defined. The model algorithms selected for this study were based on site characteristics, available data, and for diagnostic and predictive purposes. The model algorithms are described in table 11.

Calibration factors provide means for adjusting model predictions to account for site-specific conditions in order to match observed conditions. The need for site-specific calibration is indicated when significant differences between observed and predicted concentrations are found during initial model runs (Walker, 1996). The nutrient model algorithms chosen for this study (table 11) have been empirically calibrated and tested for predicting lake-mean conditions (Walker, 1996). The BATHTUB error analysis calculations indicate that sedimentation rates predicted by these models are generally accurate to within a factor of 2 for phosphorus and a factor of 3 for nitrogen (Walker, 1996). To account for this error, nutrient calibration factors can be adjusted within the nominal ranges of 0.5 to 2.0 and 0.33 to 3 for phosphorus and nitrogen, respectively. For this study, calibration coefficients for each water-quality constituent were applied globally to the base model prior to running diagnostic and predictive scenarios. The calibration factors are, by model default, set to 1. The model calibration factors used to adjust the predicted water-quality conditions for this study ranged from 1 to 1.7 and fell within the acceptable ranges for each water-quality constituent (total phosphorus, 1.67; total nitrogen 1.09; and chlorophyll *a*, 1.23).

Table 11. Model algorithms selected when running BATHTUB simulations for Silver Lake, Oceana County, Michigan.

Select model	Options	Model process	Description (excerpt from Walker, 1996)
Conservative substance	0	Not computed	Conservative substance concentration is user-defined, typically chloride; can be used for verification of water budgets or calibration of longitudinal dispersion rates.
Phosphorus balance	1	Second order, available phosphorus	Performs mass balance calculations on available phosphorus, a weighted sum of orthophosphorus and non-orthophosphorus which places a heavier emphasis on the orthophosphorus (more biologically available) component.
Nitrogen balance	1	Second order, available nitrogen	The nitrogen models are structured similarly, although nitrogen balances are much less sensitive to inflow nutrient partitioning than are phosphorus balances, probably because inflow nitrogen tends to be less strongly associated with suspended sediments.
Chlorophyll *a*	1	Function of phosphorus, nitrogen, light, and temperature	Eutrophication response models relate observed or predicted pool nutrient levels to measures of algal density and related water quality conditions.
Secchi depth	1	Function of chlorophyll *a* and turbidity	Model default, secchi reported as a function of chlorophyll a and turbidity.
Dispersion	1	Fischer numeric	For a given segment width, mean depth, and outflow, numeric dispersion is proportional to segment length. By selecting segment lengths to keep numeric dispersion rates less than the estimated values, the effects of numeric dispersion on the calculations can be approximately controlled.
Phosphorus calibration	2	Concentrations	The empirical models implemented in BATHTUB are generalizations about reservoir behavior. When applied to data from a particular reservoir without site-specific calibration, observations may differ from predictions by a factor of two or more. Such differences reflect data limitations (measurement or estimation errors in the average inflow and outflow concentrations), as well as unique features of the particular reservoir. A procedure to calibrate the model to match observed reservoir conditions is provided in BATHTUB.
Nitrogen calibration	2	Concentrations	Same as above.
Error analysis	1	Model and data	The first-order error analysis procedure implemented by BATHTUB can be used to estimate the uncertainty in model predictions derived from uncertainty in model inputs and uncertainty inherent in the empirical models.
Availability factors	1	Use for model 1 only	Selected as orthophosphorus and organic nitrogen values were specified; calculates nutrient balances based upon available nutrient loads.
Mass-balance tables	0	Use observed concentrations	Use observed segment concentrations to calculate outflow and storage terms.

