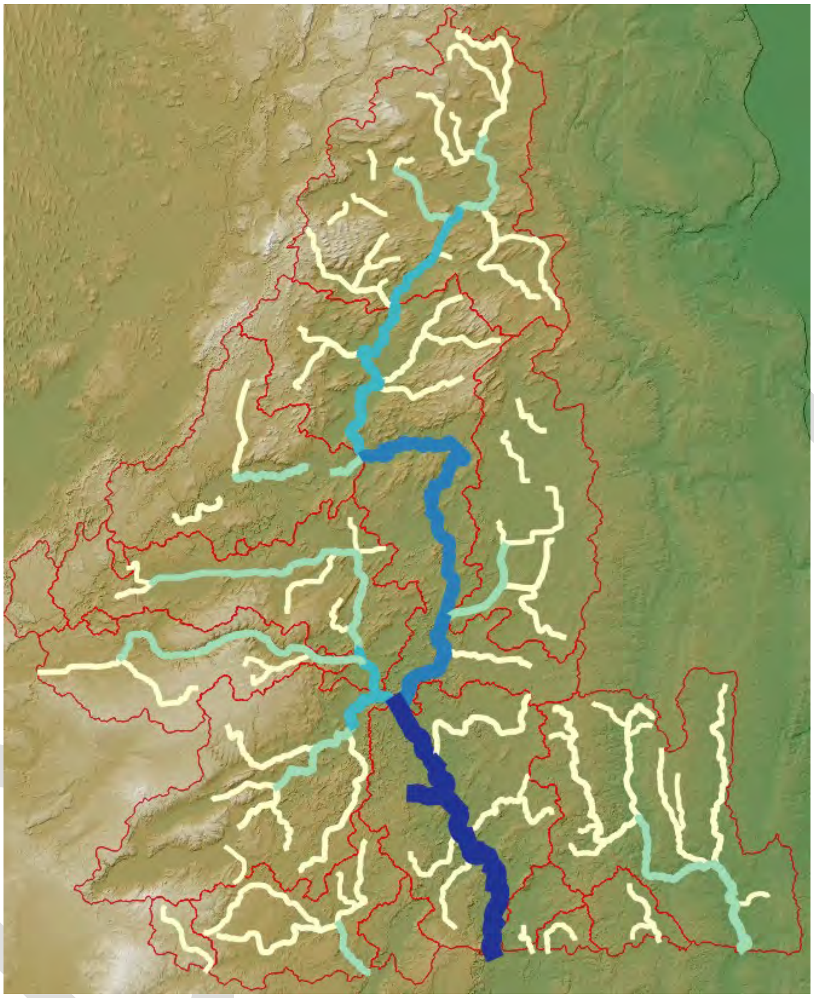
Fox Illinois River Basin TMDL: SWAT Model Setup, Calibration, and Validation Report



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1. PROJECT BACKGROUND

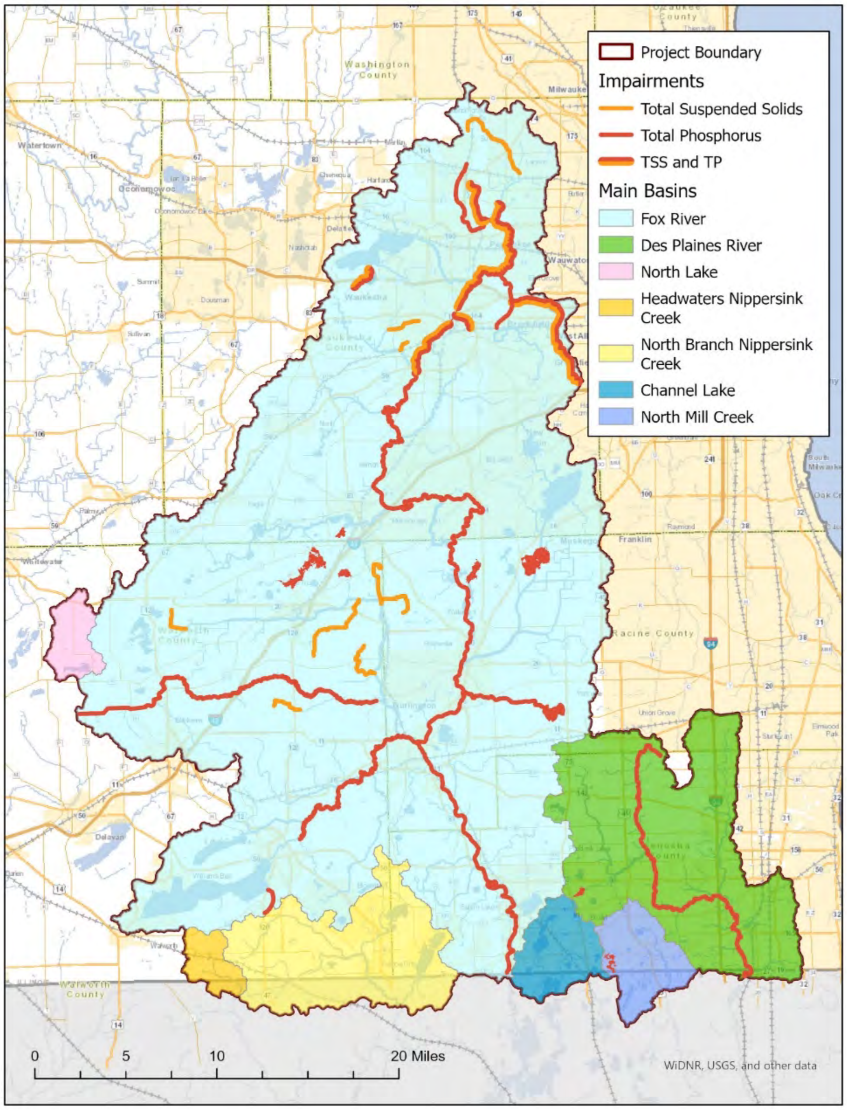
The Wisconsin Department of Natural Resources (Department), together with many partners, is working to improve the surface water quality of tributaries, streams, rivers, and lakes within the Fox Illinois River Basin. To strengthen these ongoing efforts, the Department is developing a Total Maximum Daily Load (TMDL) for the river basin. 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 phosphorus and total suspended solids. The TMDL study will provide a strategic framework and pollutant reduction goals for surface water quality improvement within the FOXIL river basins.

