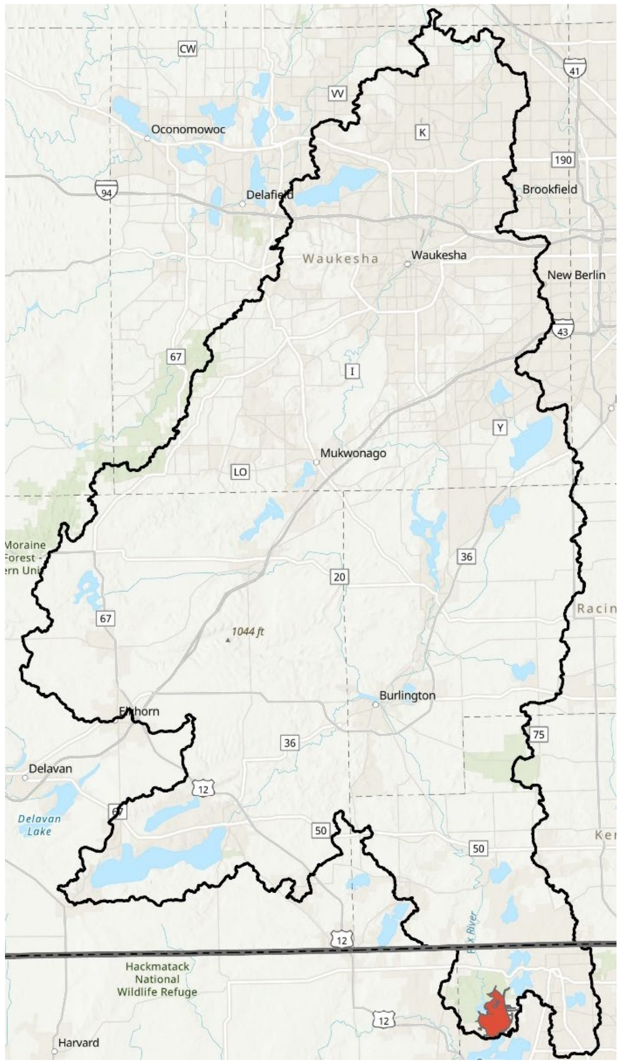
Fox Illinois River Basin TMDL: Grass Lake (IL) Phosphorus Modeling



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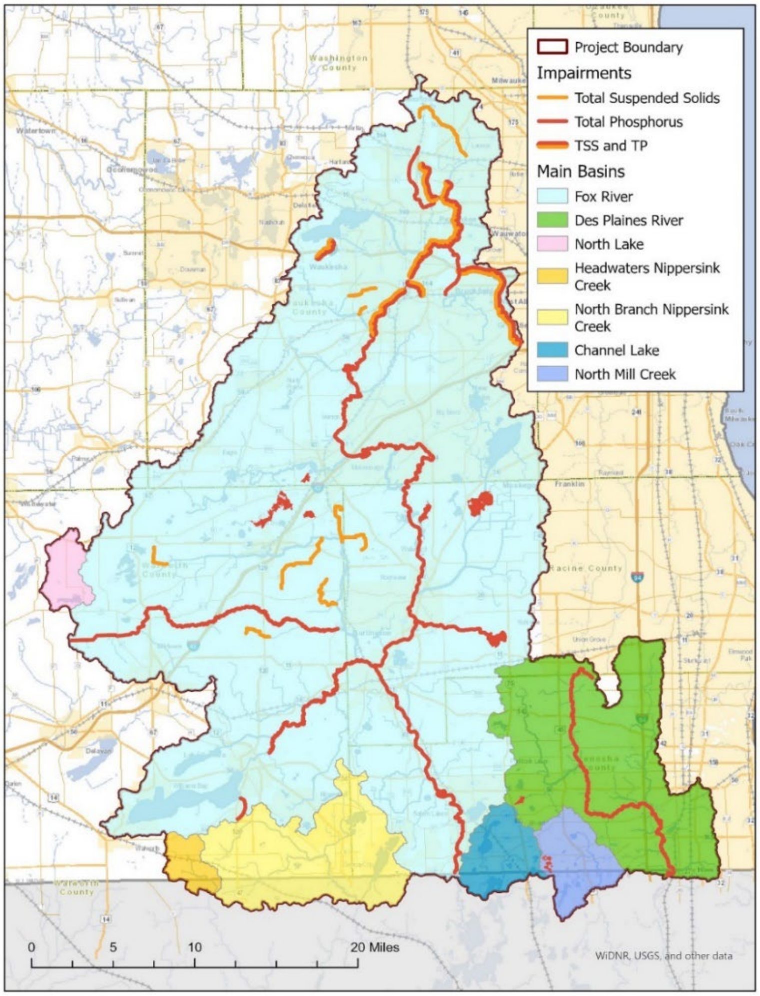
1. TMDL PROJECT BACKGROUND

The Wisconsin Department of Natural Resources (DNR), together with many partners, is working to improve the surface water quality of tributaries, streams, rivers, and lakes in the region centered around the Fox Illinois River. To strengthen these ongoing efforts, the DNR is developing a Total Maximum Daily Load (TMDL) for the region. The TMDL for this study area, referred to as the Fox Illinois River (FOXIL) TMDL, is a multi-year effort addressing surface water quality impairments caused by total phosphorus (TP) and total suspended solids (TSS). The TMDL study will provide a strategic framework and pollutant reduction goals for surface water quality improvement within the FOXIL region.

The FOXIL TMDL study area is located in southeastern Wisconsin. The study area includes the Fox River, the Des Plaines River, Nippersink Creek, North Mill Creek, and Channel Lake watersheds. The study area is primarily located in Racine, Kenosha, Walworth, and Waukesha counties. It is approximately bounded by Waukesha to the north, Lake Geneva to the southwest, and the western portions of Kenosha to the southeast. The FOXIL TMDL study area covers approximately 1,060 square miles within Wisconsin, which is approximately two percent of the state. Within the study area, some lakes and streams are impaired due to excessive loadings of TP and TSS and sediment (Wisconsin Department of Natural Resources 2022). Impaired waters are those waters not meeting their water quality standard, and they are listed as impaired on Wisconsin's 303(d) list. The extent of the TMDL and the impaired waterbodies are shown in Figure 1.1.

The FOXIL TMDL is being developed to address loads originating from point and nonpoint sources in Wisconsin; however, sources within Wisconsin contribute loading to waterbodies within Illinois. One of these waterbodies, Grass Lake, is located in Illinois and is approximately three miles south of the Wisconsin border. The majority of inflow into Grass Lake originates from the Fox River basin within Wisconsin's boundaries. As required under the Clean Water Act, a TMDL developed by Wisconsin must protect the water quality standards of downstream waterbodies. For this TMDL the relevant downstream waterbody is Grass Lake. As part of the overall TMDL development process, the DNR evaluated the loading capacity of Grass Lake using updated data and modeling that accounts for internal loadings. The loading capacity for Grass Lake will be used to determine a TMDL for sources in Wisconsin.

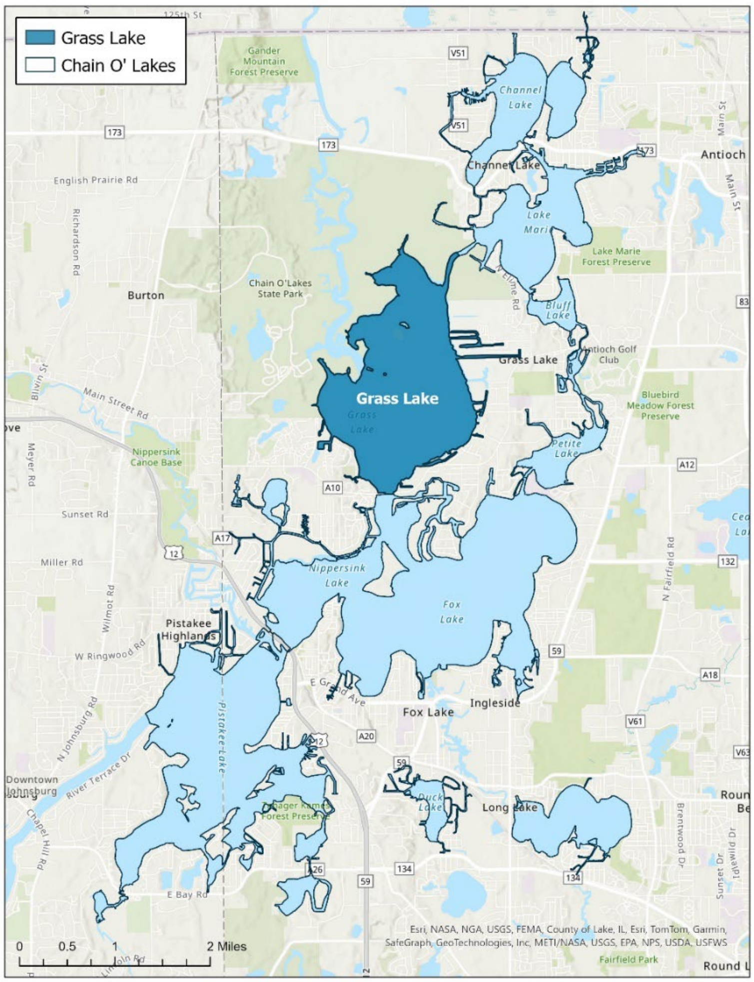
FIGURE 1.1
Extent of Fox Illinois TMDL Study Area



2. GRASS LAKE BACKGROUND

Grass Lake is a shallow glacial lake in Lake County, IL. It is the upstream-most lake within a series of lakes known as the Chain O’ Lakes. The Chain O’ Lakes consists of fifteen lakes in Lake County and McHenry County in Illinois that are interconnected with the Fox River (Fox Waterway Agency 2024). The Chain O’ Lakes and Grass Lake are shown in Figure 2.1. Grass Lake is the upstream-most lake within the Chain O’ Lakes that receives flow from the Fox River, so it is the primary focus of the lake modeling. A detailed schematic of the interconnections of the Chain O’ Lakes is provided in Appendix A.

FIGURE 2.1
Chain O’ Lakes and Grass Lake



2.1. Grass Lake Characteristics

The surface area of Grass Lake is 1,623 acres, and the average depth is 2.3 feet (Fox Waterway Agency 2024). The main source of water flowing into Grass Lake is the Fox River, but the lake also receives flow from direct drainage and from Lake Marie. Over 96 percent of the watershed area draining to Grass Lake is located in Wisconsin. Grass Lake is listed as impaired by the Illinois Environmental Protection Agency (Illinois EPA) for TP (Illinois Environmental Protection Agency 2022, Appendix A-2).

2.2. Illinois TP Standards for Lakes and Reservoirs

The State of Illinois has a numeric criterion for phosphorus, as TP, in lakes and reservoirs over 20 acres. Illinois administrative code (Ill. Admin. Code tit. 35, § 302.205) states:

> Phosphorus. Phosphorus (STORET number 00665): After December 31, 1983, Phosphorus as P shall not exceed 0.05 mg/l in any reservoir or lake with a surface area of 8.1 hectares (20 acres) or more, or in any stream at the point where it enters any such reservoir or lake.

2.3. Illinois Fox River/Chain O' Lakes TMDL

The Illinois EPA has developed a TMDL for the Fox River and Chain O' Lakes (Illinois EPA's TMDL), which was approved by the U.S. Environmental Protection Agency (U.S. EPA) in June 2020. The TMDL covers 26 lakes impaired for TP (Illinois Environmental Protection Agency 2020), and Grass Lake is included in the TMDL.

Illinois EPA's TMDL for Grass Lake is calculated using the Simplified Lake Assessment Model (SLAM) developed by CDM Smith. SLAM is an enhanced version of the U.S. EPA's BATHTUB model that includes explicit lake/sediment interactions (Illinois Environmental Protection Agency 2020). The model requires data about inflow volume, inflow phosphorus loads, and lake characteristics. Inputs for flows and loads from the Fox River are estimated using area-weighted flows from the U.S. Geological Survey (USGS) station at New Munster and monthly average concentrations from a monitoring station on the Fox River upstream of Grass Lake in Illinois (DT-35). Loads from areas directly draining to Grass Lake are estimated using export coefficients, and loads from Lake Marie are estimated using output from the SLAM model developed by CDM Smith for Lake Marie.

Illinois EPA's TMDL establishes wasteload allocations and load allocations for external sources of phosphorus discharging to Grass Lake. However, the TMDL report states, "No allocations or reductions have been developed in this study for the portions of the watershed within Wisconsin (Illinois Environmental Protection Agency 2020, xvi)." As such, DNR conducted an analysis to calculate the appropriate loading capacity and associated allocations for Wisconsin's portion of the loading to Grass Lake.

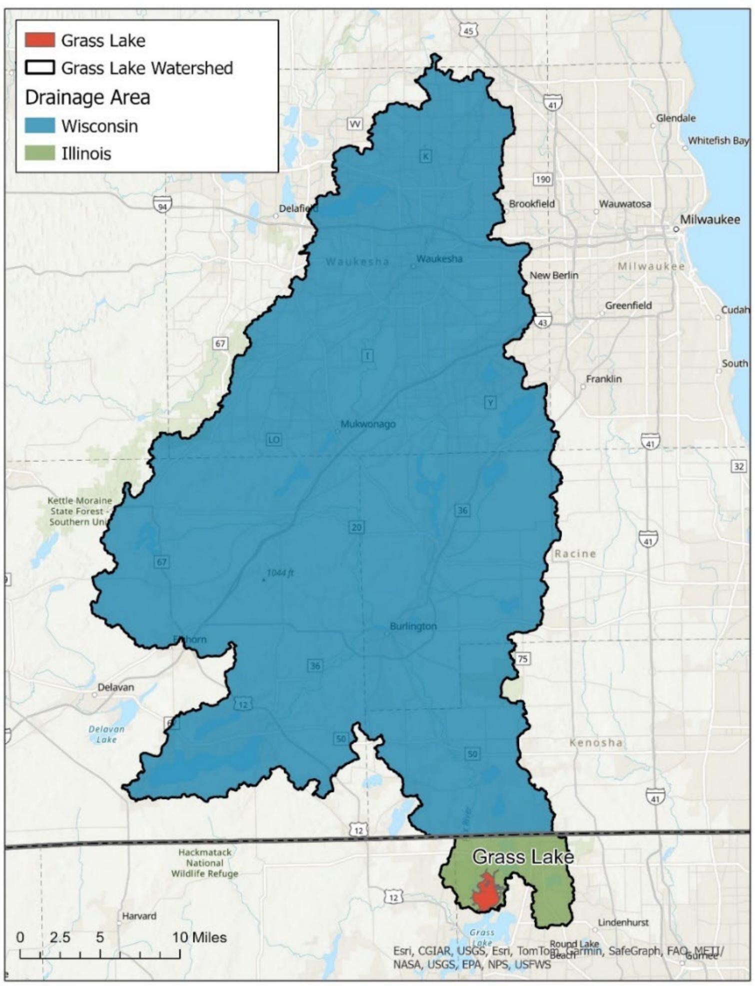
3. GRASS LAKE AND FOXIL TMDL

The TMDL developed by Illinois EPA for Grass Lake inherently includes pollutant loads from Wisconsin by estimating pollutant loads in the Fox River, which accounts for a majority of the pollutant discharges into Grass Lake. However, Illinois EPA's TMDL does not explicitly assign allocations for Wisconsin (Illinois Environmental Protection Agency 2020, xvi). Although the TMDL does not assign allocations for Wisconsin sources, the DNR is obligated to consider the impact of loads from Wisconsin on downstream water bodies in the development of its Fox River TMDL. The DNR must ensure that allocations that allow for the attainment of Illinois' water quality standards are assigned.

3.1. Wisconsin DNR Obligations

Water quality in Grass Lake is influenced by TP loads originating in Wisconsin. Figure 3.1 shows the watershed area contributing to Grass Lake. The total drainage area contributing to Grass Lake is approximately 906 square miles. Of this drainage area, over 96 percent is within Wisconsin.

FIGURE 3.1
Grass Lake Watershed



The CWA under 40 CFR § 131.10(b) (2010) states, *"In designating uses of a water body and the appropriate criteria for those uses, the State shall take into consideration the water quality standards of downstream waters and shall ensure that its water quality standards provide for the attainment and maintenance of the water quality standards of downstream waters."* Downstream waters are interpreted by U.S. EPA to include both intra- and inter-state waters (U.S. Environmental Protection Agency 2014).