Management Scenario Simulation Approach

Several nutrient modification scenarios were modeled to illustrate the effect of changing input nutrient concentrations on the trophic status of Silver Lake as well as algal bloom occurrence. Only nutrient inputs that could be adjusted by employing a nutrient management practice around the lake were tested. Thus, only groundwater and surface-water pathways of nutrients to the lake were adjusted. The atmospheric pathway would likely not be affected by any management practice employed by the community around Silver Lake. Likewise, the groundwater on the west side of Silver Lake was not adjusted, because no controllable source of nutrients was identified for that side of the lake. Thirty separate scenarios were developed to assess the effects of nutrient input adjustment on the trophic status of the lake. The calibration coefficients determined for the base scenario were held constant for all the management scenarios. Results from those scenarios are provided in table 12. The results of these scenarios provide a basis to assess the amount nutrient inputs may need to change to have an effect on the trophic status of Silver Lake. Also, the nutrient input adjustments listed in table 12 were modeled to predict the number of days that Silver Lake would likely experience algal blooms. Finally, three scenarios were modeled to examine the potential effect on the trophic status of Silver Lake from converting residences around the lake from on-site septic waste disposal to a centralized sewage system.

Table 12. Nutrient concentration adjustment scenarios simulated using the BATHTUB model.

	Adjusted source, in percent		
	Groundwater[1]	Hunter Creek	Combination of groundwater[1], Hunter Creek, and lawn runoff
Phosphorus and nitrogen concentration adjustment	−75	−75	−75
	−50	−50	−50
	−25	−25	−25
	25	25	25
	50	50	50
	75	75	75
	100	100	100
	200	200	200
	300	300	300
	400	400	400

[1] Groundwater inputs were only adjusted for north, east, and south quadrants and the drain tile component in the north quadrant.

BATHTUB Model Simulations

This section describes the BATHTUB model simulations that were processed in order to predict future lake responses as a result of nutrient reductions or increases and other site-specific scenarios.

Nutrient Loading Scenarios

Nutrient adjustment scenarios of phosphorus and nitrogen to Silver Lake were processed using the BATHTUB model. Results of the simulations for groundwater, Hunter Creek, as well as a combination of sources are presented in table 12.

Trophic Status

The trophic status of Silver Lake is directly affected by changes in nutrient loading; thus, the predicted changes in nutrient loading and associated trophic status were examined. Carlson's TSI was calculated to identify changes in trophic status using the equations for Secchi depth, phosphorus, and chlorophyll *a* (Carlson, 1977) (also see, Trophic Status and Lake Classification section).

The groundwater, Hunter Creek, and combination of sources (groundwater + Hunter Creek + lawn runoff) nutrient loading scenarios for phosphorus and nitrogen are presented in figure 20. Results from the baseline, or base model, are highlighted in pink and indicate the calibrated dataset. Based on Carlson's TSI, the baseline calibrated dataset indicates that Silver Lake is eutrophic. Thus, all nutrient loading scenarios begin with the lake being eutrophic. All scenarios that involve an increase in nutrient loading result in an increase in lake eutrophication.

Changes in groundwater nutrient loading of phosphorus and nitrogen were simulated by adjusting groundwater contributions from the north, east, and south quadrants of Silver Lake as well as groundwater contribution from the drain tiles at the north end of the lake. A reduction or increase in groundwater nutrient loading from the west quadrant of Silver Lake is not likely to change from the current conditions. Thus the nutrient loading for the west quadrant of Silver Lake stayed at baseline conditions for all scenario testing. According to the BATHTUB model, if groundwater loading of phosphorus and nitrogen were decreased by 75 percent, and all of the other nutrient inputs stayed the same, the condition of Silver Lake would most likely range from highly mesotrophic to eutrophic (the current condition of Silver Lake). If nutrient loading continued to increase in groundwater, for instance as a result of aging septic fields or the introduction of more homes on the lake, the lake would continue to remain eutrophic with more frequent algal blooms.

BATHTUB model simulations of changes in nutrient loading of phosphorus and nitrogen in Hunter Creek are presented in figure 20. If nutrient loading from Hunter Creek decreased by 50 percent or 75 percent, and all of the other nutrient inputs stayed the same as the baseline dataset, Silver Lake would remain eutrophic based on TSI calculations using phosphorus and chlorophyll *a*. Only under the TSI scenario based on Secchi depth would the trophic status of the lake develop into highly mesotrophic. Therefore, the reduction of nutrients from Hunter Creek alone may not be enough to effectively improve the trophic status and related water quality issues in Silver Lake as simulated by the BATHTUB model.