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 FOXILTMDL study area covers approximately 1,060 square miles within Wisconsin, which is approximately 2 percent of the state. Within the study area, some lakes and streams are impaired due to excessive loadings of total phosphorus (TP) and total suspended solids (TSS) and sediment (Wisconsin Department of Natural Resources, 2022), which means they are not meeting their water quality criteria. The extent of the TMDL and the waterbodies that are listed as impaired on the 303(d) list, as of the 2024 list, are shown in Figure 1.1.

An important component of TMDL development is the development of a watershed model. The watershed model incorporates information about land use, slopes, soils, climate, agricultural management, and other landscape features to estimate runoff, streamflow, and nonpoint pollutant loads. The results of the watershed model serve two purposes: calculating flows for ungauged portions of the basin and determining existing nonpoint source loads. This report details the development and the results of the watershed model.

FIGURE 1.1

Extent of Fox Illinois TMDL Study Area



2. BASIC MODEL CONFIGURATION

Watershed models are developed to estimate runoff, streamflow, and pollutant loading. Watershed models require inputs related to land use, landscape characteristics, climate, and agricultural management. The following section describes the basic configuration of the watershed model used in this TMDL.

2.1. SWAT and SWAT+

The Soil and Water Assessment Tool (SWAT) is a hydrologic model that is used to simulate runoff and quantify the impact of land management practices in large, complex watersheds. The original SWAT model has undergone revisions in recent years and is now available under the name SWAT+. The watershed model for the FOXIL TMDL was developed using SWAT+. The following sections provide a brief overview of SWAT and SWAT+.

2.1.1. SWAT Background

SWAT has been used in previous TMDLs developed by the Department. Details of the model are described in respective TMDL reports. The TMDL developed for the Wisconsin River includes a detailed explanation of the SWAT model, which is reproduced below (Wisconsin Department of Natural Resources, 2019):

> The SWAT model is the product of over 30 years of efforts to accurately simulate large-scale watershed hydrology using field-scale scientific findings. It has been used to simulate watersheds all across the globe due to its ability to simulate diverse landscapes, its openly published source code, and the ability of users to control a large degree of detail within the default model. The primary outputs of a SWAT model are quantities (streamflow or water yield) and qualities (masses of physical and chemical components concentrated in water) of water at selected sites at a daily time step.
>
> At its core, SWAT relies on field-level units that deliver water, sediment, and chemicals to streams. The unit in SWAT is referred to as the Hydrologic Response Unit (HRU). Each SWAT HRU is defined by a discrete combination of landcover, soil, and slope characteristics. Within each HRU, the user defines what crop is growing, if and how crops are managed (e.g., fertilizer applied to an agricultural crop), how the crop responds to its direct environment and management (weather, soil, and slope), and how water responds (both surface and groundwater) to the combination of plant growth processes and the direct physical environment (with some exceptional equations such as those used to simulate hydrologic response within urban areas).
>
> SWAT HRUs are aggregated into subbasins. Subbasins collect water and other pollutants generated by each of its HRUs, and either routes it through small surface flow paths (“tributaries”), or through sub-surface flow, which SWAT separates into interflow, shallow aquifer, and deep aquifer components.
>
> The combination of tributary and groundwater flow is then delivered to SWAT “reaches”. SWAT reaches represent streams and rivers. The primary properties of reaches in SWAT are geometric (e.g., length, width, depth, and gradient), however recent advances in SWAT allow users to simulate other water-quality processes within reaches, such as the deposition, re-suspension, and transformation of physical and chemical constituents though the alteration of water chemistry within models.

2.1.2. SWAT+

SWAT has undergone significant revisions in recent years, which have culminated in the creation of SWAT+ (Bieger, et al., 2017). SWAT+ utilizes the same basic algorithms as the original SWAT model, but SWAT+ has enhanced capabilities that provide additional flexibility when developing a watershed model. SWAT+ itself is a command-line executable file that runs on text file inputs, and revision 60.5.7 (SWAT Development Team, 2024a) was used for the FOXIL TMDL.

Two additional programs—QSWAT+ and SWAT+ Editor—are available from the SWAT development team to help facilitate the creation of the text input files. QSWAT+ is an interface that operates in QGIS, which is an open-source geographic information system software (QGIS.org, 2024). Initial setup for the FOXIL TMDL was completed using QSWAT+ version 2.4.7. The setup required uploading spatial data about land use, topography, and soils, which are described in the following sections. The SWAT+ Editor is a user interface that provides easy modification of SWAT+ inputs. SWAT+ Editor version 2.3.3 was used to upload climate and point source data and to make initial modifications to the model. A list of the software versions used for the development of the project are outlined in Table 2.1.