The requirement for upstream states to not violate water quality standards in downstream states was also reinforced in the Supreme Court decision in *Arkansas vs. Oklahoma* (1992). In the decision, Justice Stevens held that *"the Clean Water Act clearly authorized EPA to require that point sources in upstream states not violate water quality standards in downstream states, and that the EPA's interpretation of those standards governed (*Ludwiszewski 1992*)."*

The majority of the Grass Lake watershed is located within Wisconsin, and pollutant loads originating in Wisconsin are contributing to the water quality impairment of Grass Lake. For the FOXIL TMDL, the DNR must include Illinois' water quality criterion of 0.05 mg/L for Grass Lake in its TMDL process.

3.2. Need for Additional Modeling

Although the Illinois EPA's TMDL establishes a loading capacity for Grass Lake, the model developed for the TMDL is not consistent with the methods and assumptions used in the development of the FOXIL TMDL. To address the differences, the DNR conducted supplemental modeling to ensure that future load and wasteload allocations from Wisconsin sources are consistent with the methods used in the FOXIL TMDL and other TMDLs in Wisconsin. Supplemental modeling to calculate loading capacity of Grass Lake was required for the following reasons:

1. No allocations for Wisconsin: The Illinois EPA's TMDL report explicitly states that no allocations or reductions are assigned to the portions of the watershed in Wisconsin (Illinois Environmental Protection Agency 2020). To establish allocations for loads originating in Wisconsin, the loading capacity of Grass Lake had to be reevaluated to correspond with the time period and flows used in the FOXIL TMDL, as explained below.

2. Consistency in timeframe: The DNR has developed a watershed model in SWAT+ to estimate pollutant loads and flows for water bodies within the FOXIL TMDL study area. The SWAT+ model is calibrated for the time period from 2011 through 2022, whereas the allocations and reductions for the Illinois EPA's TMDL were developed for the time period from 2000 through July 2016. To ensure loading capacity estimates for Grass Lake correspond with the FOXIL SWAT+ model, a consistent timeframe of pollutant load calculations was required. As a result, an updated model for Grass Lake evaluating pollutant loads and flows from 2011 through 2022 was developed.

3. Consistency in estimating baseline loads: The SWAT+ model developed by the DNR for the FOXIL TMDL is calibrated to pollutant loads estimated using daily flows and *daily* concentrations for the Fox River. The pollutant loads for the Fox River in Illinois EPA's TMDL were estimated using daily flows and *average monthly* pollutant concentrations (Illinois Environmental Protection Agency 2020). The use of monthly average pollutant concentrations rather than daily pollutant concentrations can result in slightly different loading estimates, so a Grass Lake model using pollutant loads estimated from daily pollutant concentrations was developed to maintain consistency with the SWAT+ model.

4. Consistency in approach for lake loading capacity: The DNR developed two TMDLs with downstream large shallow lake systems; the Wisconsin River (Wisconsin Department of Natural Resources 2019) and the Upper Fox & Wolf Rivers (Wisconsin Department of Natural Resources 2020). In these TMDLs, a lake response model based on research of shallow lakes (Jensen, et al. 2006) was applied to estimate loading capacities of lakes on the mainstem of major rivers. Lake response for the Illinois EPA's TMDL was evaluated using the SLAM model.

The impact of these factors is summarized in Section 7.3 of this report.

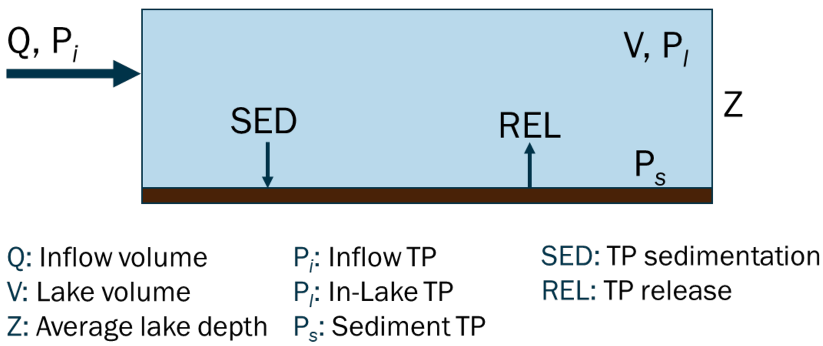
4. JENSEN SHALLOW LAKE MODEL

Phosphorus lake dynamics in Grass Lake were represented using an empirical mass balance model described in a paper by Jensen et al. (2006). The model estimates in-lake TP concentration using daily inflow, daily TP load, and daily water temperature. Details of the Jensen model are provided in the following sections.

4.1. Theory

The model developed by Jensen et al. (2006) uses external phosphorus loading, accumulated phosphorus in the sediment, hydraulic retention time, and water temperature to estimate daily in-lake phosphorus concentrations. Inputs for the model include incoming flow, incoming phosphorus load, parameters related to TP sedimentation, parameters related to TP release from sediments, and lake characteristics. A simple representation of the inputs and outputs for the Jensen equations is provided in Figure 4.1.

FIGURE 4.1
Characteristics of the Jensen equations



Sedimentation of TP is calculated using an empirical constant representing TP sedimentation rate and a constant relating TP sedimentation rate to temperature. Release of TP from lake sediments is calculated using a constant representing TP release and an empirical constant relating TP release to temperature. TP loads from external sources, TP loads lost to sedimentation, and TP loads generated from sediment release are combined with lake volume and incoming flows to estimate in-lake concentration. Equations and additional details of the model are provided in Jensen et al. (2006) and Appendix B.

4.2. DNR Excel-Based Jensen Model

The Jensen Shallow Lake Model (Jensen model) is a lake response model developed by staff at the DNR and USGS used for shallow lakes and reservoirs on the mainstem of major rivers. The Jensen model incorporates the equations from Jensen et al. (2006) into a Microsoft Excel (Microsoft Corporation 2024) workbook. The model is available for download on DNR's website (Wisconsin Department of Natural Resources 2018).

An application of the Jensen model for the Upper Pool Lakes of Lake Winnebago and Lake Winnebago is described in detail in a report produced by USGS (Robertson, et al. 2018). The report provides additional information about the model's development and the equations. Previously, the Jensen model was used to calculate lake loading capacity for two TMDLs in Wisconsin: the Wisconsin River TMDL (Wisconsin Department of Natural Resources 2011) and the Upper Fox and Wolf Rivers TMDL (Wisconsin Department of Natural Resources 2020)

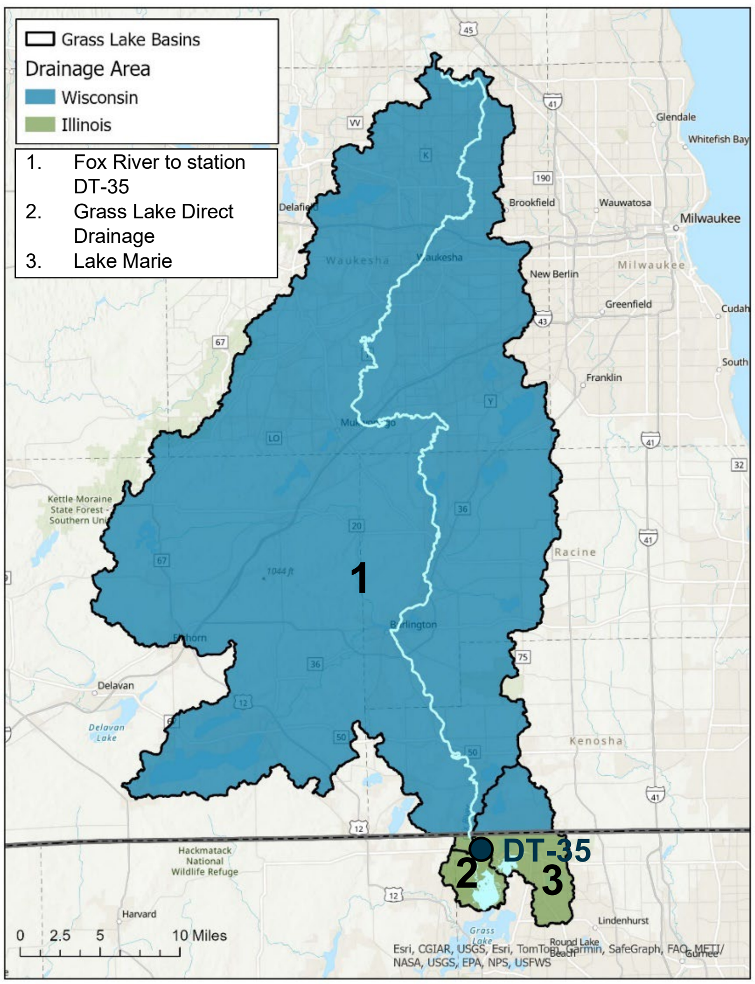
5. JENSEN MODEL INPUTS

The Jensen model requires information about lake characteristics, external flows and loads, and water temperature. The following sections summarize the sources of the input data used to develop and calibrate the Jensen Model. A list of all data sources is provided in Appendix C.

5.1. Grass Lake Setting

Grass Lake receives flows from the Fox River, direct drainage, and Lake Marie. To characterize flows and loads into Grass Lake, the basin is divided into three areas: the Fox River above the long-term monitoring station in Illinois (DT-35), direct drainage into the Grass Lake below station DT-35, and outflow from Lake Marie. These areas align with areas defined in Illinois EPA's TMDL (Illinois Environmental Protection Agency 2020). The three areas are shown in Figure 5.1.

FIGURE 5.1
Grass Lake Drainage Areas



The Fox River watershed above monitoring station DT-35 makes up 94.8 percent of the total watershed area for Grass Lake, with 99.8 percent is located in Wisconsin. A portion of the Lake Marie watershed is also in Wisconsin, and all of the direct drainage to Grass Lake is located within Illinois. Overall, more than 96 percent of the Grass Lake watershed lies within Wisconsin. A breakdown of the watersheds draining to Grass Lake is shown in Table 5.1. Flow from Lake Marie is divided between Grass Lake and Bluff Lake, but Table 5.1 presents the entire drainage area of the Lake Marie watershed.

TABLE 5.1
Watersheds Draining to Grass Lake

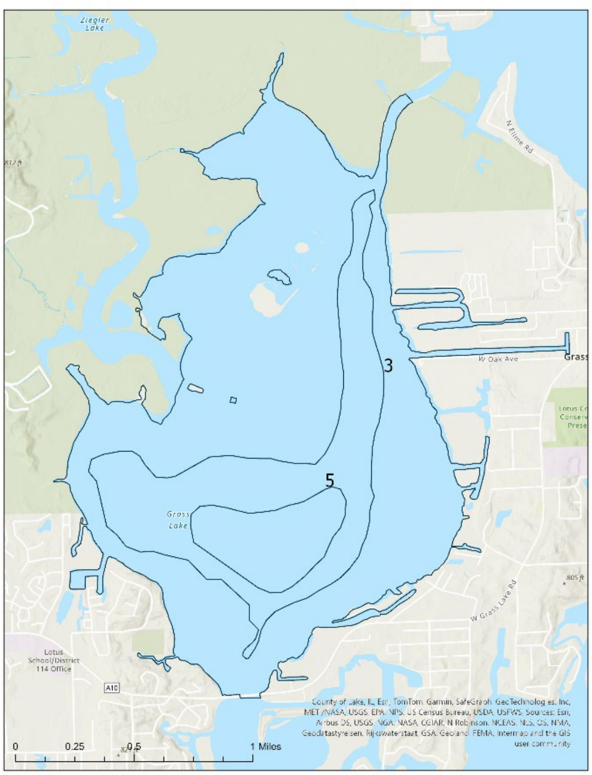
	Drainage Area (ac)			% of Total	
Waterbody	Wisconsin	Illinois	Total	Wisconsin	Illinois
Fox River to DT-35	548,628	1,132	549,760	99.8%	0.2%
Grass Lake Direct Drainage		7,048	7,048	0.0%	100.0%
Lake Marie*	9,453	13,609	23,062	41.0%	59.0%
Total to Grass Lake	**558,081**	**21,789**	**579,870**	**96.2%**	**3.8%**

**51% of flow from Lake Marie discharges to Grass Lake, and 49% discharges to Bluff Lake*

5.2. Grass Lake Characteristics

Other important inputs for the Jensen model are lake characteristics: lake area, lake volume, and lake depth. Grass Lake has an area of 1,623 acres, a volume of 3,652 acre-feet, and an average depth of 2.3 ft (Illinois Environmental Protection Agency 2020). The extents of Grass Lake and its approximate bathymetry are provided in Figure 5.2. Bathymetry data are adapted from Austen et al. (Austen, et al. 1993).

FIGURE 5.2
Grass Lake Extents and Bathymetry



5.3. Grass Lake External Loads

External flows and loads into Grass Lake originate from three primary sources: the Fox River, direct drainage to Grass Lake, and Lake Marie. The following sections describe the data sources used to estimate incoming loads and flows.

5.3.1. Fox River Flows and Total Phosphorus

The Fox River contributes the majority of flows and pollutant loads to Grass Lake. Discharge and pollutant concentration data are regularly collected for the Fox River. Flow data are available from USGS monitoring station at New Munster, WI, and pollutant concentrations are available from monitoring performed at station DT-35 in Illinois. These sources were used to develop datasets that were incorporated into a lake-response model for Grass Lake. A description of the data sources and the methods to develop datasets for the model is provided below.

5.3.1.1. Flows

The USGS operates a continuous flow gage on the Fox River at New Munster, WI (05545750). Flows for the gage were downloaded from the Water Quality Portal (U.S. Geological Survey 2024). To estimate flows at DT-35, a drainage area ratio was applied. This approach estimates flow at an ungauged location by multiplying the flow at a location with flow data by the ratio of watershed areas for the ungauged and the gauged locations. The method for estimating flows at the Fox River at DT-35 is summarized in Equation 5.1.

$$Q_{DT-35} = Q_{New\ Munster} \times \frac{Area_{DT-35}}{Area_{New\ Munster}} \qquad \text{Equation 5.1}$$

The watershed area at DT-35 is approximately 859 square miles, and the watershed area at New Munster is approximately 796 square miles (Wisconsin Department of Natural Resources 2024). The average annual flows from 2001 through 2022 at New Munster and DT-35 are shown in Figure 5.3.

5.3.1.2. TP Concentrations

Illinois maintains an ambient water quality network of 146 stations where water quality samples are collected every six weeks (Illinois Environmental Protection Agency 2014). One of these stations is located on the Fox River at the DT-35 station, which is shown in Figure 5.1. TP concentrations for the Fox River at DT-35 (IL_EPA_WQX_DT-35) from 2001 to 2022 were downloaded from the Water Quality Portal (National Water Quality Monitoring Council 2024). The TP concentration measurements for this period are shown in Figure 5.4, and the data are summarized in Table 5.2.