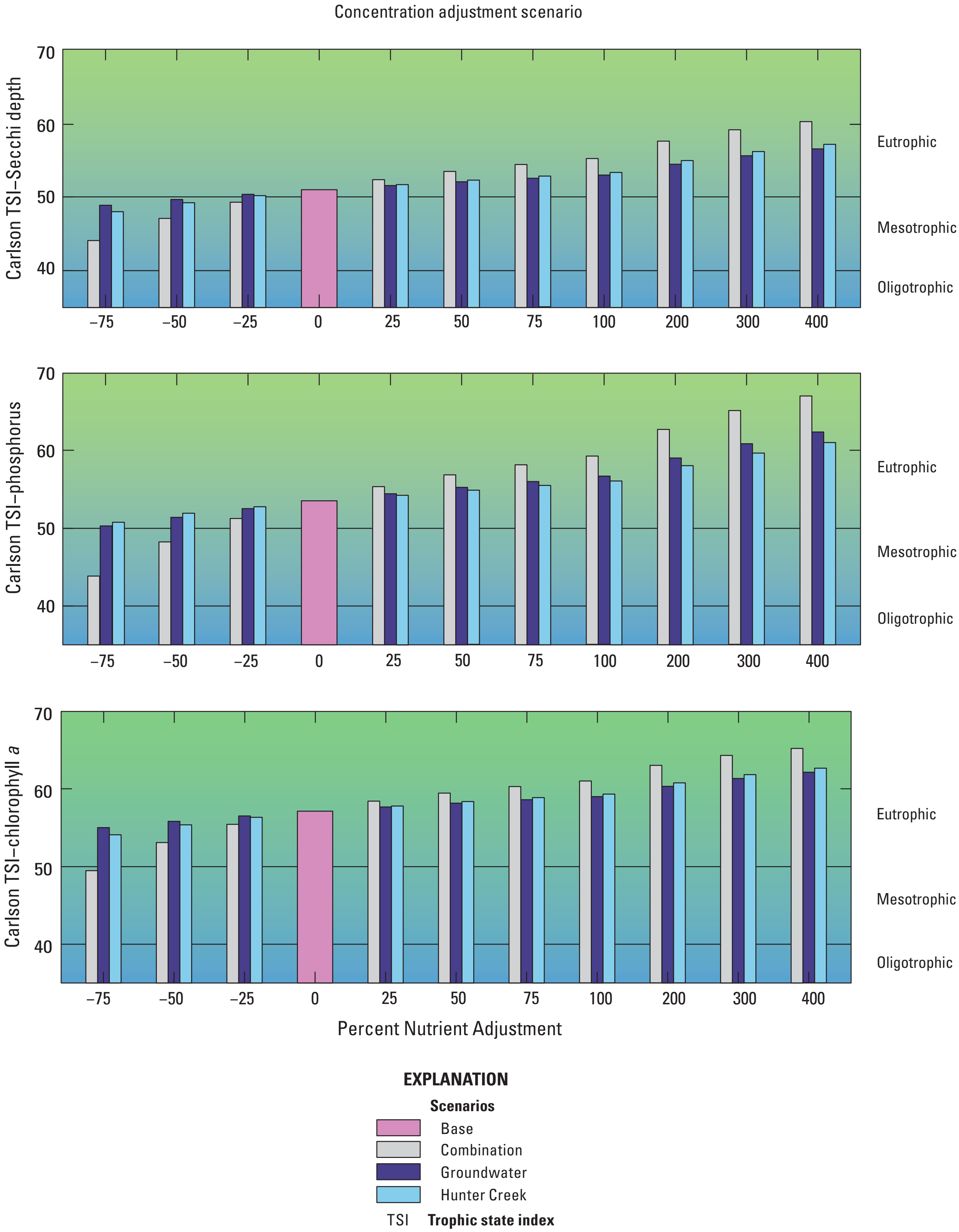

Figure 20. Summary of nutrient loading scenarios using the BATHTUB model for Silver Lake, Oceana County, Michigan. (Based on Carlson's Trophic State Index (TSI) values, less than 40 represents oligotrophic conditions, 40–50 mesotrophic, and greater than 50 represents eutrophic conditions.)