TABLE 2.1

Software Versions Used for SWAT+ Model Development

Software	Version	Reference
SWAT+ Executable	60.5.7	(SWAT Development Team, 2024a)
QSWAT+	2.4.7	(SWAT Development Team, 2024a)
SWAT+ Editor	2.3.3	(SWAT Development Team, 2024a)
QGIS	3.22.8	(QGIS.org, 2024)

2.2. Subbasin Delineation

The first step in the SWAT+ model configuration was delineation of subbasins. Subbasins were delineated to capture transitions in hydrology and water quality criteria. The following information was used to inform the extents of model subbasins:

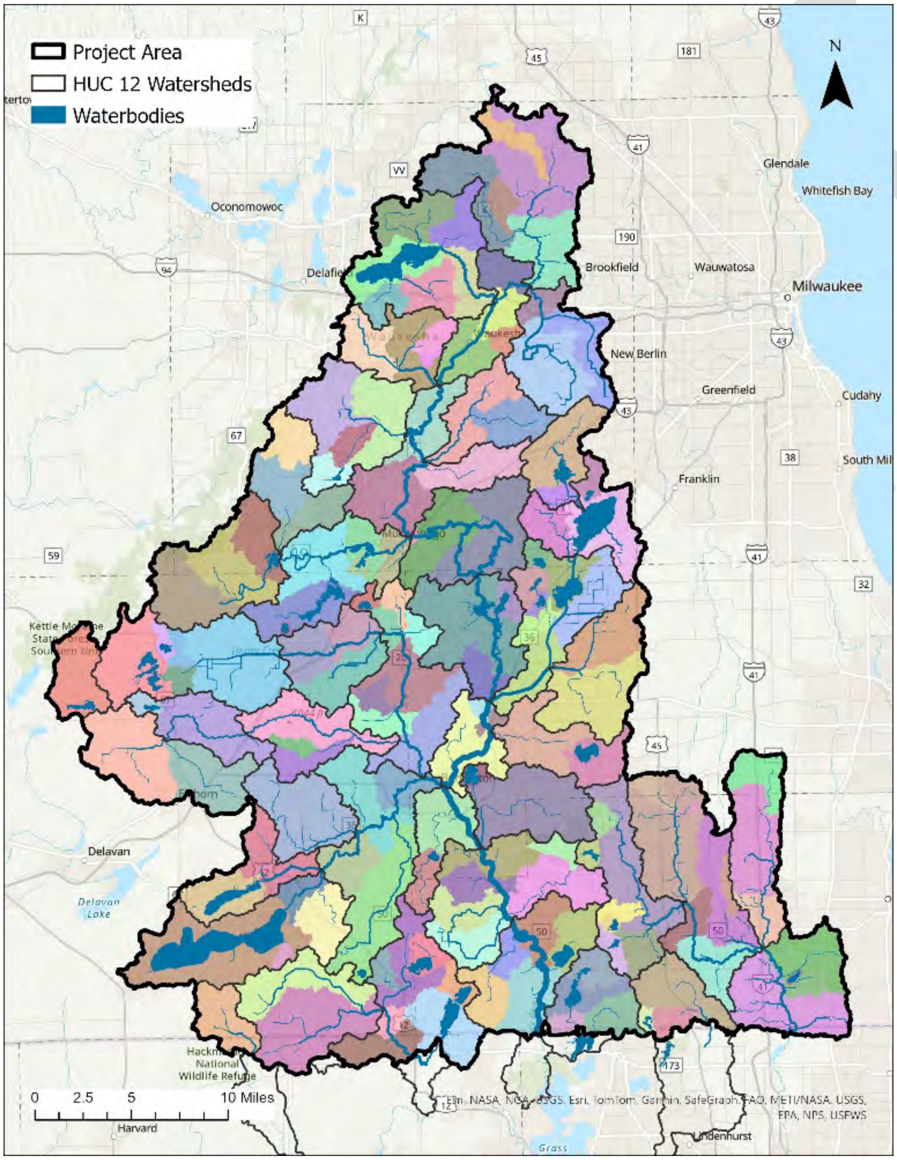
- HUC 12 watershed boundaries: Hydrologic unit code (HUC) 12 boundaries are standardized watersheds created and maintained by the United States Geologic Survey (USGS). The watersheds are widely recognized and commonly used for watershed-scale projects.
- Monitoring stations and USGS gages: The model was calibrated using data collected by the Department and by USGS, and the locations of the monitoring stations were used to identify downstream boundaries of the model subbasins.
- Permitted point source outfalls: Downstream boundaries for model subbasins were drawn to be located near permitted point source outfalls.
- Adaptive management plan points of compliance: Downstream boundaries for model subbasins were drawn to reflect the points of compliance for existing adaptive management plans developed under ch. NR217.18, Wis. Adm. Code.
- Water quality criteria: Downstream boundaries for model subbasins were drawn at locations where the river/stream water quality criteria for TP changes.
- River or stream impairment status: Downstream boundaries for model subbasins were drawn at locations where water quality impairments for TP or TSS change.
- Large lakes (>100 acres): Downstream boundaries for model subbasins were drawn for lakes with an area greater than 100 acres.