FIGURE 5.3
Average Annual Flows at Fox River at DT-35

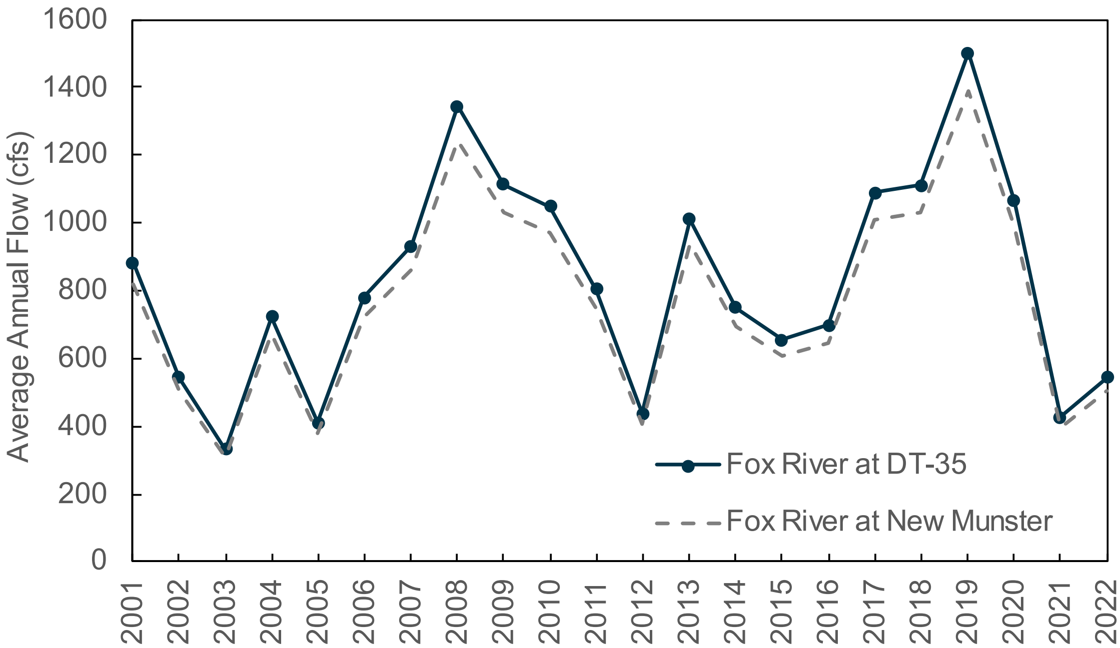


FIGURE 5.4
TP Concentration Measurements for Fox River at DT-35

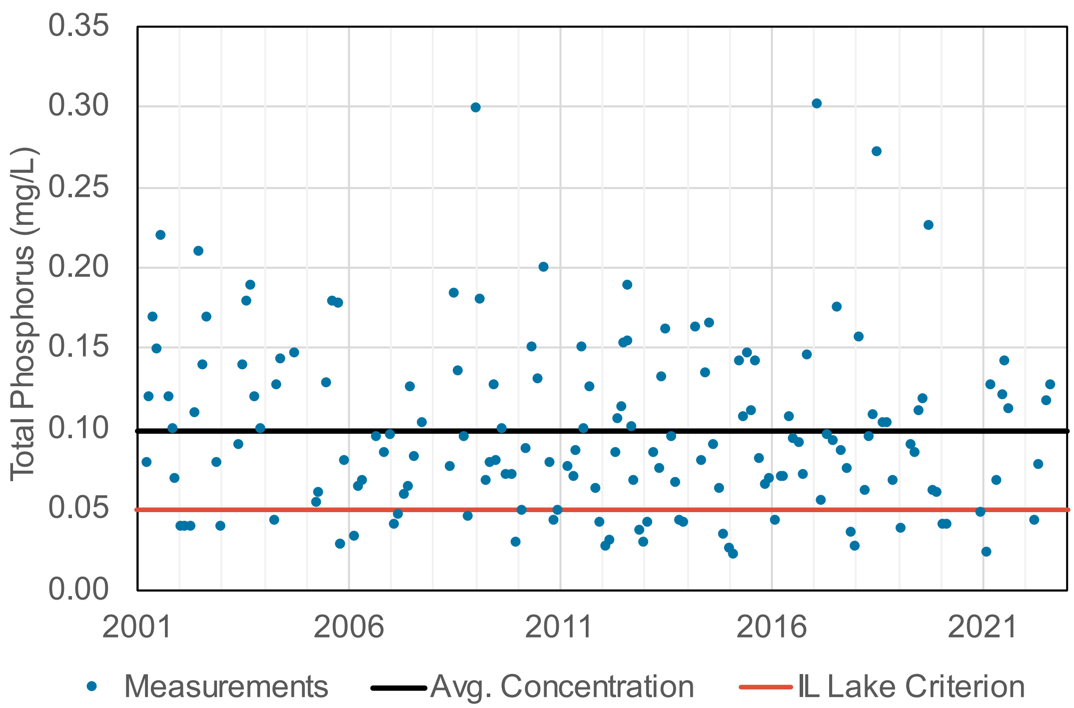


TABLE 5.2
Summary of TP Concentration Measurements for Fox River at DT-35

Station Name	# of Samples	Period of Record	TP Concentration (mg/L)		
			Mean	Minimum	Maximum
Fox River at DT-35	164	2001-2022	0.099	0.023	0.302

5.3.1.3. TP Loads using LOADEST

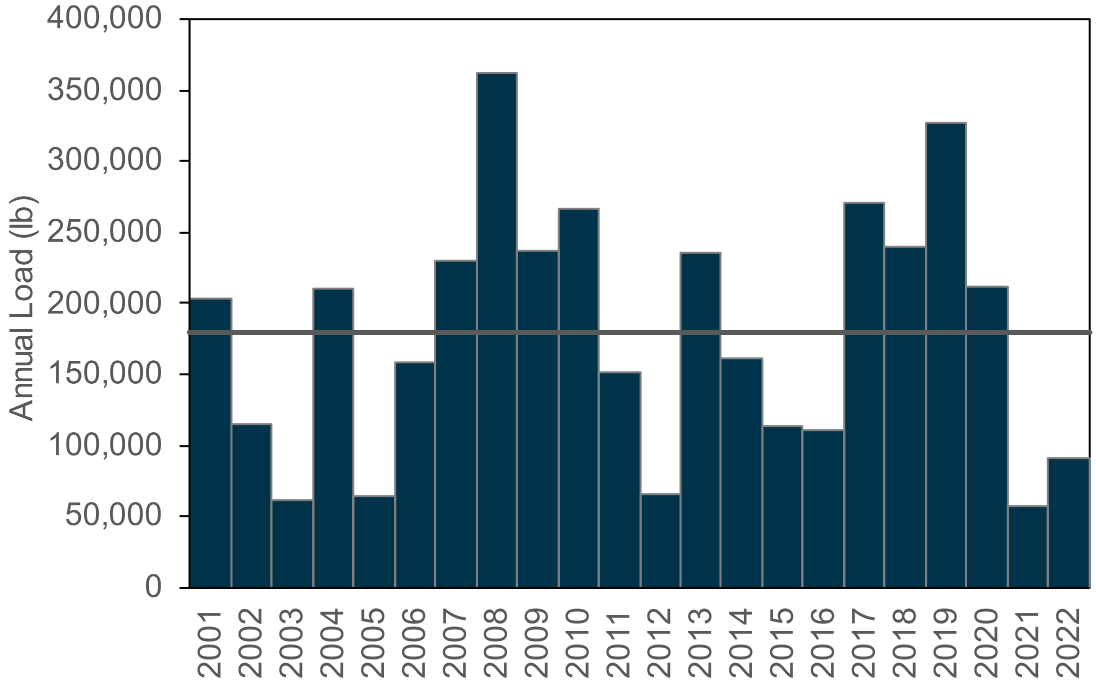
Daily TP loads for the Fox River at DT-35 were estimated using the USGS Load Estimator (LOADEST) model (Runkel, Crawford and Cohn 2004). LOADEST was chosen to estimate pollutant loads because the watershed model developed for the Fox Illinois River TMDL uses a modified version of LOADEST to estimate loads for the calibration and validation datasets (Wisconsin Department of Natural Resources 2024). Using a consistent approach for load estimation ensures that pollutant loads from the watershed model and those from the Grass Lake model are directly comparable.

LOADEST estimates constituent pollutant loads in streams and rivers using daily streamflow and periodic constituent concentration measurements. LOADEST develops nine different regression models that are functions of streamflow and decimal time. Results from the models are compared to observations to determine which model most accurately predicts pollutant loads.

The LOADEST analysis for the Fox River at DT-35 was performed using rloadest (Runkel and De Cicco 2017) package in the R programming language for statistical computing (R Core Team 2020). The rloadest package implements the methodology from the USGS LOADEST model in an R programming environment. For the Fox River at DT-35, the LOADEST model in rloadest was applied to flow and TP concentration data for a 22-year period from 2001 to 2022. Model number 7 from rloadest most accurately predicted loads. The regression equation for model number 7 is provided in Equation 5.2. In the equation P represents TP concentration, Q represents streamflow and T represents decimal time, and a_0 through a_4 are model coefficients. The estimated annual average TP loads for the Fox River at DT-35, as estimated by LOADEST, are summarized in Figure 5.5.

$$lnP = a_0 + a_1 lnQ + a_2 \sin(2\pi T) + a_3 \cos(2\pi T) + a_4 T \qquad \text{Equation 5.2}$$

FIGURE 5.5
Annual TP Loads At Fox River at DT-35 Estimated from LOADEST



5.3.2. Grass Lake Direct Drainage and Lake Marie Flows and Total Phosphorus

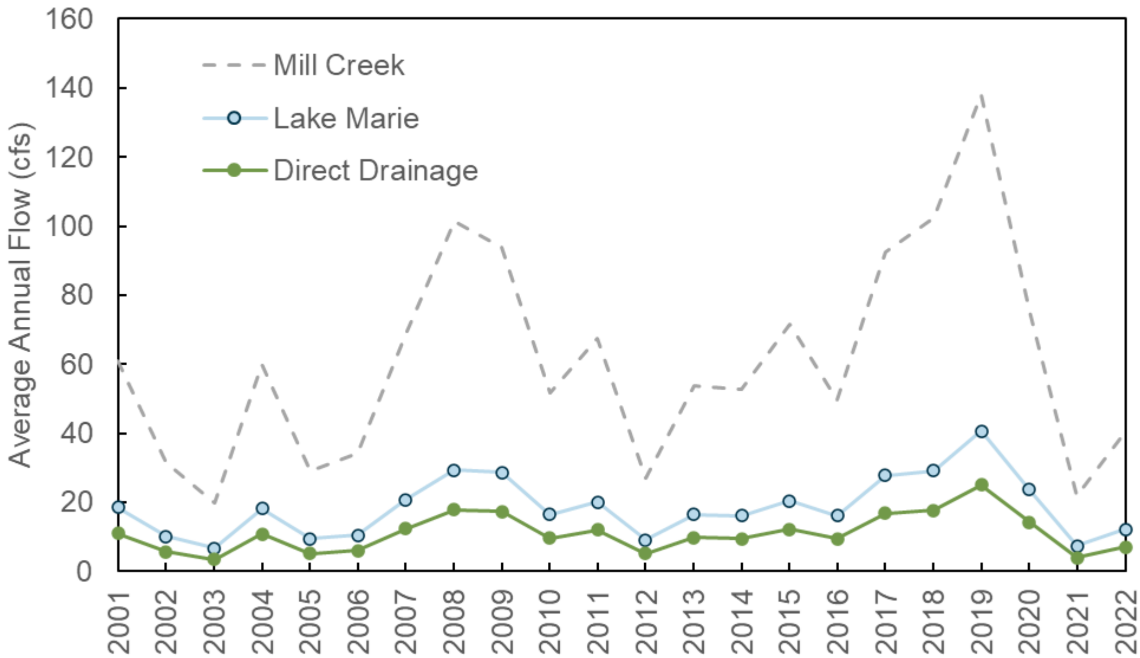
Detailed flow and concentration data were not available for the Grass Lake direct drainage areas or for Lake Marie (see Figure 5.1), so LOADEST could not be used to estimate concentrations and loads. Flow from a nearby USGS gage and information from Illinois EPA's TMDL were used to estimate daily flows and loads from these two sources. The following sections describe the approach.

5.3.2.1. Mill Creek Flows

The USGS operates a stream gage on Mill Creek at Old Mill Creek, IL (05527950). This gage is located in a subbasin that is adjacent to the Chain O' Lakes, and the general development patterns in its watershed are similar to those found in the Chain O' Lakes watershed (Illinois Environmental Protection Agency 2020). The Illinois EPA's TMDL used flow data from Mill Creek to estimate flow rates for ungauged portions of the study area, which includes the direct drainage areas for Grass Lake and Lake Marie. Flow records from the gage on Mill Creek are available from the Water Quality Portal (U.S. Geological Survey 2024).

For the Jensen model inputs, flows for direct drainage and Lake Marie were calculated using the drainage area ratio method described in Section 5.3.1.1. The upstream watershed area of the Mill Creek gage is 61 square miles, the watershed area of the direct drainage to Grass Lake is 11 square miles, and the upstream watershed area for Lake Marie is 34.5 square miles (Illinois Environmental Protection Agency 2020). The drainage area ratios for the two watersheds were applied to calculate a continuous discharge record. According to Illinois EPA's TMDL report, only 51 percent of discharge from Lake Marie flows to Grass Lak, while the remaining 49 percent flows to Bluff Lake. The estimated discharge from Lake Marie into Grass Lake was calculated by multiplying the total estimated flow from Lake Marie by 0.51. The average annual estimated flows from Lake Marie and the Grass Lake direct drainage are shown in Figure 5.6.

FIGURE 5.6
Average Annual Flow from Direct Drainage and Lake Marie



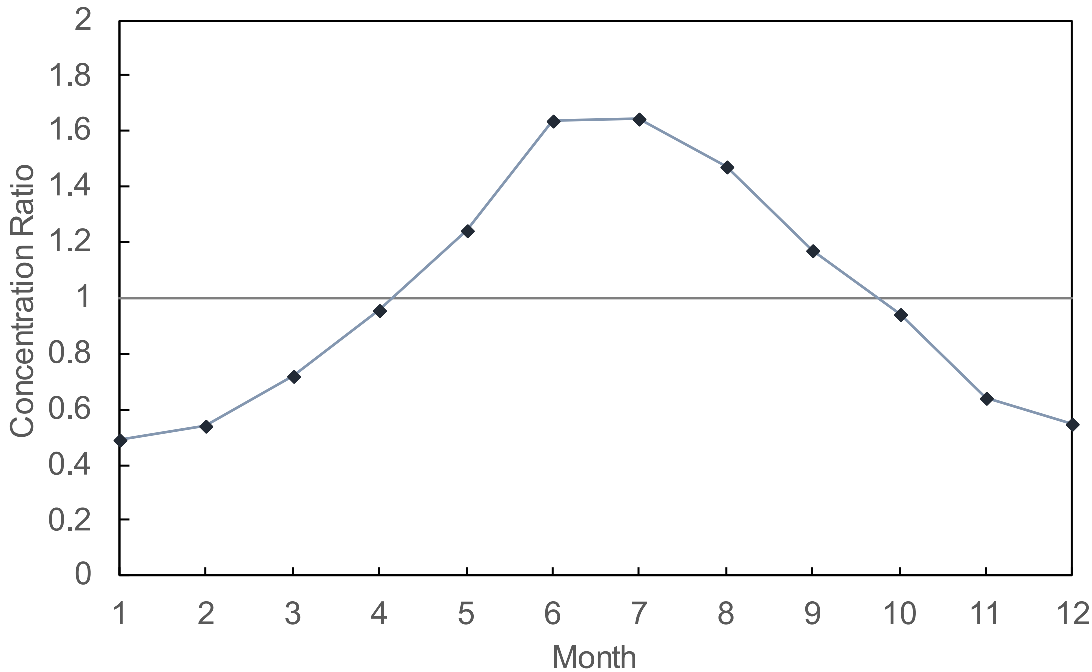
5.3.2.2. Loads

Average annual TP loads into Grass Lake from direct drainage and Lake Marie are provided in Illinois EPA's TMDL report. In the report, loads for the direct drainage are calculated using export coefficients applied to estimated land uses, while the loads for Lake Marie are derived from the output of the Lake Marie SLAM model. These values were used in this analysis because they are readily available and provide an accurate estimate of actual loads from these sources.

Loads for the two sources are reported in Illinois EPA's TMDL as annual average values. The average annual TP load from direct drainage is 1,562 lb/yr, and the average annual TP load from Lake Marie is 2,272 lb/yr (Illinois Environmental Protection Agency 2020, 1-61). The average annual TP load from Lake Marie accounts for the flow split between Grass Lake and Bluff Lake. Because the lake response model requires daily TP load estimates, the annual averages were adjusted to generate daily values. The following steps outline the process for estimating daily TP loads:

1. Daily TP loads and flows from the Fox River at DT-35 LOADEST estimates were used to calculate a ratio of the monthly average concentration divided by the annual average concentration for each month. For example, the ratio for February was 0.539—indicating that if the average annual concentration were 0.1 mg/L, the average concentration in February would be 0.0539 mg/L. Similarly, the ratio for July was 1.64, corresponding to a monthly average of 0.164 mg/L for the same annual baseline. A figure of the concentration ratios is provided in Figure 5.7.

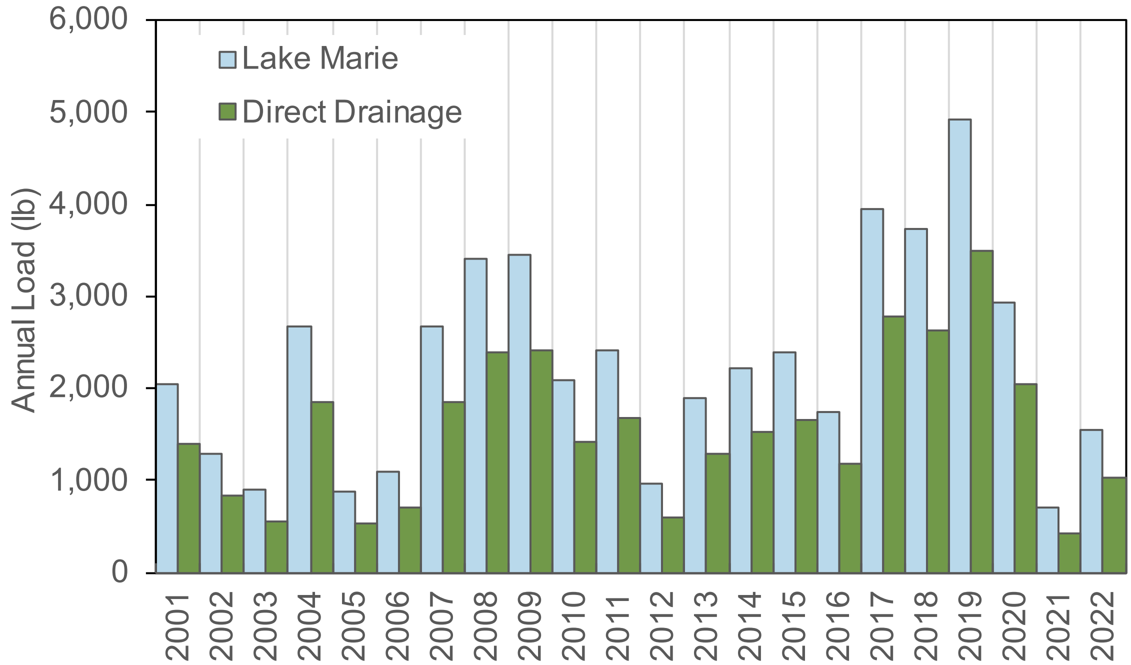
FIGURE 5.7
Ratio of Average Monthly Concentration to Annual Concentration



2. The average annual TP concentration for Lake Marie and the direct drainage were calculated by dividing the average annual TP load by the corresponding average annual flows. The resulting concentrations were 0.072 mg/L for direct drainage and 0.062 mg/L for Lake Marie.
3. The average TP concentration for each day in the analysis period was calculated by multiplying the ratio in step 1 by the average annual concentration in step 2.
4. The average TP load for each day was calculated by multiplying the daily TP concentration by the daily flow, which were estimated from the drainage area ratio and data from the Mill Creek USGS gage.