By reducing the input of multiple manageable nutrient sources, the BATHTUB model indicates that there is a better likelihood of positively impacting the trophic status of Silver Lake and reducing algal bloom frequency. Multiple nutrient sources, including groundwater contribution from the north, east, and south quadrants, Hunter Creek, and lawn runoff were evaluated as these sources offer the best opportunity for future nutrient management. Both phosphorus and nitrogen scenarios were run for each of these three sources, collectively referred to in figure 20 as Combination. Increases in nutrients continue to push the lake into a higher eutrophic state; however, a reduction of nutrients indicates a move towards mesotrophy. Using the TSI equation for Secchi depth, a combination of source reduction of only 25 percent would be sufficient to classify Silver Lake as mesotrophic. A reduction of phosphorus and nitrogen by 75 percent would classify Silver Lake as mesotrophic using all three of Carlson's TSI equations which is indicative of improved water quality, water clarity, and reduced algal bloom frequency. Similarly, an annual phosphorus loading reduction from the current condition (1,342 lb) to 549 lb and a change in the annual nitrogen loading to 22,580 lb would be necessary to classify Silver Lake as mesotrophic based on all three TSI equations.

Changes in Percentage of Days with Algal Blooms

Algal blooms can negatively impact the recreational use of a lake and also have an impact on lake aesthetics. Some algal blooms can also be potentially hazardous to human and pet health. Silver Lake has a history of algal bloom occurrence during the summer and fall months, and in October 2012, an algal bloom was reported in Hunter Creek. Chlorophyll *a* is used to measure algal productivity in the water and the higher the chlorophyll concentrations, the more severe the algal bloom intensities. Carlson describes that the range of chlorophyll *a* concentrations indicating eutrophic conditions range from 7.3 to 20 µg/L (Carlson, 1977), thus for this study it was determined that chlorophyll *a* concentrations greater than 10 µg/L may indicate that an algal bloom is present. Simulations were run using the BATHTUB model to evaluate the number of days Silver Lake could experience algal blooms as a result of an increase and decrease in phosphorus and nitrogen loading from groundwater, Hunter Creek, as well as a combination of sources (table 13).

During the course of this study, measured chlorophyll *a* concentrations ranged from 0.7 to 39 µg/L and averaged approximately 15 µg/L. According to the BATHTUB model, Silver Lake currently experiences about 231 days of the year where chlorophyll *a* concentrations are greater than 10 µg/L and about 80 days of the year where chlorophyll *a* concentrations are greater than 20 µg/L (conditions may be appropriate for algal blooms). The model estimates approximately 28 days where chlorophyll *a* concentrations exceed 30 µg/L (severe algal blooms are likely), and about 11 days where chlorophyll *a* concentrations exceed 40 µg/L (severe algal blooms) (table 13).

However, if phosphorus and nitrogen loading to Silver Lake decreases, the number of days that algal blooms may be present also would decrease. If the phosphorus and nitrogen loading from Hunter Creek is decreased (and all other sources are not altered), Silver Lake will continue to experience algal blooms but less frequently that what is experienced currently. On the other hand, if nutrient loads increase from Hunter Creek, Silver Lake will experience more frequent and more intense algal blooms (table 13). If the nutrient loading from groundwater alone was decreased, the overall impact on Silver Lake would not be as effective at reducing algal bloom frequency as the reduction of nutrient loading from Hunter Creek. The same scenario applies if phosphorus and nitrogen loading from groundwater were increased.

The third scenario includes an increase and decrease in phosphorus and nitrogen loading from nutrient sources that are the most likely to be managed and include groundwater, Hunter Creek, and lawn runoff. According to the BATHTUB model, a 50-percent reduction of phosphorus and nitrogen from all three of these sources would result in a considerable decrease in algal bloom frequency (from 231 to 132 days) and severity, and a 75-percent reduction would greatly reduce algal bloom occurrence on Silver Lake (from 231 to 57 days) with severe algal blooms essentially eliminated (chlorophyll *a* >30 µg/L, from 231 days to 1 day) (table 13).

Reduced Septic Input to Silver Lake

By using the range of SR values and the range of potential Es values, load scenarios from septic systems to Silver Lake and to nearby tributaries to Silver Lake were estimated. A summary of the medium (most likely), low, and high estimates for septic loads to Silver Lake are presented in table 10.