- WHDPlus subbasin boundaries: The Wisconsin Hydrography Dataset Plus (WHDPlus) dataset (Diebel, Menuz, & Ruesch, 2013) includes high-resolution subbasins for Wisconsin that are more detailed than the HUC 12s . Model subbasins were delineated by aggregating subbasins from WHDPlus.

Using the above information, 158 model subbasins were identified within the study area. The delineation resulted in model subbasins with an average size of approximately 4,400 acres (6.9 square miles). The final delineation of subbasins is shown in Figure 2.1.

FIGURE 2.1

Final Delineation of SWAT+ Model Subbasins



Esri, NASA, NGA, USGS, Esri, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, USFWS

2.3. Hydrologic Response Unit (HRU) Definition

The geospatial data were used to establish hydrologic response units (HRUs). HRUs were classified as unique combinations of land use, soils, and slope classes within each model subbasin. The initial model setup contained tens of thousands of the unique HRU combinations. Since the model simulates runoff and pollutant loading for each individual HRU, retaining the large number of HRUs would have resulted in impractically long run times.

As a result, the number of HRUs was decreased to a manageable quantity by setting a minimum area threshold based on land cover, soils, and slopes. The minimum area threshold prevents the definition of HRUs for land cover and soil classes that cover only a small proportion of a subbasin, thereby reducing the total number of HRUs and improving model efficiency. When selecting minimum area thresholds, the Department weighed implications for model efficiency (fewer HRUs resulting in shorter runtimes and allowing for additional fine-tuning of model parameters during calibration) and the resolution needed for TMDL development. The selected area thresholds were determined through an iterative process, where an initial set of values was selected and refined based on the effects on model efficiency and resulting level of detail. After the consolidation and summary of geospatial data, a total of 6,738 HRUs were defined for the study area. Details about the datasets and the minimum thresholds are described below.

2.3.1. Land Cover and Land Management

Land cover and land management were an important input for the SWAT+ model. Wiscland 2, which is a land cover database developed by the Department and other partners (Wisconsin Department of Natural Resources, 2016), was used as a baseline for defining land use and land management. Modifications and enhancements to the Wiscland 2 dataset were required to ensure the land cover and land management inputs to the SWAT+ model adequately represented existing conditions on the landscape. The following sections describe the processes for determining land cover and land management. A more thorough explanation of the process is provided in Appendix A.

2.3.1.1. Wisconsin Land Cover

The initial land cover dataset for the model was developed from the Wiscland 2 land cover dataset (Wisconsin Department of Natural Resources, 2016). The Wiscland 2 dataset was summarized into 10 main categories: open water, forest, wetland, grassland, pasture, continuous corn, corn grain, dairy rotation, urban high-density, and urban low-density. The summarized land cover dataset was provided to county conservationists in Waukesha, Walworth, Racine, and Kenosha County for their review. The county conservationists provided input about areas where land cover data from Wiscland 2 did not accurately reflect current land cover, either due to limitations in the Wiscland 2 dataset or changes in land use since the dataset was developed. Details about the changes proposed by the county conservationists are provided in a report about agricultural surveys that were presented to the county conservationists (Wisconsin Department of Natural Resources, 2023a).

A summary of the survey methods and results is provided in the Agricultural survey summary. Results of the agricultural survey were aggregated to represent the dominant agricultural practices in each sub-model. This aggregation was appropriate because the purpose of the SWAT+ model is to estimate subbasin-scale sediment and phosphorus loads, thus the inclusion of fine-level agricultural practices in the SWAT model does not provide added value to the TMDL calculation at the subbasin scale. However, the overall complexity of the data received from this survey is intended to be used for TMDL implementation. This approach of using land cover datasets to map crop types and local knowledge of county LWCDs to determine typical farming practices associated with each crop is consistent with methods described by Kirsch et al. (2002), Larose et al. (2007), and Heathman et al. (2008).

2.3.1.2. Illinois Land Cover

The Wiscland 2 dataset only includes information about land cover within the boundaries of Wisconsin. In the southern portion of the study area, some land areas within Illinois drain into waterbodies located in Wisconsin. A supplemental land cover dataset was developed to represent these land areas in Illinois. The general methodology used in the development of the Wiscland 2 dataset was applied to Illinois to establish a land cover dataset for Illinois that was consistent with the land cover dataset in Wisconsin. The methodology utilized twelve years of data from the Cropland Data Layer (United States Department of Agriculture, 2022) and a definition of field boundaries from the Ag Data Commons (James & Tomer, 2021). Additional information about the development of the Illinois Land Cover dataset is provided in Appendix A.

2.3.1.3. Land Management

Once a land cover dataset that accurately represented land use in the study area was established, land management practices for agricultural lands were evaluated. Information about crop rotations and tillage practices was provided by county conservationists. Crop rotations and tillage practices were combined to define unique agricultural land cover and land use categories. The final land cover and land use dataset for the model configuration included two tillage practices for continuous corn, three tillage practices for cash grain, and two tillage practices over two unique crop rotations for dairy rotations. Additional details about the crop rotations and tillage practices are provided in Section 3.1.

2.3.1.4. Final Land Management and Land Cover Dataset for HRU Definition

Land use and land management practices for Wisconsin and Illinois were combined into a single dataset. To reduce the total number of HRUs in the model, the dataset was simplified to remove land uses with very small areas. Main agricultural categories—continuous corn, cash grain, and dairy—were split based on tillage and crop rotation. The minimum area threshold approach in QSWAT+ would have removed a number of these sub-divided land use classes, so a custom approach to establish a minimum area threshold for land cover had to be developed. The methodology to adjust the land cover dataset was adapted from the DNR's Northeast Lakeshore TMDL (Wisconsin Department of Natural Resources, 2023c) and is described in detail in Appendix A.