The total annual TP loads were calculated by summing the daily loads for each year. The total annual TP loads are shown in Figure 5.8.

FIGURE 5.8
Total Annual TP Loads from Direct Drainage and Lake Marie



5.3.3. Total Grass Lake TP Loading

Daily TP loads from the Fox River at DT-35 were combined with the daily TP loads from direct drainage and Lake Marie to estimate total daily TP load entering Grass Lake from external sources. The total TP loading into Grass Lake by year is shown in Figure 5.9. To estimate contributions by state, TP loads from each source were multiplied by the percentage of the source area located in either Wisconsin or Illinois, as listed in Table 5.1. Average annual TP loads from each source and each state are summarized in Table 5.3. For the time period analyzed (2001 to 2022), 98 percent of all TP loads into Grass Lake originated from Wisconsin.

FIGURE 5.9
Total External Loads into Grass Lake

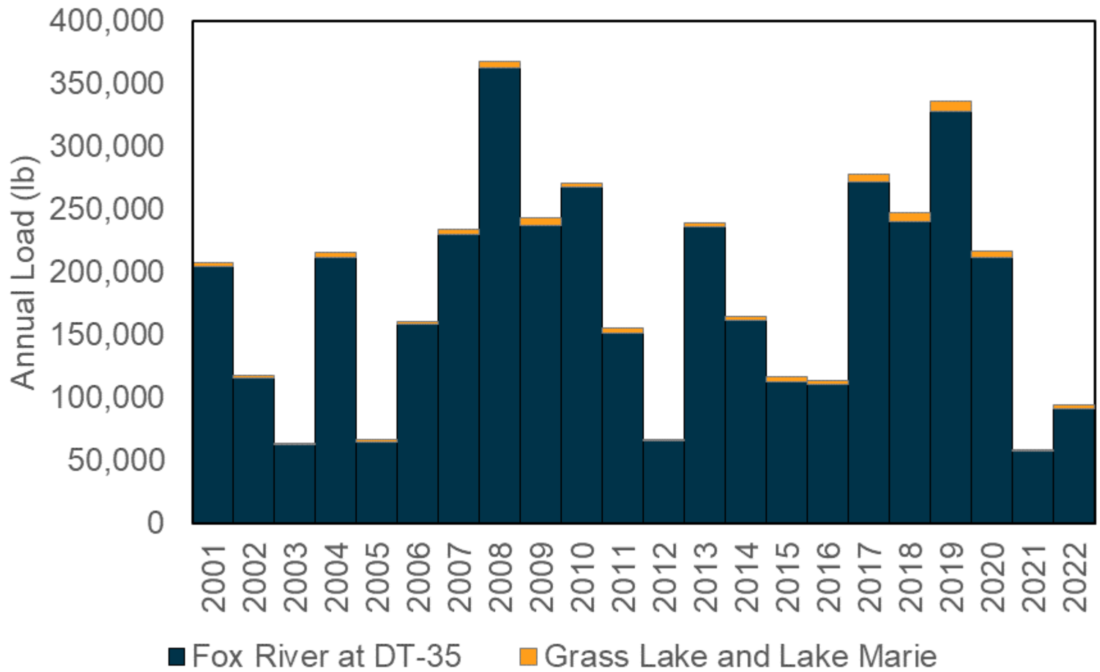


TABLE 5.3
Average Annual External TP Loads into Grass Lake by State

	2001-2022 Average Annual TP Load (lb)		
Waterbody	Wisconsin	Illinois	Total
Fox River to DT-35	179,149	359	179,508
Grass Lake Direct Drainage	0	1,562	1,562
Lake Marie	932	1,340	2,272
Total Loads (lb)	180,081	3,261	183,342
Percent of Loads (%)	**98.2%**	**1.8%**	

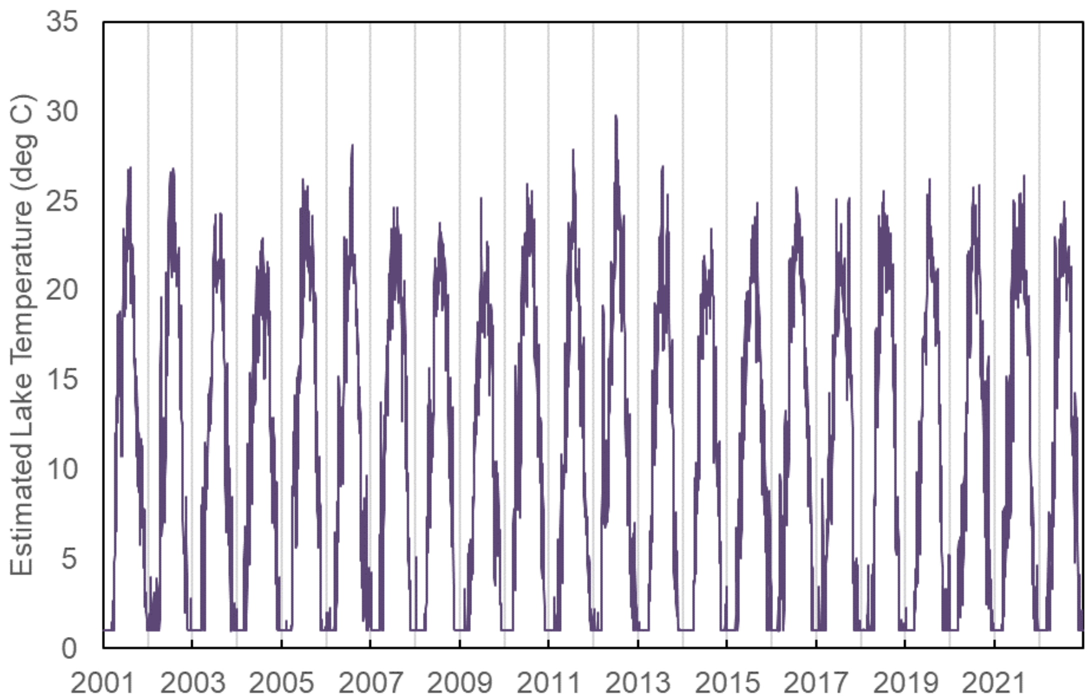
5.4. Water and Sediment Temperature

The Jensen model required water temperature at the surface and temperature at the sediment-water interface. Surface water temperature was estimated using average daily air temperature data. Daily minimum and maximum air temperature data were downloaded from Daymet (Thornton, et al. 2024). Daymet is a gridded, continuous dataset with 1- kilometer resolution covering the entire contiguous United States. The Daymet website includes a Single Pixel Extraction Tool that was used to download daily weather data, and the center of Grass Lake was selected as the location for data downloading.

An adjustment to the Daymet data was necessary to ensure consistency with the Jensen model inputs. Daymet provides 365 days of climate data per year, starting on January 1st, and does not include the 366th day in leap years. To address this, air temperature values for December 31 in leap years were set equal to those from December 30

Daymet provides maximum and minimum air temperature for each day. The average daily air temperature was estimated by averaging the maximum and minimum values. Water temperature at the surface was estimated by calculating a rolling average of the air temperature of the previous five days. On days when the five-day rolling average was below 1°C, the water temperature was set to 1°C. Since Grass Lake is a shallow, non-stratified lake, the temperature at the sediment-water interface was assumed to be equal to the water temperature at the surface. Average estimated daily temperatures for Grass Lake are provided in Figure 5.10.

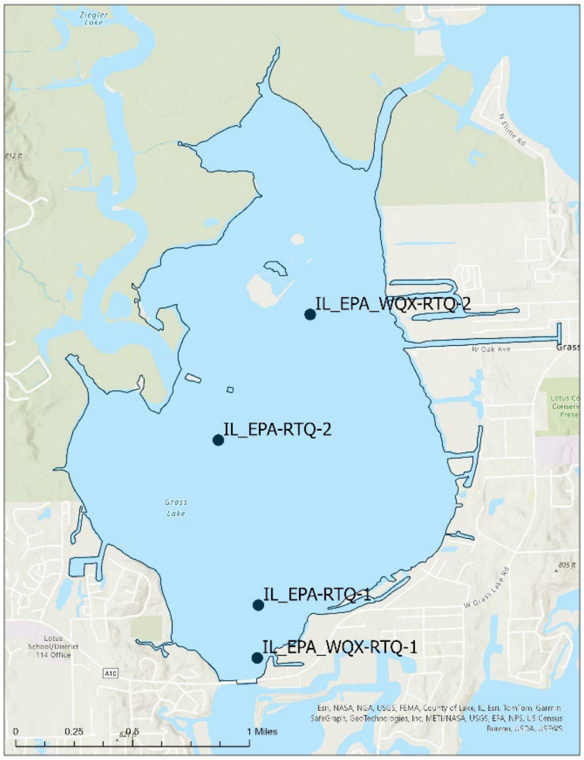
FIGURE 5.10
Average Daily Temperature in Grass Lake



5.5. Grass Lake TP Concentration Data

The final input for the Jensen model was observed TP concentration data within Grass Lake. These data are required for model calibration and to verify that the model accurately represents true in-lake TP concentrations. Phosphorus data for Grass Lake were obtained from the Water Quality Portal (National Water Quality Monitoring Council 2024) for 2001 to 2022. The locations of sample collection are identified as IL_EPA-RTQ-1 and IL_EPA-RTQ-2 before 2006 and IL_EPA_WQX_RTQ-1 and IL_EPA_WQX_RTQ-2 from 2006 onward. The monitoring stations are shown in Figure 5.11.

FIGURE 5.11
Grass Lake Monitoring Stations from Water Quality Portal



On each monitoring day, TP concentration data were available at two stations, and the average of the two measurements was used as the daily TP concentration for model calibration. Concentration data were only available between May and October and for every three to five years. Phosphorus data were available for 2002, 2005, 2008, 2012, 2017, and 2022. Data for 2002 and 2005, however, were reported as phosphate-phosphorus rather than TP. Because phosphate and TP are not directly comparable, only the TP data from 2008, 2012, 2017, and 2022 were used to estimate TP concentrations in Grass Lake. The results for the monitoring data are provided in Figure 5.12. The figure shows the individual concentration measurements in light blue and the average of the two concentration measurements in dark blue. The concentration data are summarized in Table 5.4. A summary of the observations used in the model calibration are provided in Appendix D.

FIGURE 5.12
Grass Lake Monitoring Data

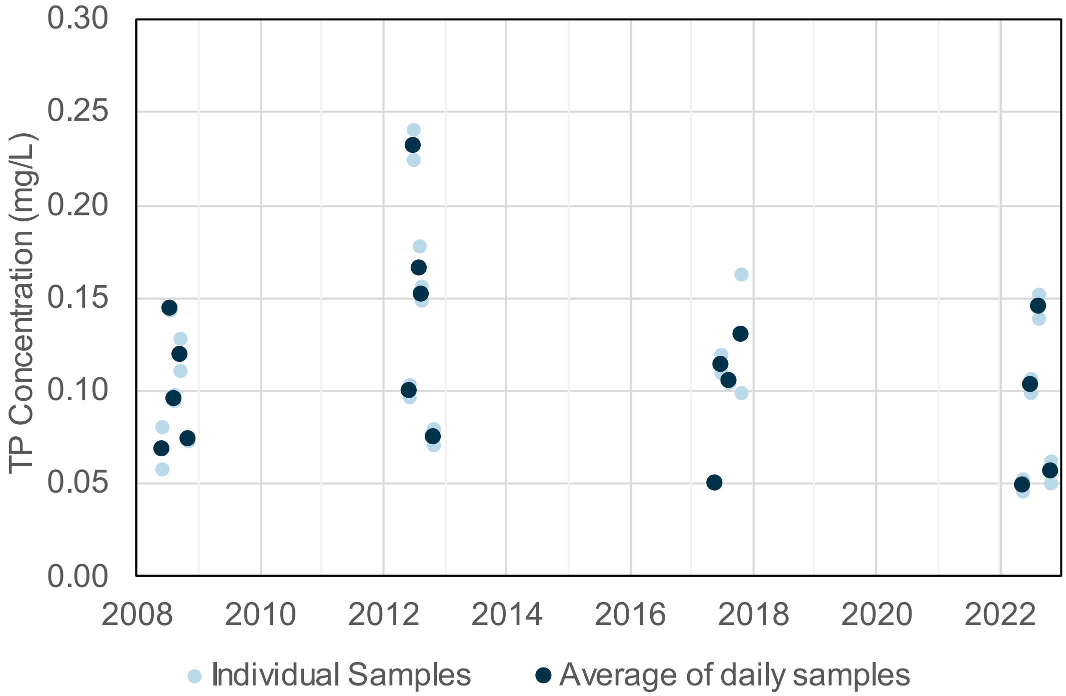


TABLE 5.4
Grass Lake Monitoring Data Summary

Year	# of Days Sampled	Start Month	End Month	TP Concentration (mg/L)		
				Mean	Minimum	Minimum
2008	5	5	10	0.101	0.070	0.145
2012	5	5	10	0.146	0.076	0.233
2017	4	5	10	0.101	0.051	0.131
2022	4	5	10	0.089	0.050	0.146
All	**18**			**0.111**	**0.050**	**0.233**

6. DEVELOPMENT OF THE JENSEN MODEL FOR GRASS LAKE

The input data described in the previous section were incorporated into the DNR's Jensen model. Model parameters were adjusted until modeled TP concentrations accurately represented measured TP concentration data in Grass Lake. The following sections describe the approach and the results for calibration.

6.1. Calibration Approach

The following data were input into the Jensen model: area and volume of Grass Lake (Section 5.1) loads and flows into Grass Lake (Section 5.3.3); lake surface water and sediment-water interface temperature (Section 5.4); and measured concentrations in Grass Lake (Section 5.5). Default values for the following five primary model coefficients were used to initialize the model: 5 g/m^2 for the initial sediment P concentration, 0.047 for the P sediment constant, 0.0 for the temperature dependence of P sedimentation, 5.95e-4 for the sediment P release constant, and 0.080 for the temperature dependence of P release. The default values for these parameters are consistent with the values published in Jensen et al. (2006).

The Jensen model developed by the DNR required a minor modification to be applied to Grass Lake. The equation for in-lake water column P incorporates a term equal to the ratio of volume of daily flow to lake volume. On days with high flow into Grass Lake, the value of the term was greater than one—i.e, the volume of flow into Grass Lake was greater than the total volume of Grass Lake. The Jensen model becomes unstable when this occurs, so the maximum value of the term was capped at one. This adjustment was required to ensure stability of the model, but it did not have a noticeable impact on the overall performance of the model. It also represents a conservative assumption that preserves the characterization of Grass Lake as a lake, rather than a riverine system—even though the lake can behave more like a river under high-flow conditions.

Once the model inputs were incorporated into the modified Jensen model, the Solver routine in Excel was applied to solve for optimal values of the four primary model coefficients and the initial sediment P concentration. The values were optimized to minimize the sum of square errors between the daily measured TP concentrations in Grass Lake and the corresponding estimated TP concentrations. As described in Robertson et al. (2018): "Solver adjusts the values in the decision variable cells (four coefficients and initial P_{Sed}) to minimize the value in an objective cell (sum of square errors between measured and estimated in-lake TP concentrations) using a Generalized Reduced Gradient Nonlinear method (FrontlineSolvers 2017)."