The observed load of phosphorus and nitrogen from both groundwater and streams to Silver Lake is likely conservative. As indicated in the Study Methods and Sampling Sites section, two of the monitoring wells (east and west) were placed in zones of low expected septic contamination, while two wells (north and south) were placed in areas of high expected septic contamination. Septic loading models from the south, east, and north wells' groundwater contribution area were all calibrated to observed data by adjusting the SR value until the model predicted an observed background value for each well. By placing wells in zones of high and low expected loads, our monitoring program likely provides a robust description of the median septic contributions to shallow groundwater adjacent to Silver Lake.

Scenarios were also run using the BATHTUB model to predict the effect of eliminated septic load to Silver Lake as a result of sewer installation. These scenarios were based on the low, medium (most likely), and high estimates for septic loads from both groundwater and surface water sources, including Hunter Creek, as summarized in table 10. Figure 21 illustrates the modeled impact of the conversion of septic systems to sewer on the trophic status of Silver Lake using the BATHTUB model.

Table 13. Simulated algal bloom frequency for Silver Lake, Oceana County, Michigan, in response to changes in phosphorus and nitrogen loading scenarios.

[µg/L, micrograms per liter; >, greater than]

Change in nutrient concentration, in percent	Number of days per year with algal blooms by load adjustment scenario		
	Groundwater	Hunter Creek	Combination of groundwater, Hunter Creek, and lawn runoff
Chlorophyll *a*, >10 µg/L			
−75	181	152	57.3
−50	200	187	132
−25	217	212	190
0	231	231	231
25	243	246	260
50	254	259	280
75	264	269	295
100	272	278	307
Chlorophyll *a*, >20 µg/L			
−75	47.1	33.6	6.2
−50	58.4	50.4	25.6
−25	69.4	65.7	52.2
0	79.6	79.6	79.6
25	89.8	92.3	105
50	99.6	104	128
75	109	115	147
100	118	125	164
Chlorophyll *a*, >30 µg/L			
−75	13.5	8.8	1.1
−50	17.9	14.9	6.2
−25	23.0	21.2	15.7
0	27.7	27.7	27.7
25	32.9	34.3	41.2
50	38.0	40.5	54.4
75	43.1	46.7	67.5
100	48.2	52.9	79.6
Chlorophyll *a*, >40 µg/L			
−75	4.4	2.6	0.4
−50	6.2	5.1	1.8
−25	8.4	7.7	5.5
0	10.6	10.6	10.6
25	13.1	13.5	17.2
50	15.7	16.8	24.1
75	18.3	20.1	31.8
100	20.8	23.4	39.1