2.3.2. Slope

A gridded slope dataset for the study area was created within the QSWAT+ GIS interface using a 30-meter DEM grid (Wisconsin Department of Natural Resources, 2019), which is derived from the 7.5 minute DEMs published by USGS. Slope classes were consolidated by using a single slope classification for the entire study area, so no minimum threshold for HRU determination had to be established. The DEM and the slopes calculated by QSWAT+ are provided in Appendix A.

2.3.3. Soils

Soil types for the model were characterized using the gridded Soil Survey Geographic (gSSURGO) dataset (Soil Survey Staff, 2022) for Wisconsin and Illinois. The gridded soil rasters were incorporated into the model using the QSWAT+ GIS interface, and the relevant soil parameters were automatically cross-referenced within a soils database built into SWAT+. The SSURGO, rather than STATSGO, was selected for incorporation into the watershed model because previous research has indicated that high resolution soils datasets tend to provide more accurate results in hydrologic and water quality modeling (Mendick, Sullivan, & Watermolen, 2008).

The extent of all SSURGO soil components is displayed in Appendix A. For HRU determination soils were consolidated by setting a minimum area threshold of 6 percent. Areas containing soil types that did not meet the 6 percent threshold were redistributed to the remaining soil types in each subbasin. The redistribution of soil classes was performed by QSWAT+.

2.4. Weather and Climate Data

SWAT+ uses average daily precipitation, daily maximum and minimum temperature, solar radiation, relative humidity, and wind speed for its calculations. The SWAT+ model contains weather generators to develop climate datasets based on location. For the development of the watershed model, however, site- and time-specific climate data was incorporated to ensure a more accurate representation of the model.

Precipitation, temperature, solar radiation, and relative humidity data were downloaded from Daymet (Thornton, Shrestha, Wei, Thornton, & Kao, 2022). Daymet is a gridded, continuous dataset with 1 square kilometer resolution for the entire contiguous United States. The project is led by the National Aeronautics and Space Administration (NASA). The Daymet website includes a Single Pixel Extraction Tool that was used to download daily weather data. The center point of each SWAT subbasin was input to the Single Pixel Extraction Tool to acquire weather data for each subbasin. The precipitation, temperature, and solar radiation values from Daymet were input to SWAT directly. Data from Daymet required two adjustments to ensure consistency with the inputs required by SWAT+. First, the downloaded Daymet data only provides 365 days of climate data for each year starting on January 1st. As a result, the final day of the year for leap years was not available. For these years, the 366th day of the year (December 31st) was set equal to data from the 365th day (December 30th).

Additionally, the Daymet data provided information about vapor pressure, but the SWAT+ model required inputs for relative humidity. Relative humidity was calculated by estimating the saturated vapor pressure from the Antoine equation (Equation 2.1) and dividing the measured vapor pressure by the saturated vapor pressure (Equation 2.2).

$$\log_{10} P_{sat} = 8.1 - \frac{1731}{233+T}$$ Equation 2.1

P_{sat}: Saturated vapor pressure (mmHg)
T: Average daily temperature (K)

$$RH = \frac{e_{vp}}{P_{sat} * C}$$ Equation 2.2

e_{vp}: Observed vapor pressure (Pa)
P_{sat}: Saturated vapor pressure (mmHg)
C: 133.32 Pa/mmHg

Potential Evapotranspiration (PET) is simulated within SWAT using the Penman-Monteith equation. The Penman-Monteith equation estimates PET using the observed daily temperature, precipitation, and solar radiation data described in the previous section. Previous SWAT modeling in Wisconsin has demonstrated the Penman-Monteith equation is optimal for ET simulation (Wisconsin Department of Natural Resources, 2016)

When the Penman-Monteith method is selected to calculate potential evapotranspiration, SWAT requires wind speed data. Wind speed data were not available from Daymet, so average daily wind speeds were downloaded from the National Centers for Environmental Information's Climate Data

Online tool (National Centers for Environmental Information, 2024). Average daily wind speed across the study area was assumed to be similar, so daily wind data for the Kenosha Regional Airport (USW00004845) was applied across the entire study area.

2.5. Point Sources

Permitted point sources include both individual wastewater permits and permits from municipal separate storm sewer systems (MS4s). Direct loads from facilities with individual wastewater permits were incorporated directly in the model, and areas within MS4 areas were delineated as separate land use categories within SWAT+.

2.5.1. Individual Wastewater Permits

A complete inventory of individual wastewater permits was conducted to identify all facilities permits to discharge wastewater to surface water through the Wisconsin Pollutant Discharge Elimination System (WDPES). Within the study area, 27 facilities with individual WPDES permits were identified. The wastewater facilities identified included 17 municipal facilities, six private facilities, three industrial facilities, one state facility. The exact location of the outfalls for each wastewater facility was confirmed through consultation with regional DNR staff. A full list and a map of the facilities is provided in Appendix B.

Data for discharge volume, TP, and TSS were downloaded from the Department's System for Wastewater Applications, Monitoring, and Permits (SWAMP) database, which consolidates all data submitted to the Department from individual facilities. Point source data were loaded into the SWAT+ model as daily averages for each month.