6.2. Exclusion of Monitoring Results

The Jensen model was calibrated by minimizing the sum of squared errors between observed and predicted TP concentrations. This optimization places greater weight to predictions with large errors, which can unduly influence model performance. During the model calibration process, the observed values on June 20, 2012; May 11, 2017; and May 11, 2022 consistently produced large deviations from the model's predicted predicted values.

To evaluate the influence of individual observations on the analysis, the Jensen model was calibrated using the full set of observations. The observed TP concentrations and corresponding predictions were then imported into the R programming language for statistical computing (R Core Team, 2020). A linear regression was fitted to the data, and diagnostic metrics were used to evaluate the influence of each observation. Based on the results, the three dates mentioned above were identified as influential outliers and ultimately excluded from the final calibration dataset.

The observation on June 20, 2012, was determined to be highly influential based on two standard diagnostic measures: Cook's distance (*cooks.distance* function in R) and the Studentized residuals (*rstudent* function in R). The Cook's distance for the observation was 1.46, and the Studentized residual was -2.57. A Cook's distance of greater than 1 and an absolute value of Studentized residual greater than 2 generally indicative of a highly influential datapoint (Cook and Weisberg 1982).

Since the observation on June 20, 2012, was identified as being highly influential, the observed value was investigated to determine if it should be excluded from the calibration dataset. The concentration of the observation (0.23 mg/L) was the highest of all samples collected, and it was approximately 35% higher than the next largest sample (0.17 mg/L). Additionally, the estimated flow rate into Grass Lake on June 20, 2012, was 6.4 m^3/s, which is in the lower 90^{th} percentile of all flows estimated. Grass Lake is shallow heavily used for recreation. Activities such as boating can resuspend sediment from the bottom of the lake, leading to elevated in-lake TP concentrations. These conditions suggest that the unusually high TP concentration may have resulted from sediment resuspension rather than external loading, supporting the decision to exclude the observation from model calibration.

The observations on May 11, 2017, and May 11, 2022, were also identified as potentially influential based on discrepancies between the observed and predicted results. On both dates, the model predicted TP concentrations greater than 0.10 mg/L, while the measured in-lake concentrations were only 0.05 mg/L. However, the observations did not meet the standard thresholds for high influence: the Cooks distance for the observations was less than one, and the Studentized residuals for the observations were approximately 1.6.

Although results on the two dates were not formally classified as highly influential, further investigation suggested the sampled results may have underrepresented the actual in-lake concentrations. On both dates, high flow conditions resulted in residence times of less than two days. In the days leading up to the sampling, the incoming concentrations from the Fox River were greater than 0.10 mg/L, yet the measured in-lake concentrations were only 0.05 mg/L. Under such short residence times, the inflow concentration would be expected to closely reflect in-lake concentration. On other high-flow days such as July 8, 2008, and August 8, 2017, in-lake concentrations were within 40% of inflow concentration. Therefore, it is likely the samples collected on May 11, 2017, and May 11, 2022 may not have been representative of the actual conditions.

Excluding values from a calibration dataset requires with caution and strong justification. However, the Jensen model is highly sensitive to individual observations, and the inclusion of non-representative data can negatively impact calibration. Given the evidence described above, the observations on June 20, 2012; May 11, 2017; and May 11, 2022 were excluded from the final calibration dataset.

6.3. Calibration Results

The model was calibrated using data from 2008 through 2022 with the three observations described in Section 6.2 removed. During initial calibration, the parameter for sedimentation rate was exceeding 0.6 m/day. This value was significantly higher than the sedimentation parameters observed in other lakes, so a condition requiring the sedimentation constant to be between 0 and 0.3 was incorporated into the model. The initial sediment concentration was set to 15 g/m^2, which is consistent with observations in other lakes. The optimized values of the five model coefficients are summarized in Table 6.1. The table also includes a comparison to calibrated values from the Wisconsin River TMDL (Wisconsin Department of Natural Resources 2019), the Upper Fox and Wolf Basin TMDL (Wisconsin Department of Natural Resources 2020), and the original Jensen research (Jensen, et al. 2006).

TABLE 6.1
Optimized Values for Grass Lake Jensen Model

Parameter	**Grass Lake**	Wisconsin River TMDL	Upper Fox Wolf TMDL	Jensen (2006)
Sedimentation rate, bS ($m\ d^{-1}$)	**0.300**	0.0871 - 0.2903	0.0523	0.0470
Temp. dependence of bS, tS	**0.0494**	-0.041 - 0.0244	0.0606 - 0.0639	0
Sediment release rate, bF ($g\ m^{-2}\ d^{-1}$)	**0.00176**	0.0047 - 0.0252	0.0004 - 0.0005	0.0006
Temp. dependence of bF, tF	**0.089**	0 - 0.0939	0.1175 - 0.3209	0.0800
Initial sediment conc., Ps ($g\ m^{-2}$)	**15**	5.5	15.0	*varies*

Parameters for the calibrated Grass Lake Jensen model were different from the parameters in the other calibrated models. Differences are expected because each individual lake has unique properties that affect sedimentation and release.

To confirm the performance of the model, individual in-lake TP concentrations from the Jensen model were compared to the measured concentrations in Grass Lake. A time series of the estimated and observed in-lake TP concentrations is shown in Figure 6.1. The comparison of individual modeled versus observed results is shown in Figure 6.2. The two figures show the observations used for calibration the model (blue) as well as the observation excluded from the calibration of the Jensen model (red).

FIGURE 6.1
In-Lake Concentrations from Grass Lake Jensen Model

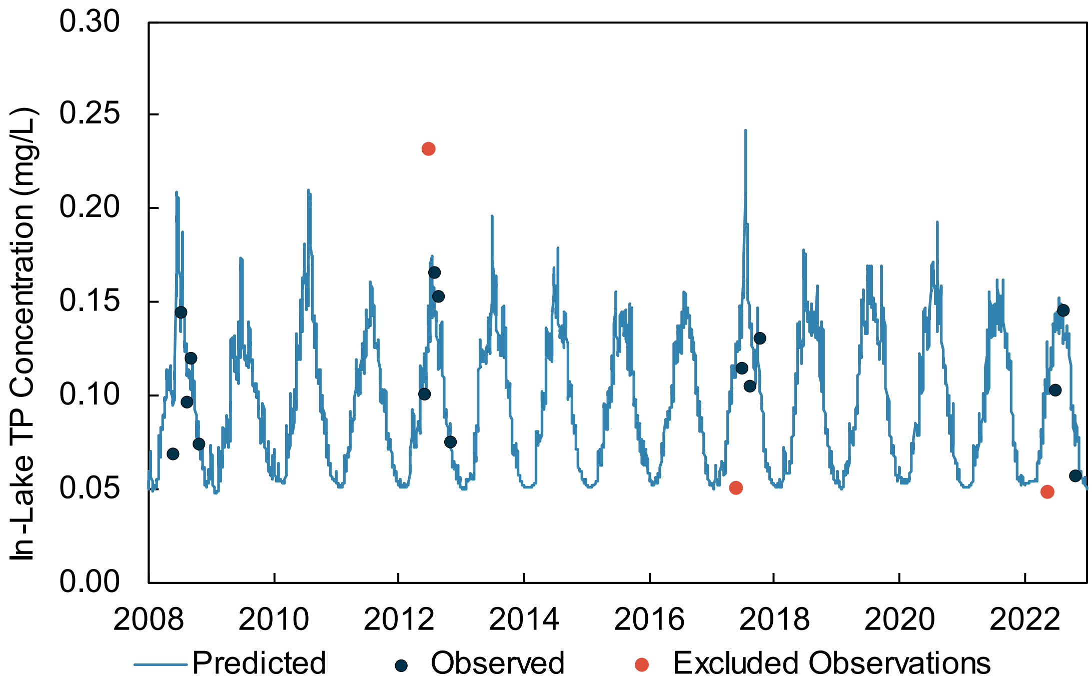
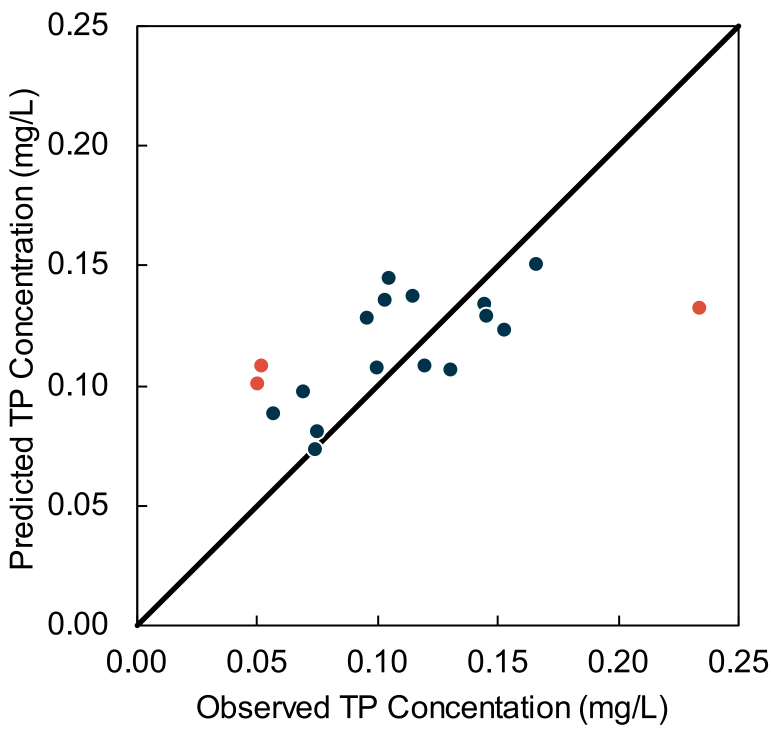


FIGURE 6.2
Modeled and Observed Concentrations from Grass Lake Model



The average TP concentration for the observations is 0.111 mg/L, and the average predicted concentration on the corresponding days is 0.116 mg/L.

Residual plots comparing the residuals (observed concentration minus predicted concentration) are provided in Appendix E. Residual plots provide insight into the model's performance under different conditions. The residual plots were evaluated to better understand model performance, and the following patterns were observed.

- Observed in-lake concentration: The model tends to underpredict TP concentration on days with high observed in-lake concentrations and overpredicts TP concentration on days with lower observed in-lake concentrations.
- Flow rate: The model underpredicts TP concentration at low flow rates (<5 cms).
- Day of year: No noticeable pattern was found in the difference between observed and predicted TP concentrations relative to the time of year.
- Temperature: No discernible pattern was found between the difference in observed and predicted TP concentrations and water temperature.

The Jensen model is designed as a simplified representation of phosphorus sedimentation and release in shallow lakes. It is not intended to account for all processes that can influence in-lake phosphorus concentration, such as resuspension of sediment due to recreation and plant and algae growth.

7. REDUCTIONS AND LOADING CAPACITY FOR GRASS LAKE

The Grass Lake model was developed to estimate reductions in TP loading required for Grass Lake to meet Illinois' TP criterion. Understanding the loading capacity is necessary for determining allocations for the FOXIL TMDL. The following sections describe how the Jensen model was used to determine the reductions and the loading capacity.

7.1. Method for Estimating Reductions and Loading Capacity

The calibrated model established the values of the four coefficients and the initial sediment phosphorus concentration. External phosphorus loads were reduced until the modeled in-lake concentrations met Illinois' criterion for TP in lakes and reservoirs. The following sections describe the approach used to determine required reductions.

7.1.1. Translation of P Criterion

As stated in Section 2.2, Illinois has a total phosphorus criterion of 0.05 mg/L for all lakes and reservoirs. However, Illinois' code does not provide any additional guidance into how the criterion should be applied when determining impairments. In the Illinois EPA's TMDL, attainment of the TP criterion was interpreted to mean that the 90th percentile of daily TP concentrations must not exceed 0.05 mg/L (Illinois Environmental Protection Agency 2020, 2-5). This interpretation algisn with Illinois' *Integrated Water Quality Report*, which states, "If 10% or more of the surface total-phosphorus values exceed the criterion (0.05 mg/L), then we identify phosphorus (total) as a cause of non-attainment (Illinois Environmental Protection Agency 2022, 46)."

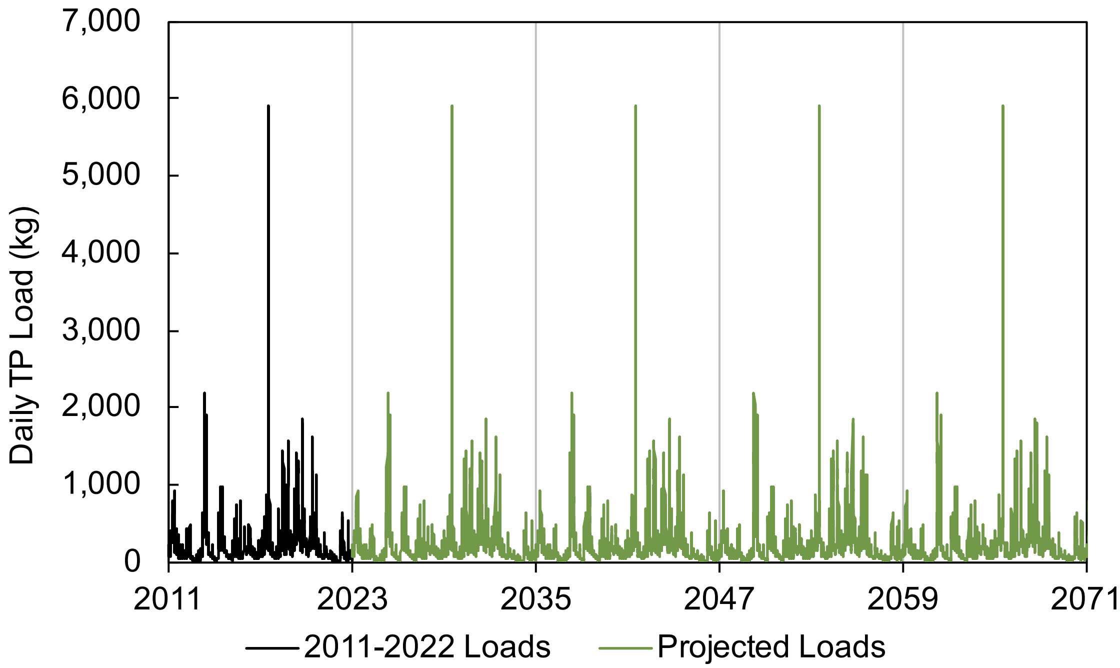
To ensure consistency with the Illinois EPA's TMDL and the *Integrated Water Quality Report*, loading capacity for Grass Lake was defined as the phosphorus load that results in TP concentrations at or below 0.05 mg/L on at least 90 percent of days. This same approach was also used in Wisconsin for the Rock River Basin TMDL (Wisconsin Department of Natural Resources 2011) and Milwaukee River Basin TMDL (Wisconsin Department of Natural Resources 2018).

7.1.2. Forecasted Flows and Loads

As external phosphorus loads into a lake are reduced, the phosphorus accumulated in the sediments decreases. This reduction in sediment phosphorus results from both a decline in the amount of phosphorus settling out of the water column and the continued release of phosphorus from existing sediments. As the accumulated phosphorus in the sediments decreases, internal phosphorus loading from the sediments also declines. However, the response of internal loading of phosphorus to the decrease in the external loads is not immediate. Equilibrium between external phosphorus loading and internal phosphorus loading is often delayed due to the time required to reduce legacy phosphorus in the sediment..

To project the future response of internal phosphorus dynamics in Grass Lake to a reduction in external loads, the Jensen model was applied for 48 years beyond 2022. External flows and loads for these future years were estimated by repeating the flows and TP loads from 2011 through 2022 in 12-year increments. The 2011 to 2022 period was chosen for two reasons: it aligns with the calibrated SWAT+ model developed for the FOXIL TMDL and includes a range of flow conditions (low, average, and high flows). The initial dataset used for the Jensen model is shown in Figure 7.1.

FIGURE 7.1
Projected Loads for Predicting Required Reductions



7.1.3. Required Reductions

Once the extrapolated dataset consisting of four 12-year periods was created, a percent reduction was applied to the external phosphorus loads. The percent reduction was adjusted until the 90th percentile of predicted concentration during the final time period (2059-2070) equaled 0.05 mg/L.

7.2. Reductions and Loading Capacity Results

The calibrated model and the projected loads were used to calculate the percent of phosphorus needing to be reduced in order for Grass Lake to meet Illinois EPA's water quality criterion. The percent reduction was translated to a loading capacity by multiplying baseline loads by the percent reduction. The required percent reductions and loading capacities are summarized in the following sections.