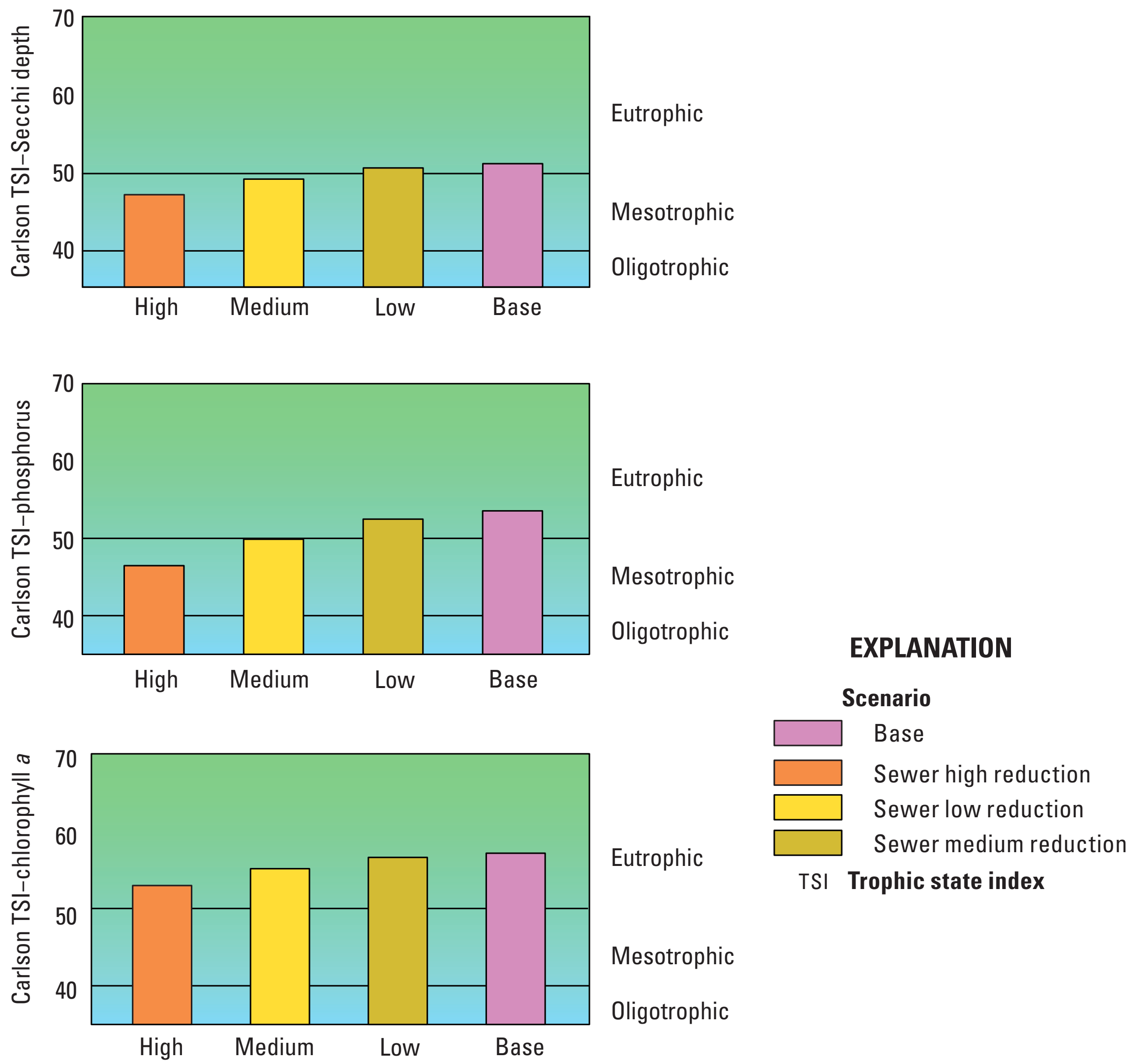

Figure 21. Simulated effect of conversion from onsite septic-waste treatment (within 200 feet of shoreline) to central sewer system using BATHTUB. (Based on Carlson's Trophic State Index (TSI) values, less than 40 represents oligotrophic conditions, 40–50 mesotrophic, and greater than 50 represents eutrophic conditions.)

Simple septic models have demonstrated that a large proportion of the phosphorus load in groundwater and Hunter Creek is likely contributed by septic systems. The septic model provides a possible range of septic loading based on the uncertainty in the load going to septic tanks and the variability of soil retention (based on septic system function). The BATHTUB model was used to evaluate the elimination of septic as a source to both groundwater and all tributaries based on the low, medium (most likely), and high loading scenarios. The BATHTUB model predicted reductions in the total phosphorus load to the lake of 9.8–48.4 percent, and simultaneous reductions in nitrogen of 0.2–2.8 percent (fig. 21). The septic-removal simulation using the likely septic-load scenario indicates that a complete removal of septic systems would improve the lake to an average mesotrophic condition. The high-septic-load scenario shows a greater improvement in trophic status, while the low-septic-load scenario indicates an improvement in lake trophic status that ranges from mesotrophic to eutrophic (fig. 21). Therefore, based on the previous BATHTUB scenarios, it is likely that the elimination of septic influence to the lake would improve the average trophic status of Silver Lake to mesotrophic.

Based on the BATHTUB model, the number of days that Silver Lake would experience algal blooms (under the medium, or most likely, septic scenario), would decrease from the current estimated 231 days (chlorophyll *a* >10 µg/L) to 184 days, or from 80 days (chlorophyll *a* >20 µg/L) to 49 days. According to the high septic efficiency model, algal bloom occurrence (chlorophyll *a* >10 µg/L) would decrease from the current status to 132 days, and based on the low septic efficiency model, algal bloom occurrence would decrease to 219 days. Using the nutrient source loading information provided in table 10, the BATHTUB model indicates that the conversion of onsite septic treatment to sewers would result in an overall improvement in lake trophic status and greatly reduce the frequency of algal blooms and algal bloom intensity on Silver Lake.