Discharge volumes, TSS loads, and TP loads were estimated for each facility using monthly and annual discharge monitoring record summaries acquired for the period 2001 through 2022. Any missing records for flow volume, TP, or TSS data were populated with:

- the overall average value for the facility;
- zero for periods identified as months without discharge; or,
- an estimate provided by the facility and verified by Department wastewater staff.

Point source discharge volumes and loads were input to SWAT+ as monthly values and were assigned to subbasins. SWAT+ allows phosphorus loads to be entered as soluble inorganic phosphorus, organic phosphorus, or a combination of the two. Point source phosphorus loads input to SWAT+ were assumed to take the form of soluble phosphorus.

2.5.2. Permitted Municipal Separate Storm Sewer Systems

Urban areas in the SWAT+ model were separated into two categories: urban areas covered by WPDES Municipal Separate Storm Sewer System (MS4) permits and urban areas not covered under an MS4 permit. The categories were established by determining the geographic extent of the permitted MS4s in the study area.

To identify the permitted MS4 boundaries, a list a list of all entities with active MS4 permits was developed. Within the study area thirty-six entities—8 cities, 17 villages, 8 towns, and 3 counties—were identified. The political boundaries of the permitted entities (Wisconsin Legislative Technology Services Bureau, 2022) was overlaid with the 2010 Urban Area boundaries from the U.S. Census Bureau (United States Census Bureau, 2017).For cities and villages, the entire corporate boundaries were identified as the permitted MS4 boundaries. For towns and counties, the urbanized areas within the boundaries were identified as permitted MS4 boundaries. A complete list and a map of permitted entities are provided in Appendix B.

The method for determining permitted MS4 boundaries for this watershed model is based on the protocol that was commonly used over the last many decades. However, for the 2020 Census, the Census Bureau made changes to its definition of urban areas (Ratcliffe, 2022). As a result, the Environmental Protection Agency has updated the methods for classifying permitted MS4 areas. The change, however, is not considered for this project because it does not impact existing MS4 permits.

3. ADDITIONAL MODEL CONFIGURATION

After the initial model configuration steps detailed in Section 2 were completed, additional information was incorporated into the model. This information included details about agricultural operations, soil phosphorus concentrations, urban areas, reservoirs , and groundwater. Details of these data are provided in the following sections.

3.1. Agricultural Operations

A comprehensive survey about agricultural practices was sent to County Conservationists in Waukesha, Walworth, Racine, and Kenosha Counties. The surveys requested information about land cover and land management practices. The results of the survey are summarized in a report from DNR (Wisconsin Department of Natural Resources, 2023a), and the basic highlights are provided below. Details regarding management practices incorporated into the SWAT+ model are provided in Appendix C.

3.1.1. Crop Rotations

County conservationists provided information about crops used in different rotations for cash grain and dairy. Nearly all cash grain rotations were defined as corn grain followed by soybeans, so a single rotation for cash grain was used. Two distinct rotations for dairy were identified. One rotation included two years of corn silage followed by one year of soybeans and winter wheat followed by three years of alfalfa. The other rotation included three years of corn silage followed by three years of alfalfa.

3.1.2. Tillage

County conservationists identified a number of tillage practices that occur within their respective counties. Predominant tillage practices for each of the agricultural land use categories—cash grain, continuous corn, and dairy rotations—were selected from the survey and were incorporated into the model. Table 3.1 summarizes the tillage practices that were included in the model.

TABLE 3.1

Tillage Practices Included in SWAT+ Model

Land Use	ID	Tillage details
Cash Grain	1	Fall: Chisel Plow Spring: Cultivator (2 passes)
	3	Fall: None Spring: Vertical
	5	Fall: Vertical Spring: Cultivator
Continuous Corn	1	Fall: Chisel Plow Spring: Cultivator (2 passes)
	3	Fall: None Spring: Vertical
Dairy Rotation	1	Fall: Chisel Plow Spring: Cultivator (2 passes) *Note: No tillage during years with alfalfa*
	2	Fall: Vertical Spring: Cultivator *Note: No tillage during years with alfalfa*

3.1.3. Inorganic Fertilizers and Manure

The county conservationists also provided estimates for the amounts of inorganic fertilizer and manure applied to different crop rotations. Since phosphorus was the primary constituent of interest being modeled, only the direct application of phosphorus in fertilizer was incorporated into the SWAT+ model. Nitrogen fertilizers were included in the model using the automatic fertilization routine built within the SWAT+. The automatic fertilization routine ensures plants never reach a deficit of the nitrogen, and its use is important to ensure crop growth is not nitrogen limited.

The estimates for manure application rates were characterized as either daily haul or liquid applications of manure. To simplify the SWAT+ model, however, all manure was estimated to be applied as liquid manure twice per year. Inorganic fertilizer was applied at a schedule defined in the agricultural surveys. Table 3.2 provides a summary of the inorganic and manure fertilizer applications that were utilized in the model.