7.2.1. Phosphorus Reductions

A single value for percent reduction was applied equally across all projected TP loads. A percent reduction of 66.2 percent resulted in 90 percent of days equal to or less than 0.05 mg/L for the 2059-2070 timeframe. The projected loads with the 66.2 percent reduction applied is presented in Figure 7.2. The resulting in-lake concentrations from the reductions are presented in Figure 7.3.

FIGURE 7.2
Reduced Projected Loads To Meet the Illinois TP Criterion

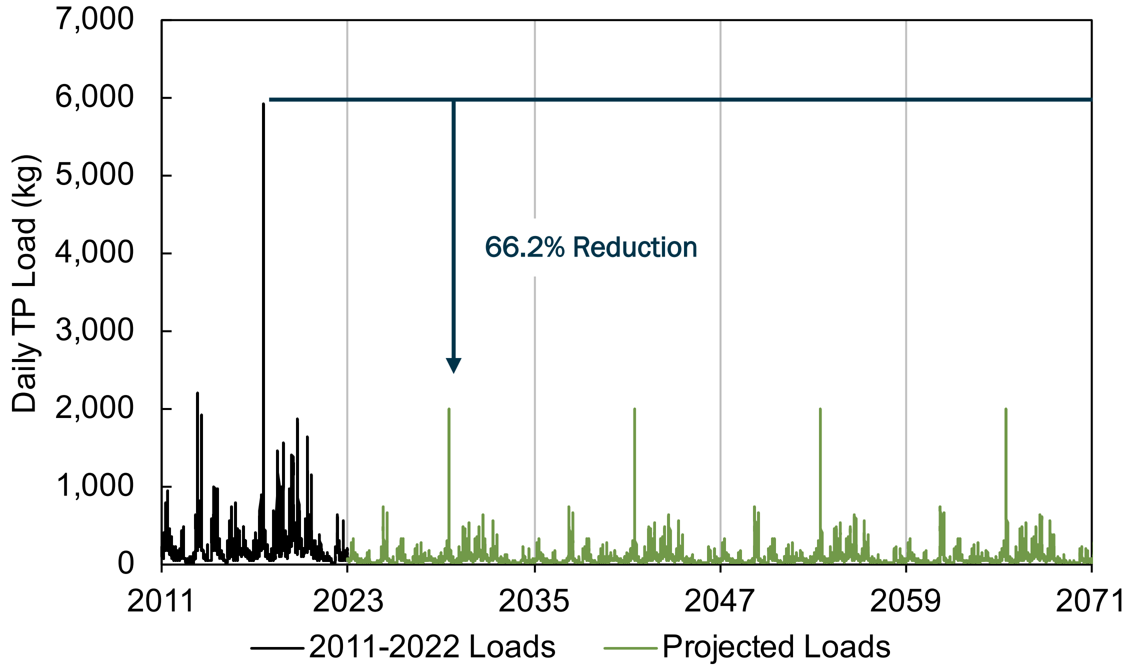
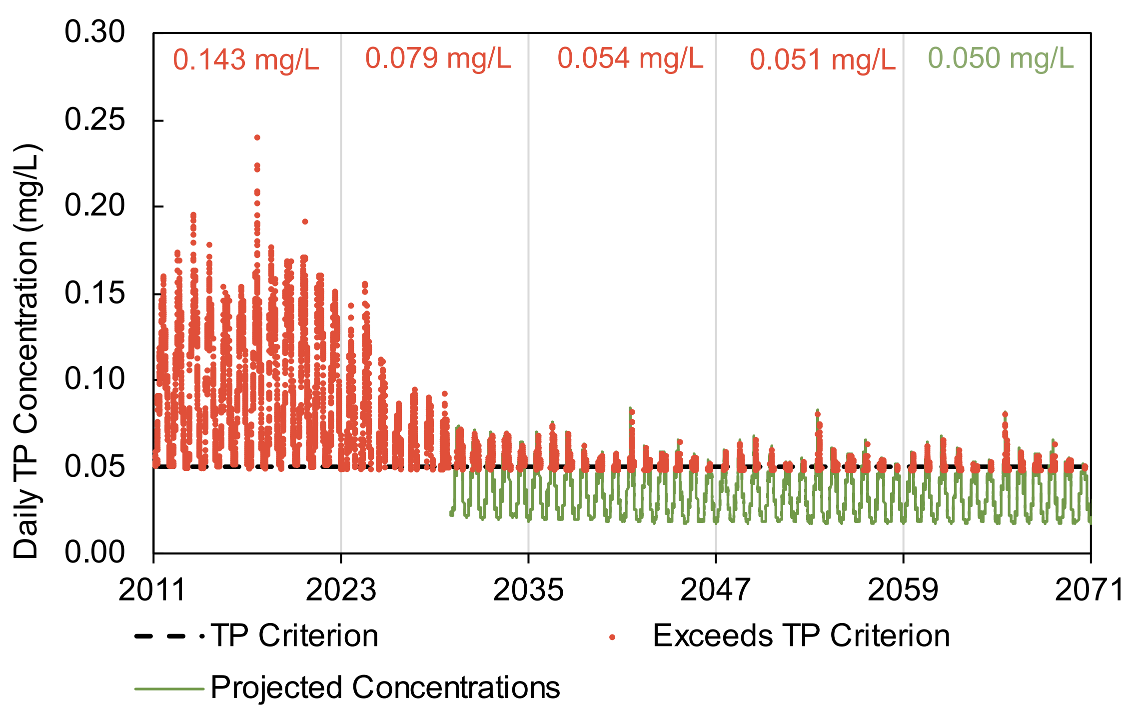
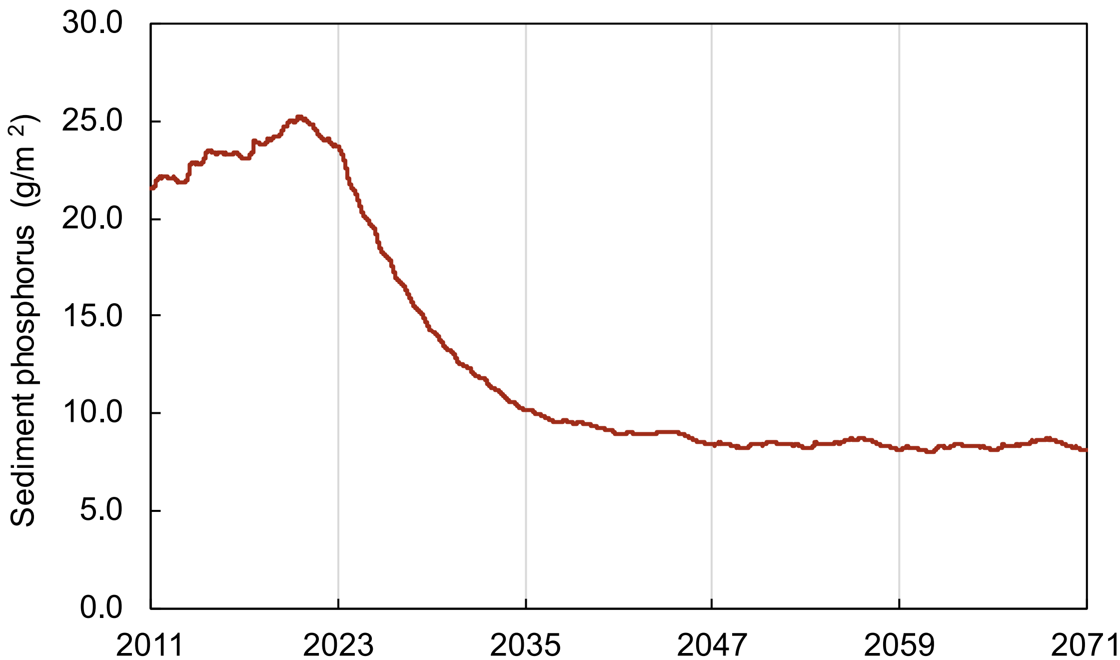


FIGURE 7.3
Projected In-Lake TP Concentrations
Numbers on figure indicate 90th percentile concentration for each time period



The steady decrease in in-lake TP concentration over time reflects the decrease in internal loading. As shown in Figure 7.4, the internal sediment phosphorus content steadily decreased from 2023 through 2059 and started to reach an equilibrium between 2059 through 2071.

FIGURE 7.4
Sediment Phosphorus Content in Grass Lake



7.2.2. Loading Capacity of Grass Lake

The final loads calculated for the 2059 to 2070 time period represent the loading capacity for Grass Lake. Loading capacity refers to the maximum amount of phosphorus the lake can receive without exceeding the water quality criterion. The average annual baseline loads (from 2011 to 2022) and the final average annual loading capacity (from 2059 to 2070) are presented in Table 7.1.

TABLE 7.1
Baseline Loads and Loading Capacity for Grass Lake

	Load (lb/yr)		
Source	Baseline Load	Loading Capacity	% Reduction
Fox River at DT-35 (WI)	169,412	57,261	66.2%
Fox River at DT-35 (IL)	350	118	66.2%
Direct Drainage	1,698	574	66.2%
Lake Marie	2,458	831	66.2%
Total External Loading	173,917	58,784	66.2%
Internal Loading	7,329	3,333	54.5%
Total	181,246	62,117	65.7%

7.2.3. Loading Capacities for FOXIL TMDL

The loading capacities presented in Table 7.1 are divided among four external loading sources: Fox River at DT-35 from Wisconsin, Fox River at DT-35 from Illinois, direct drainage, and Lake Marie. The percent reduction required for Grass Lake was applied uniformly across all four sources. The Fox River load at DT-35 was split into contributions from Wisconsin and Illinois to calculate a total maximum daily load specifically for the Wisconsin portion. Overall, 99.8 percent of drainage area at DT-35 lies within Wisconsin, and 0.2 percent is in Illinois. These percentages were applied to the total baseline load and loading capacity for the Fox River at DT-35 to determine the final values for each state.

The row labeled "Fox River at DT-35 (WI)" in Table 7.1 represents the maximum allowable total phosphorus load from the Fox River at the Wisconsin border. This average annual value of 57,261 lb/yr will be used when assigning allocations for the FOXIL TMDL. The allocation of loading capacity for the Fox River in Wisconsin is equal to 97.3 percent of the total external loading capacity for Grass Lake.

7.3. Comparison of Illinois EPA's TMDL and Jensen Model Results

While the Illinois EPA's TMDL does not explicitly assign allocations to Wisconsin, it does establish a loading capacity for Grass Lake. As discussed in Section 3.2, the modeling performed for Illinois EPA's TMDL was not consistent with the methods used to develop the FOXIL TMDL. Therefore, additional modeling was necessary to produce a loading capacity for Grass Lake that aligns with the FOXIL TMDL framework.

Although the modeling approaches differ, comparing the results from the Illinois EPA's TMDL and the Jensen model for Grass Lake provides insight into how methodological differences may affect outcomes. A summary of the modeling approaches used for the Illinois EPA's TMDL and the Jensen model is provided in Table 7.2. A comparison of the results of the two approaches is summarized in Table 7.3.

TABLE 7.2
Modeling approaches from Illinois EPA's TMDL and Jensen Model

Model Name	Timeframe	Lake Response Model	Inflow concentrations	Internal loading
Illinois EPA's TMDL	2000-2016	SLAM	Monthly average	SLAM
Jensen Model 2059-2070	2059-2070	Jensen	LOADEST	Jensen

TABLE 7.3
Results for Grass Lake Baselines and Loading Capacities

	Baseline (lb/day)			Loading Capacity (lb/day)			
Name	External	Internal	Total	External	Internal	Total	% Ext. Load Reduction
Illinois EPA's TMDL	395	29.4	424	79	22.1	101	80%
Jensen Model 2059-2070	476	20.1	496	161	9.2	170	66.2%

The total loading capacity of Grass Lake calculated in the Illinois EPA's TMDL was 101 pounds per day, and the loading capacity calculated by the Jensen model was 170 pounds per day. The difference in loading capacity is attributed to four main factors: the timeframe used for establishing baseline loads (2000-2016 vs. 2011-2022), the method used to estimate incoming daily loads (monthly average TP concentration vs. LOADEST), the model used (SLAM vs. Jensen), and the evaluation of internal loading (initial reduction vs. future reduction).

The DNR did not have access to the model input files or the modeling software that was used to generate the loading capacity for the Illinois EPA's TMDL. To investigate potential sources of differences between the two approaches, the DNR developed a simplified version of the continuously stirred tank reactor (CSTR) model, with modifications to account for internal loading. This simplified model was used to approximate the behavior of the SLAM model used in the Illinois EPA's TMDL. The approximate source differences in loading capacity between Illinois EPA's TMDL and the Jensen model is presented in Table 7.4.

TABLE 7.4

Sources of differences in CSTR model and Jensen Model

Model Change	Original model characteristic	Updated model characteristic	Difference in Loading Capacity (lb/day)	% of Difference
Model calibration	SLAM	CSTR	2	3%
Timeframe	2000-2016	2011-2022	18	26%
Baseline loads	Monthly conc.	LOADEST	18	27%
Model	CSTR	Jensen	21	32%
Timeline	2023-2034	2059-2070	8	12%
Total	Illinois EPA's TMDL	DNR Jensen Modeling	68	100%

Nearly 40 percent of the difference in estimated loading capacity between the SLAM model and the Jensen model is attributed to the timeframes used for the modeling. When the CSTR model is modeled for 2011 to 2022 rather than 2000 to 2016, the estimated loading capacity of Grass Lake increases by approximately 26 percent. An additional 12 percent increase in capacity results from accounting for the long-term decline in internal phosphorus loading. For the Jensen model, the timeframe of 2023 to 2034 represents the first time period where reductions are applied.

Another key source of difference between the two models is the calculation of incoming loads. When the loads from the Fox River at DT-35 are calculated using LOADEST rather than monthly average concentrations, the calculated loading capacity of Grass Lake increases by approximately 27 percent. The final major contributor to the difference in loading capacity is the underlying model structure and assumptions. The difference in the two models accounts for roughly 32 percent of the difference in calculated loading capacity of Grass Lake. The Illinois EPA's TMDL for Grass Lake relies on default values for nutrient uptake and settling rates built into the SLAM model (Illinois Environmental Protection Agency 2020, 1-61), whereas the Jensen model is explicitly calibrated for the settling and release of TP. The default values for the SLAM model are described as a conservative model assumption, and the resulting lower loading capacity confirms that assumption.

The comparison discussed above was performed to evaluate the differences between the two modeling approaches. The differences in results are attributed to the difference in model inputs, model time periods, and underlying model approaches. While the two approaches produce different estimates of loading capacity, both are valid and appropriate for their respective purposes.

8. CONCLUSIONS

Grass Lake is listed on Illinois' 303(d) list as impaired for total phosphorus. The impairment on Grass Lake in Illinois is assessed in the Fox River and Chain O' Lakes TMDL developed by the Illinois EPA; however, the TMDL does not assign specific allocations for waters in Wisconsin. Wisconsin is obligated under the Clean Water Act to consider the water quality standards of downstream waterbodies when developing TMDLs, so additional modeling for Grass Lake was required to determine a TMDL for the Fox River entering Illinois.

The original modeling performed for the Illinois EPA's TMDL was not sufficient for characterizing the loading capacity for the FOXIL TMDL. First, the Illinois EPA's TMDL was not developed to assign specific TP allocations to Wisconsin. Second, the timeframe used to develop the Illinois EPA's TMDL model was not consistent with the SWAT+ model developed for the FOXIL TMDL. Third, the method for estimating daily TP loads used in the Illinois EPA's TMDL was not consistent with the approach Wisconsin used to calibrate the SWAT+ model for the FOXIL TMDL. Finally, the lake modeling method used in the Illinois EPA's TMDL has not been used for other Wisconsin TMDLs. The modeling for the Illinois EPA's TMDL was appropriate for its intended purposes, but the limitations required additional modeling to determine Grass Lake's loading capacity for the FOXIL TMDL.

To calculate the TP loading capacity of Grass Lake for the FOXIL TMDL, a model developed by the DNR and based on research on shallow lakes by Jensen et al. (2006) was used. The model has been effectively used in Wisconsin for other TMDLs. Inputs for the Jensen model were developed using flows from USGS gages, upstream drainage areas, water quality monitoring, and TP loads estimated from Illinois EPA's TMDL. The Jensen model was calibrated by comparing modeled TP concentrations to measured TP concentrations in Grass Lake over a 14-year time period.

The calibrated Jensen model was used to estimate the reductions required for Grass Lake to meet its water quality criterion for phosphorus. Once the total loading capacity for Grass Lake was determined, the total value was translated to a TMDL for the Fox River at the Wisconsin border. The modeling determined that an average annual load of 57,261 pounds TP per year or less from the Fox River in Wisconsin would allow Grass Lake to meet Illinois' water quality criterion.