Summary and Conclusions

Silver Lake is a 672-acre inland lake located in Oceana County, Michigan, and is a major tourist destination due to its proximity to Lake Michigan and the surrounding outdoor recreational opportunities. In recent years, Silver Lake exhibited patterns of high phosphorus concentrations, elevated chlorophyll *a* concentrations, and nuisance algal blooms. Previous studies conducted indicated that Silver Lake was experiencing advanced eutrophication and more frequent algal blooms in recent years. As a result, the Silver Lake Improvement Board (SLIB) concluded that a detailed interpretive study was necessary. The U.S. Geological Survey (USGS), in cooperation with the Silver Lake Improvement Board and in collaboration with the Annis Water Resources Institute (AWRI) of Grand Valley State University, designed a study to assess the hydrologic and nutrient inputs to Silver Lake, as well as identify the conditions that affect the nutrient chemistry and production of algal blooms in the lake. This information can inform water-resource managers in developing various management strategies to prevent or reduce the occurrence of future algal blooms.

USGS and AWRI scientists collected data from November 2012 to December 2014 to provide information for future management decisions for Silver Lake. Silver Lake can be classified as a polymictic (well mixed) lake with a residence time of approximately 223 days.

On an annual basis, the primary contributor of water to Silver Lake is Hunter Creek, at 52.2 percent. Other water sources include groundwater (30.6 percent), direct precipitation (10.3 percent), the tributary at the State Park (4.1 percent), and the tributary at North Shore Drive (2.8 percent). During the spring season, Hunter Creek is the dominant source (62.6 percent) of water to the lake; however, in the summer the primary contributor of water to the lake becomes groundwater (43.7 percent). In the fall, both Hunter Creek and groundwater contribute similar proportions (42.8 and 36.5 percent, respectively) of the overall water budget and during winter Hunter Creek again becomes the dominant source (54.9 percent) of water to the lake. The primary component of water loss from Silver Lake is the outflow of water from Silver Lake via Silver Creek, which accounts for 91.9 percent of all water leaving Silver Lake. The remaining 8.1 percent is lost through evaporation.

Study results indicated that Silver Lake is colimited by both phosphorus and nitrogen, based on both the bioassay results and the nitrogen:phosphorus ratios in the lake. As a result, both phosphorus and nitrogen are deemed critical nutrients in the development of algal blooms and lake eutrophication. Although 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 must be reduced to control algal blooms. Study results indicate that the largest controllable nutrient to Silver Lake is phosphorus.

Based on the average total phosphorus and total nitrogen concentrations in Silver Lake and the U.S. Environmental Protection Agency (EPA) nutrient criteria recommendation for phosphorus and nitrogen, the lake is classified as eutrophic. Silver Lake also was classified as eutrophic using Carlson's TSI approximately 63 percent of the time (five sampling events), mesotrophic to slightly eutrophic approximately 25 percent of the time (two sampling events), and oligotrophic to slightly mesotrophic about 13 percent of the time (one sampling event).

The likely contribution of phosphorus and nitrogen from septic systems was computed by using a model for septic transport, because septic systems sited on the lakeshore could be important sources of the phosphorus and nitrogen observed in shallow groundwater. This septic model considers the number of residences within 200 feet (ft) of the shore of the lake or surface waters that drain to the lake. Septic systems further than 200 ft from the lake still have an expected impact, but because of the longer travel distance and larger area of diffusion from these systems, the uncertainty in the estimation of their loads is too large to produce a reliable number. Further, the model included only personal residences in the septic model estimates, not commercial facilities such as campgrounds and hotels within 200 ft of the shoreline and Hunter Creek, because the septic model was not designed to accurately represent commercial facilities. If commercial facilities were included, the estimated impact (nutrient loading) of septic systems to the lake and Hunter Creek would be higher. It should be noted, however, that commercial and residential septic sources further than 200 ft from the lake are still captured in the nutrient budget from the groundwater well monitoring that includes nearby (within 200 ft) and diffuse (further than 200 ft) septic sources. As a result of these constraints, the amounts of phosphorus and nitrogen being contributed directly to the lake or tributaries to the lake, as computed using this model, are likely a conservative estimation (an underestimation) of the actual phosphorus and nitrogen loads contributed by all of the septic systems around the lake. The septic model estimated that septic systems likely contributed 47.8 percent