TABLE 3.2

Inorganic Fertilizer and Manure Applications

Crop	Fertilizer Application
Cash Grain	Apr. 30: 17.5 lb P_2O_5/ac (Inorganic fertilizer) Jun. 30: 17.5 lb P_2O_5/ac (Inorganic fertilizer)
Continuous Corn	Apr. 30: 17.5 lb P_2O_5/ac (Inorganic fertilizer) Jun. 30: 17.5 lb P_2O_5/ac (Inorganic fertilizer)
Dairy Rotations	Apr.14: 37.5 lb P_2O_5/ac (Liquid manure) Nov. 1: 37.5 lb P_2O_5/ac (Liquid manure) *Note: No fertilizer applications applied during years with alfalfa*

3.1.4. Tile Drainage

Cultivated areas in the southeastern portion of the study area, particularly in the Des Plaines River basin, utilize tile drainage to maintain suitable moisture in the fields. The exact geographic extent of tile drainage is not readily available; however, basin-specific estimates of the percent of fields that are tiled drained were provided by the county conservationists. To simplify the model, all fields within the Southern Lake Michigan Coastal Ecological Landscape were classified as fields with tile drainage. The extent of the Southern Lake Michigan Coastal Ecological Landscape is defined by DNR (Wisconsin Department of Natural Resources, 2015), and additional details about the extent are provided in subsequent chapters.

Tile drainage was not explicitly modeled using the built-in tile drainage algorithms included in SWAT+. Instead, parameters for fields classified as tile drainage were independently adjusted during the calibration process. Additional details about the calibration are provided in subsequent chapters.

3.2. Soil Phosphorus

Estimates of soil phosphorus concentrations were also incorporated into the initial model setup. The estimates were determined from information provided by county conservationists in the agricultural surveys. When available, soil phosphorus concentration was estimated for each HUC 12 in the study area. In areas where soil phosphorus concentration data were not available, estimates from adjacent HUC 12s were used as an estimate. Soil phosphorus concentration estimates ranged from 30 parts per million to 70 parts per million. Details about soil phosphorus concentration by HUC 12 is provided in a report summarizing the agricultural surveys (Wisconsin Department of Natural Resources, 2023a).

3.3. Urban Area Model

The SWAT+ model contains two routines for estimating phosphorus and sediment loads from the impervious portions of urban areas: USGS regression equations and build-up/wash-off functions. For the FOXIL SWAT+ model, the USGS regression equations were selected because they provided a better overall fit during calibration of the model. Additional details about the regression equations are provided in the original SWAT documentation (Arnold, et al., 2012) and the SWAT+ Theoretical Documentation (SWAT Development Team, 2024b).

The USGS regression equations estimate loads from impervious areas, but SWAT+ also estimates phosphorus and sediment loads from pervious urban areas. Loads from pervious urban areas are estimated using the standard equations for loading in SWAT+, although a specific plant community must be specified. For the FOXIL SWAT+ model, urban cool-season grass was selected as the appropriate plant community.

The total load from urban areas was determined in the model by adding the loads from impervious and pervious areas. For the FOXIL SWAT+ model, urban areas were defined into two categories: low-density and high-density urban. Low-density urban areas were classified as low-density residential, which assumes 12 percent impervious areas and 88 percent pervious areas. High-density urban areas were classified as medium-density residential, which assumes 38 percent impervious and 62 percent impervious. The classification of high-density urban areas as medium-density residential is consistent with past TMDLs that have been developed by the Department.

3.4. Reservoirs

All lakes and reservoirs over 100 acres within the study area were incorporated into the SWAT+ model as reservoir features. The study area contained 37 lakes and reservoirs that met this classification. The area and volume of the lakes and reservoirs were estimated from lake survey maps available from the DNR (Wisconsin Department of Natural Resources, 2024a). A list of the lakes and their properties are provided in Appendix D.

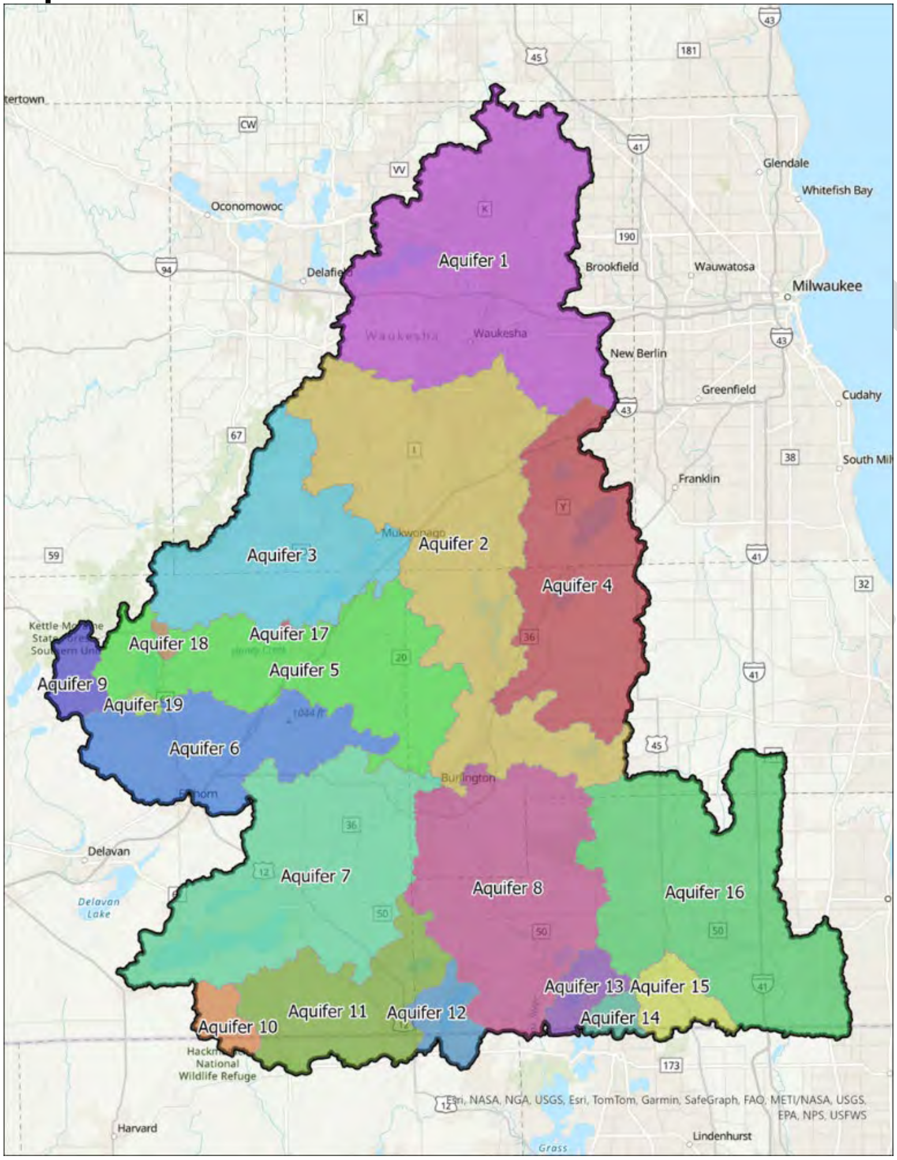
Reservoirs in the SWAT+ required information about surface area and volume at both the principal and emergency spillway. SWAT+ dynamically estimated reservoir surface area based on the information about principal and emergency spillway volumes. Accurate representation of lake surface area was important because the surface area is used to estimate evapotranspiration and direct precipitation. To ensure accurate representation of surface area, the principal and emergency spillway parameters were calculated based on the actual area and volume of the lakes. Information about the equations used to estimate surface area are provided in the SWAT+ theoretical documentation (SWAT Development Team, 2024b).