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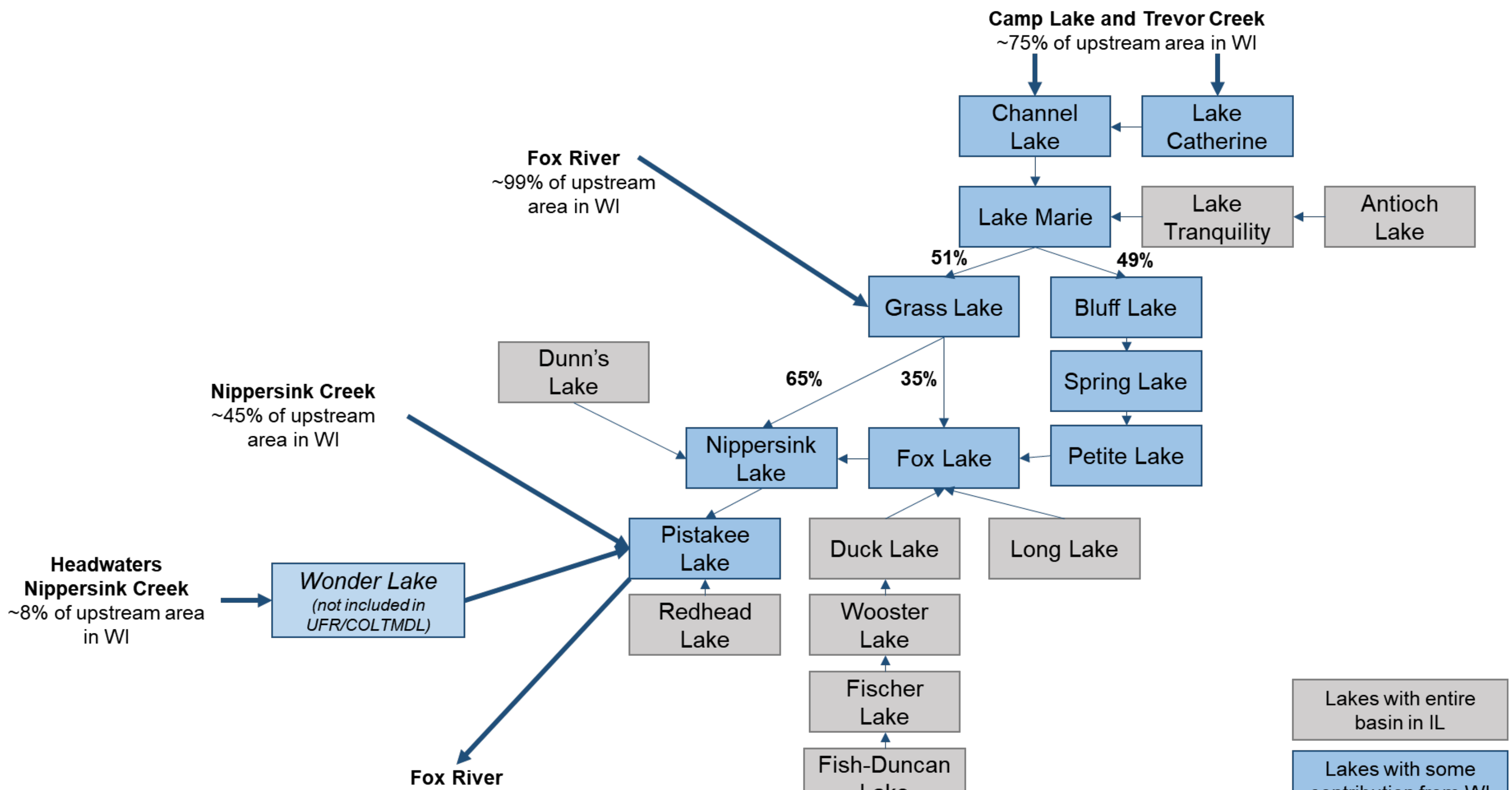
APPENDIX A

CHAIN O' LAKES CONNECTIONS



Camp Lake and Trevor Creek
~75% of upstream area in WI
Channel Lake
Lake Catherine
Fox River
~99% of upstream area in WI
Lake Marie
Lake Tranquility
Antioch Lake
51%
49%
Grass Lake
Bluff Lake
Dunn's Lake
65%
35%
Spring Lake
Nippersink Creek
~45% of upstream area in WI
Nippersink Lake
Fox Lake
Petite Lake
Pistakee Lake
Duck Lake
Long Lake
Headwaters Nippersink Creek
~8% of upstream area in WI
Wonder Lake
(not included in UFR/COLTMDL)
Redhead Lake
Wooster Lake
Fischer Lake
Fish-Duncan Lake
Fox River
Lakes with entire basin in IL
Lakes with some contribution from WI

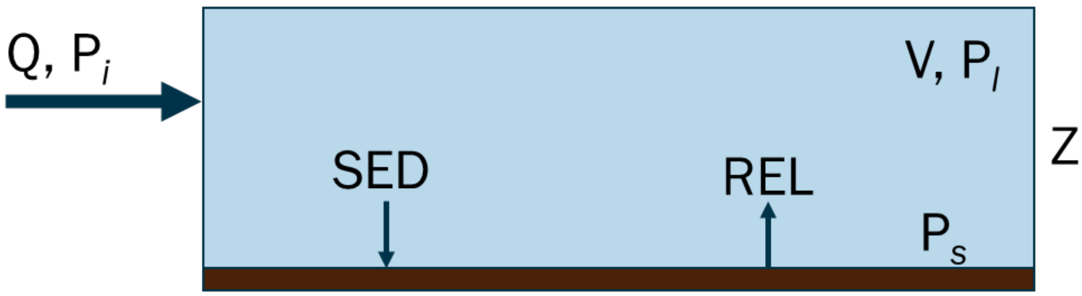
APPENDIX B

JENSEN SHALLOW LAKE MODEL DETAILS

1. JENSEN MODEL THEORY

An empirical model describing the seasonal dynamics of phosphorus in 16 shallow eutrophic lakes after external loading reduction

Jens Peder Jensen,[1] Asger Roer Pedersen, Erik Jeppesen,[1] and Martin Søndergaard



Q: Inflow volume
V: Lake volume
Z: Average lake depth

P_i: Inflow TP
P_l: In-Lake TP
P_s: Sediment TP

SED: TP sedimentation
REL: TP release

$$\frac{dP_l}{dt} = \frac{Q}{V} \times (f_d \times P_i - P_l) - \text{SED} + \text{REL}$$

$$\frac{dP_s}{dt} = \frac{Q}{V} \times (1 - f_d) \times P_i + \text{SED} - \text{REL}$$

$$f_d = 1/(1 + \sqrt{V/Q/365})$$

$$\text{SED} = bS \times (1 + tS)^{T-20} \times \frac{P_l}{Z}$$

$$\text{REL} = bF \times (1 + tF)^{T-20} \times P_s$$

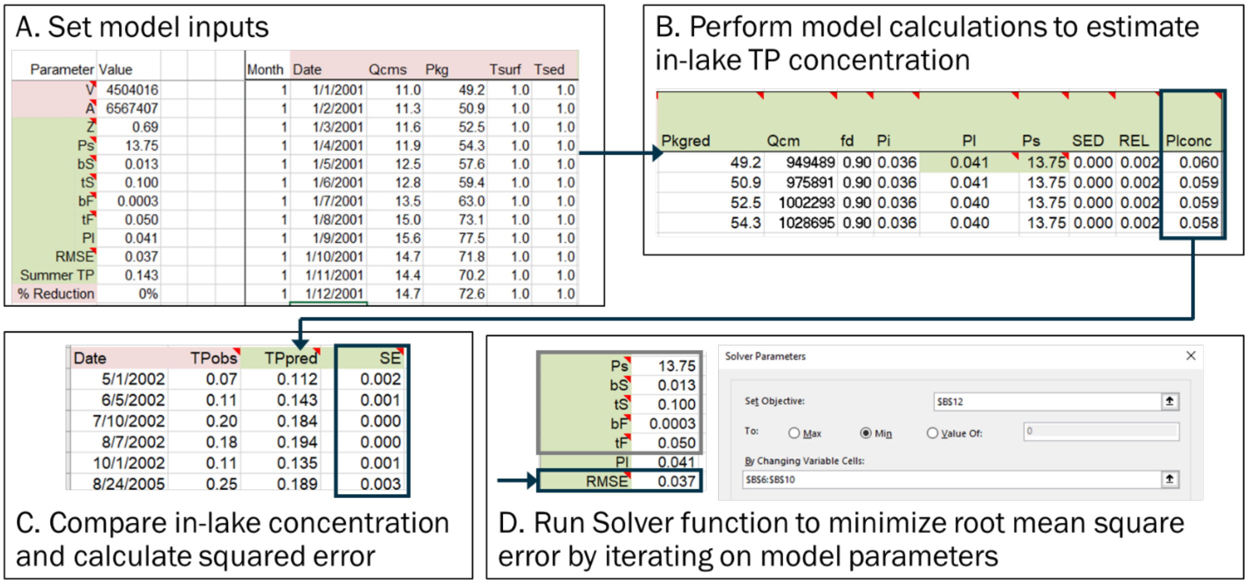
2. JENSEN MODEL BASICS

Model developed in Microsoft Excel by Wisconsin DNR

Solves equations described in Jensen (2006)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1																				
2	Parameter	Value				Month	Date	Qcms	Pkg	Tsurf	Tsed	Pkgred	Qcm	fd	Pi	Pl	Ps	SED	REL	Plconc
3	V	4504016				1	1/1/2001	11.0	49.2	1.0	1.0	49.2	949489	0.90	0.036	0.041	13.75	0.000	0.002	0.060
4	A	6567407				1	1/2/2001	11.3	50.9	1.0	1.0	50.9	975891	0.90	0.036	0.041	13.75	0.000	0.002	0.059
5	Z	0.69				1	1/3/2001	11.6	52.5	1.0	1.0	52.5	1002293	0.90	0.036	0.040	13.75	0.000	0.002	0.059
6	Ps	13.75				1	1/4/2001	11.9	54.3	1.0	1.0	54.3	1028695	0.90	0.036	0.040	13.75	0.000	0.002	0.058
7	bS	0.013				1	1/5/2001	12.5	57.6	1.0	1.0	57.6	1081499	0.90	0.037	0.040	13.75	0.000	0.002	0.058
8	tS	0.100				1	1/6/2001	12.8	59.4	1.0	1.0	59.4	1109046	0.90	0.037	0.040	13.75	0.000	0.002	0.058
9	bF	0.0003				1	1/7/2001	13.5	63.0	1.0	1.0	63.0	1162994	0.91	0.037	0.039	13.75	0.000	0.002	0.057
10	tF	0.050				1	1/8/2001	15.0	73.1	1.0	1.0	73.1	1296148	0.91	0.039	0.039	13.75	0.000	0.002	0.057
11	Pl	0.041				1	1/9/2001	15.6	77.5	1.0	1.0	77.5	1348952	0.91	0.039	0.040	13.75	0.000	0.002	0.058
12	RMSE	0.037				1	1/10/2001	14.7	71.8	1.0	1.0	71.8	1269746	0.91	0.039	0.040	13.74	0.000	0.002	0.058
13	Summer TP	0.143				1	1/11/2001	14.4	70.2	1.0	1.0	70.2	1243344	0.91	0.039	0.040	13.74	0.000	0.002	0.059
14	% Reduction	0%				1	1/12/2001	14.7	72.6	1.0	1.0	72.6	1269746	0.91	0.039	0.040	13.74	0.000	0.002	0.059
15						1	1/13/2001	15.0	75.2	1.0	1.0	75.2	1298436	0.91	0.040	0.040	13.74	0.000	0.002	0.059
16						1	1/14/2001	15.4	77.9	1.0	1.0	77.9	1327126	0.91	0.040	0.041	13.74	0.000	0.002	0.059
17	Date	TPobs	TPpred	SE		1	1/15/2001	18.2	99.0	1.0	1.0	99.0	1569320	0.92	0.043	0.041	13.74	0.000	0.002	0.060
18	5/1/2002	0.07	0.112	0.002		1	1/16/2001	21.9	131.7	1.0	1.0	131.7	1895297	0.93	0.048	0.042	13.74	0.000	0.002	0.061
19	6/5/2002	0.11	0.143	0.001		1	1/17/2001	23.2	144.7	1.0	1.0	144.7	2005481	0.93	0.049	0.044	13.74	0.000	0.002	0.065
20	7/10/2002	0.20	0.184	0.000		1	1/18/2001	22.0	134.4	1.0	1.0	134.4	1902160	0.93	0.048	0.046	13.74	0.000	0.002	0.068
21	8/7/2002	0.18	0.194	0.000		1	1/19/2001	20.8	123.9	1.0	1.0	123.9	1796552	0.92	0.047	0.047	13.74	0.000	0.002	0.069
22	10/1/2002	0.11	0.135	0.001		1	1/20/2001	21.4	130.8	1.0	1.0	130.8	1847068	0.92	0.049	0.047	13.74	0.000	0.002	0.069
23	8/24/2005	0.25	0.189	0.003		1	1/21/2001	19.0	109.2	1.0	1.0	109.2	1638139	0.92	0.046	0.048	13.74	0.000	0.002	0.070
24	10/4/2005	0.19	0.130	0.004		1	1/22/2001	18.4	105.0	1.0	1.0	105.0	1588767	0.92	0.045	0.047	13.74	0.000	0.002	0.069
25	5/21/2008	0.07	0.113	0.002		1	1/23/2001	17.1	95.2	1.0	1.0	95.2	1477439	0.92	0.044	0.047	13.74	0.000	0.002	0.068

3. JENSEN MODEL WORKFLOW



Parameter	Value
V	4504016
A	6567407
Z	0.69
Ps	13.75
bS	0.013
tS	0.100
bF	0.0003
tF	0.050
PI	0.041
RMSE	0.037
Summer TP	0.143
% Reduction	0%

Month	Date	Qcms	Pkg	Tsurf	Tsed
1	1/1/2001	11.0	49.2	1.0	1.0
1	1/2/2001	11.3	50.9	1.0	1.0
1	1/3/2001	11.6	52.5	1.0	1.0
1	1/4/2001	11.9	54.3	1.0	1.0
1	1/5/2001	12.5	57.6	1.0	1.0
1	1/6/2001	12.8	59.4	1.0	1.0
1	1/7/2001	13.5	63.0	1.0	1.0
1	1/8/2001	15.0	73.1	1.0	1.0
1	1/9/2001	15.6	77.5	1.0	1.0
1	1/10/2001	14.7	71.8	1.0	1.0
1	1/11/2001	14.4	70.2	1.0	1.0
1	1/12/2001	14.7	72.6	1.0	1.0

Pkgred	Qcm	fd	Pi	Pl	Ps	SED	REL	Plconc
49.2	949489	0.90	0.036	0.041	13.75	0.000	0.002	0.060
50.9	975891	0.90	0.036	0.041	13.75	0.000	0.002	0.059
52.5	1002293	0.90	0.036	0.040	13.75	0.000	0.002	0.059
54.3	1028695	0.90	0.036	0.040	13.75	0.000	0.002	0.058

Date	TPobs	TPpred	SE
5/1/2002	0.07	0.112	0.002
6/5/2002	0.11	0.143	0.001
7/10/2002	0.20	0.184	0.000
8/7/2002	0.18	0.194	0.000
10/1/2002	0.11	0.135	0.001
8/24/2005	0.25	0.189	0.003

Ps	13.75
bS	0.013
tS	0.100
bF	0.0003
tF	0.050
PI	0.041
RMSE	0.037

4. JENSEN MODEL INPUTS

External flows (1) and loads (2) into Grass Lake

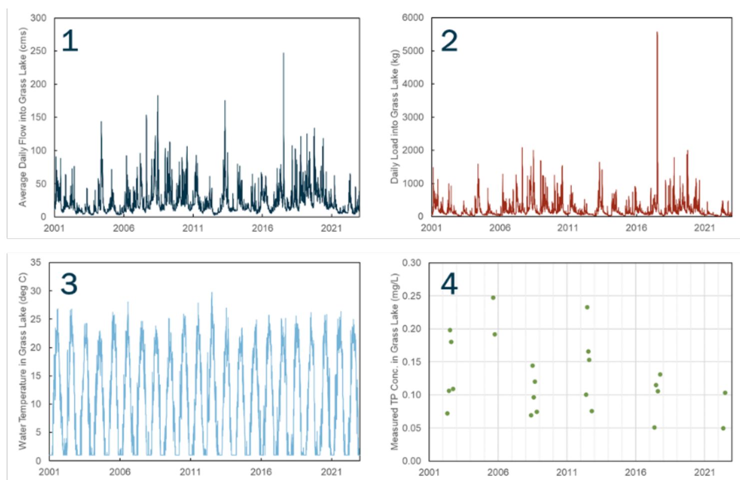
- Fox River + Lake Marie + Direct Drainage

Grass Lake water and sediment temperatures (3)

- Estimated as 5-day running average of air temp.

Measured TP concentrations in Grass Lake (4)

- Water Quality Portal from 2001-2022



5. JENSEN MODEL STEPS

Step 1. Set initial model parameters (from Upper Pool Lakes in UFW TMDL)

- P_s: Initial sediment concentration
- bS: P sedimentation constant
- tS: Temperature dependence of sedimentation
- bF: Sediment P release constant
- tF: Temperature dependence of release

Step 2. Run model to minimize RMSE

Step 3. Change P_s and re-run Solver

Step 4. Select best model parameters

APPENDIX C

DATA SOURCES FOR JENSEN SHALLOW LAKE MODEL

Type	Description	Source	Reference
Lake Characteristics	Grass Lake characteristics	Illinois EPA's TMDL	IEPA 2020
Flow	USGS Gage: Fox River at New Munster, WI	USGS	USGS 2024
Watershed Area	Upstream area of Fox River at DT-35	WEx	WDNR 2024
TP Concentration	Fox River at DT-35 water quality data	Water Quality Portal	NWQMC 2024
Flow	USGS Gage: Mill Creek at Old Mill Creek, IL	USGS	USGS 2024
Watershed Area	Upstream area of Lake Marie and Grass Lake direct drainage	Illinois EPA's TMDL	IEPA 2020
TP Load	Outflow from Lake Marie	Illinois EPA's TMDL	IEPA 2020
TP Load	Direct drainage to Grass Lake	Illinois EPA's TMDL	IEPA 2020
Temperature	Daymet	Daymet	Thornton et al. 2024
TP Concentration	Grass Lake water quality data	Water Quality Portal	NWQMC 2024

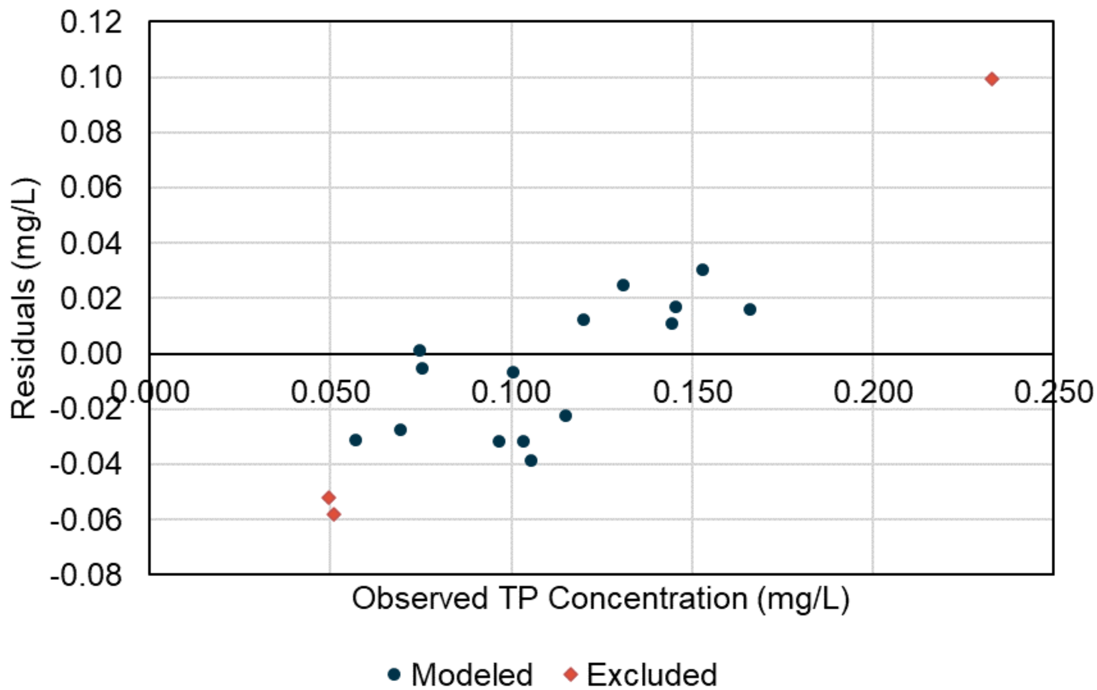
APPENDIX D

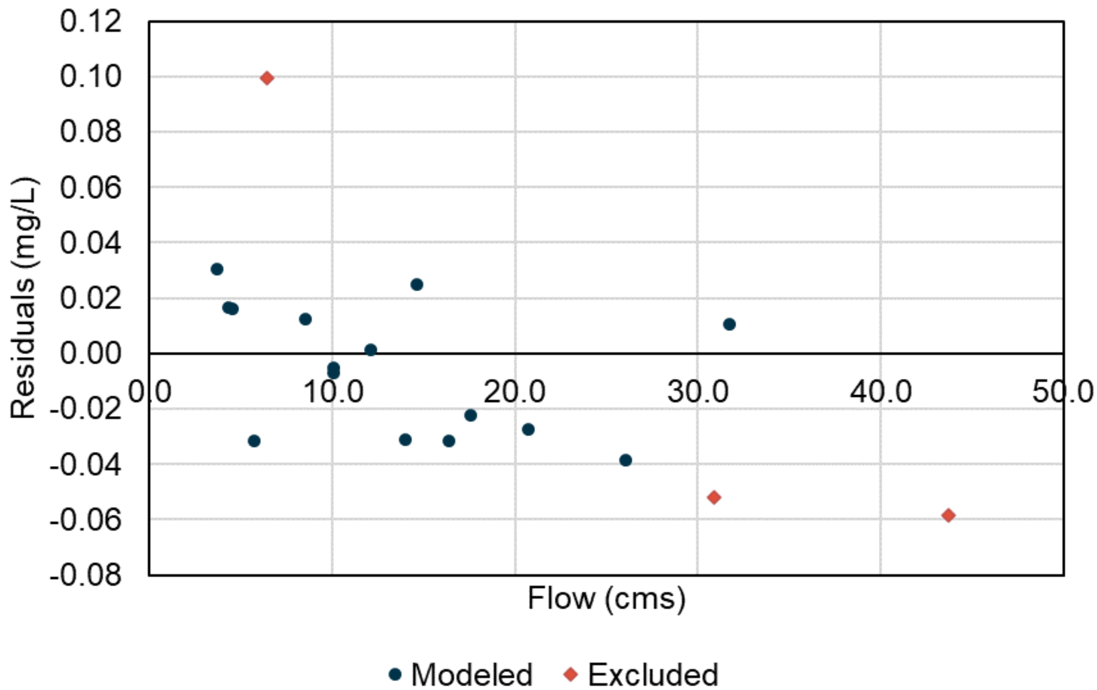
MONITORING DATA USED FOR CALIBRATION OF JENSEN MODEL

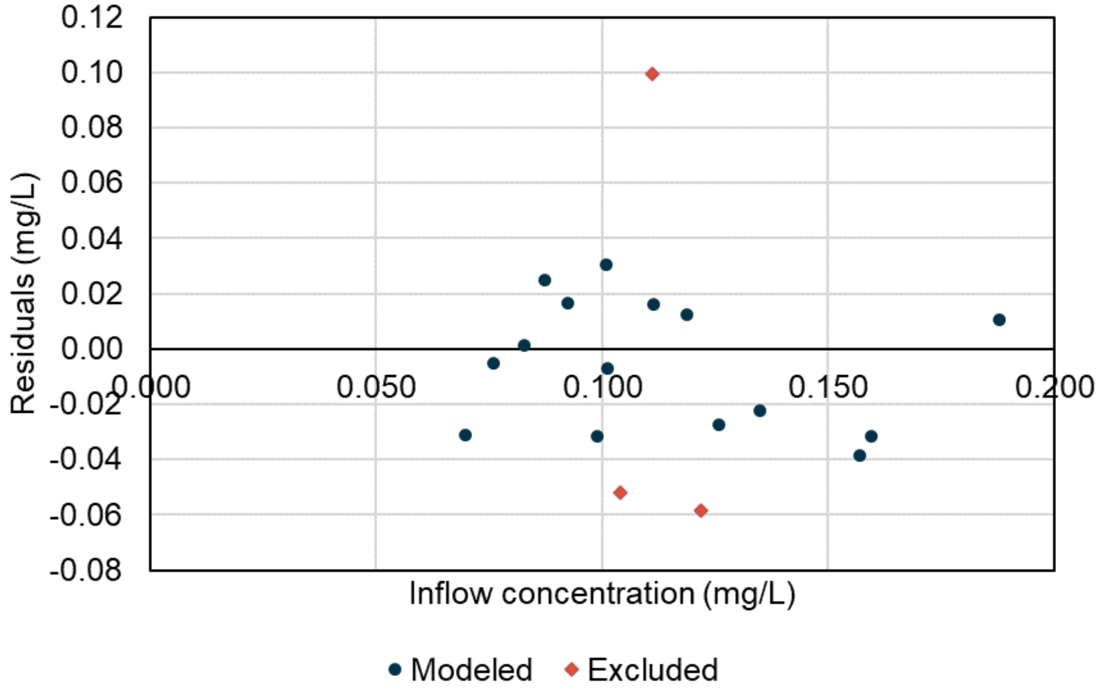
Date	Station	Sample Concentration (mg/L)	Daily Average (mg/L)
05-21-2008	RTQ-1	0.081	0.070
05-21-2008	RTQ-2	0.058	
07-08-2008	RTQ-2	0.144	0.145
07-08-2008	RTQ-1	0.145	
08-06-2008	RTQ-1	0.098	0.097
08-06-2008	RTQ-2	0.095	
09-03-2008	RTQ-1	0.129	0.120
09-03-2008	RTQ-2	0.111	
10-22-2008	RTQ-1	0.073	0.075
10-22-2008	RTQ-2	0.076	
05-23-2012	RTQ-1	0.097	0.101
05-23-2012	RTQ-2	0.104	
06-20-2012	RTQ-1	0.241	0.233
06-20-2012	RTQ-2	0.225	
07-23-2012	RTQ-1	0.154	0.166
07-23-2012	RTQ-2	0.178	
08-14-2012	RTQ-1	0.157	0.153
08-14-2012	RTQ-2	0.149	
10-22-2012	RTQ-1	0.080	0.076
10-22-2012	RTQ-2	0.071	
05-11-2017	RTQ-1	0.051	0.051
05-11-2017	RTQ-2	0.051	
06-21-2017	RTQ-1	0.110	0.115
06-21-2017	RTQ-2	0.120	
08-08-2017	RTQ-1	0.105	0.106
08-08-2017	RTQ-2	0.106	
10-11-2017	RTQ-1	0.163	0.131
10-11-2017	RTQ-2	0.099	
05-11-2022	RTQ-1	0.053	0.050
05-11-2022	RTQ-2	0.046	
06-29-2022	RTQ-1	0.100	0.104
06-29-2022	RTQ-2	0.107	
08-16-2022	RTQ-1	0.152	0.146
08-16-2022	RTQ-2	0.139	
10-26-2022	RTQ-1	0.063	0.057
10-26-2022	RTQ-2	0.051	

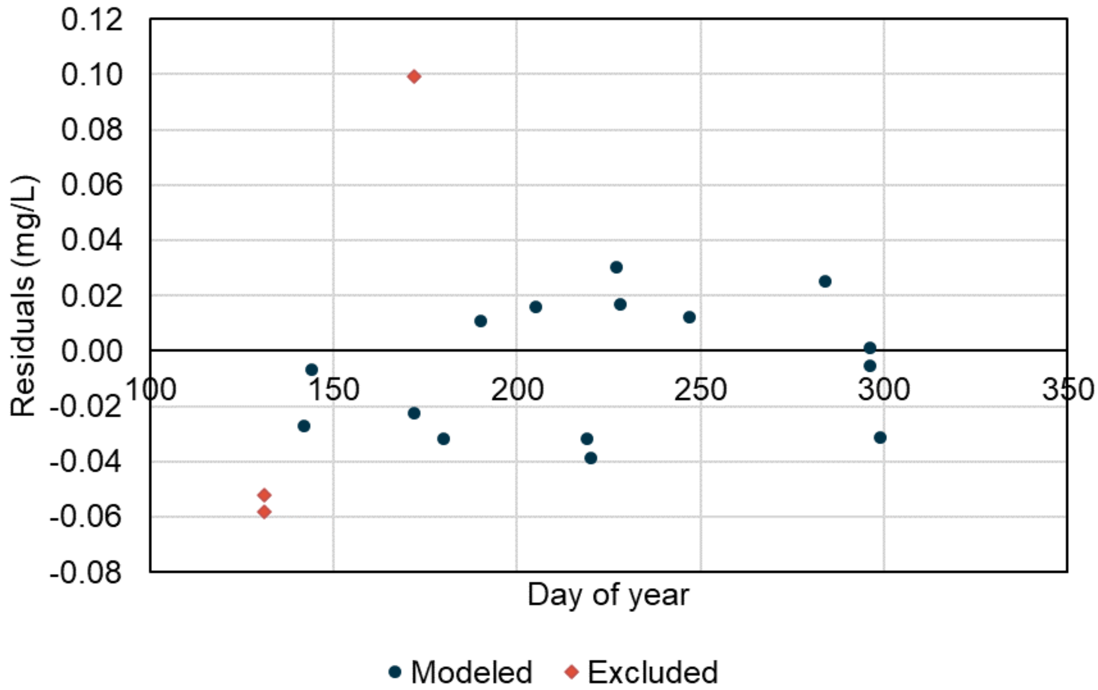
APPENDIX E

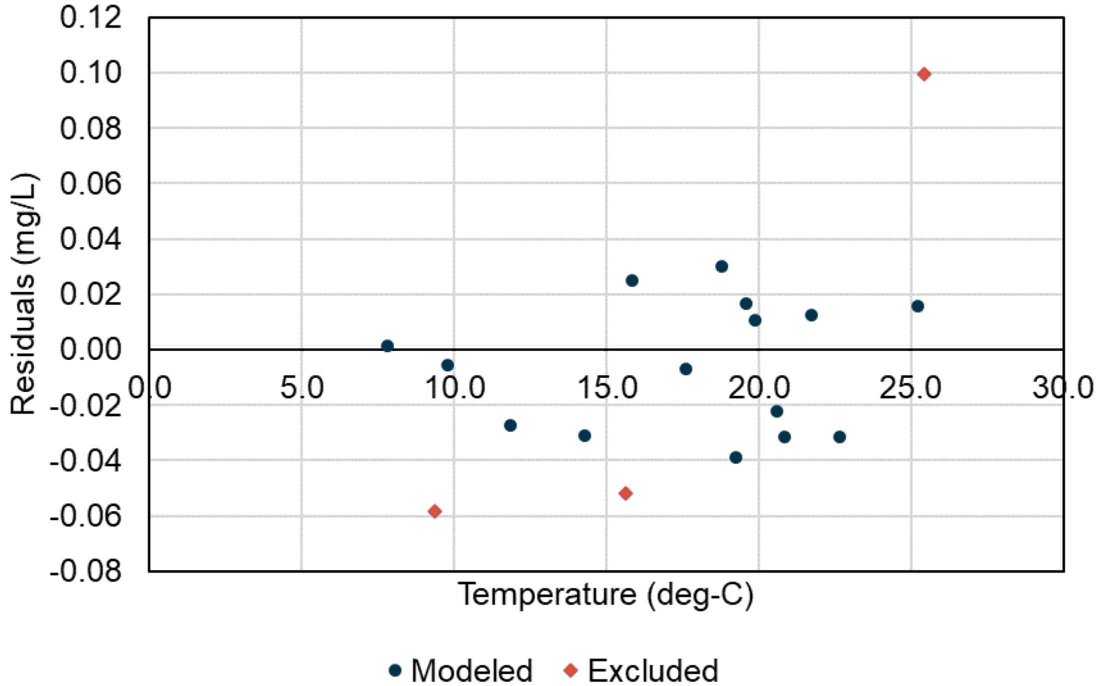
RESIDUAL PLOTS FOR JENSEN MODEL CALIBRATION


0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
Residuals (mg/L)
0.000
0.050
0.100
0.150
0.200
0.250
Observed TP Concentration (mg/L)
Modeled
Excluded


0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
Residuals (mg/L)
0.0
10.0
20.0
30.0
40.0
50.0
Flow (cms)
Modeled
Excluded


0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
Residuals (mg/L)
0.000
0.050
0.100
0.150
0.200
Inflow concentration (mg/L)
Modeled
Excluded


0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
Residuals (mg/L)
100
150
200
250
300
350
Day of year
Modeled
Excluded



0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
Residuals (mg/L)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Temperature (deg-C)
Modeled
Excluded