To characterize reservoir release rates, the SWAT+ model utilized decision tables. Decision tables allowed the timing and the rate of release from reservoirs to be characterized. For the FOXIL SWAT+ model, a simplified reservoir release using the *drawdown days* routine was used. In the *drawdown days* routine flows from the reservoir were released over a specified number of days whenever the volume exceeded the specified principal spillway volume. Values for drawdown days were initially set at 1 day but were subsequently adjusted during the calibration process.

3.5. Groundwater

One of the major changes to SWAT+ compared with SWAT was the simulation of groundwater aquifers. The original SWAT model defined one aquifer per HRU, whereas SWAT+ establishes aquifers independent from HRUs. For the FOXIL SWAT+ model, the extents of the aquifers were delineated to match the HUC 10 boundaries. Additional aquifers were added to areas with internally drained lakes and lake basins with outlets at the Illinois border. Nineteen aquifers were defined for the project area, and parameters for each of these aquifers was adjusted during calibration. The extent of the aquifer boundaries used in the model is presented in Figure 3.1.

FIGURE 3.1
Aquifers Defined in FOXIL SWAT+ Model



Esri, NASA, NGA, USGS, Esri, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, USFWS

4. CALIBRATION AND VALIDATION DATASETS

Estimates of actual flows and loads were essential for calibrating and validating the model and ensuring the model accurately represented real conditions. Data required for model evaluation included crop yield, streamflow, sediment yield, and phosphorus yield. The following sections describe the processes used to develop calibration and validation datasets.

4.1. Crop Yield Data

Accurate representation of crop growth is an important component of watershed modeling because crop growth impacts water balance through water uptake and evapotranspiration and nutrient cycling through nutrient uptake. Crop yield data were available from estimates from the county conservationists (Wisconsin Department of Natural Resources, 2023a) and from the National Agricultural Statistics Services Quick Stats Database (USDA National Agricultural Statistics Service, 2011-2022).

Yield data for corn, corn silage, soybeans, alfalfa, and winter wheat were downloaded from Quick Stats for every year between 2011 through 2022. Since yearly data were used, data from the NASS Survey rather than the NASS Census were used. Yield statistics used for model comparison were annual averages of yield data collected for Kenosha, Racine, Walworth, and Waukesha Counties. SWAT+ reports yield data in metric tons per hectare, but NASS provides results in either bushels per acre or short tons per acre. To compare the model results to the NASS survey results, NASS results had to be converted using standard published unit conversion factors and moisture content. The conversion factors used in the Wisconsin River TMDL (Wisconsin Department of Natural Resources, 2019) were also used for this analysis. A summary of the annual average crop yields and the relevant conversion factors are provided in Appendix E.

4.2. Water Chemistry and Discharge Monitoring Summary

Monitoring for the FOXIL Basin TMDL was conducted between December 2019 and May 2022. The monitoring program was required to ensure sufficient data were available for the calibration and validation of the watershed model. Water level, flow, and water chemistry data were all collected during the monitoring period. A summary of the monitoring program is provided below, but a comprehensive report detailing the monitoring efforts are available in a separate report (Wisconsin Department of Natural Resources, 2023b)

4.2.1. Water Chemistry

Water chemistry data were collected at thirteen locations in the study area. Water samples at five sites were collected by the Department, and samples at the remaining eight sites were collected by a private consultant, Cadmus, under contract with U.S. Environmental Protection Agency. Water samples were evaluated for TP, orthophosphate, and TSS. A list of the monitoring stations is provided in Table 4.1, and the locations of the stations are displayed in Figure 4.1.

TABLE 4.1

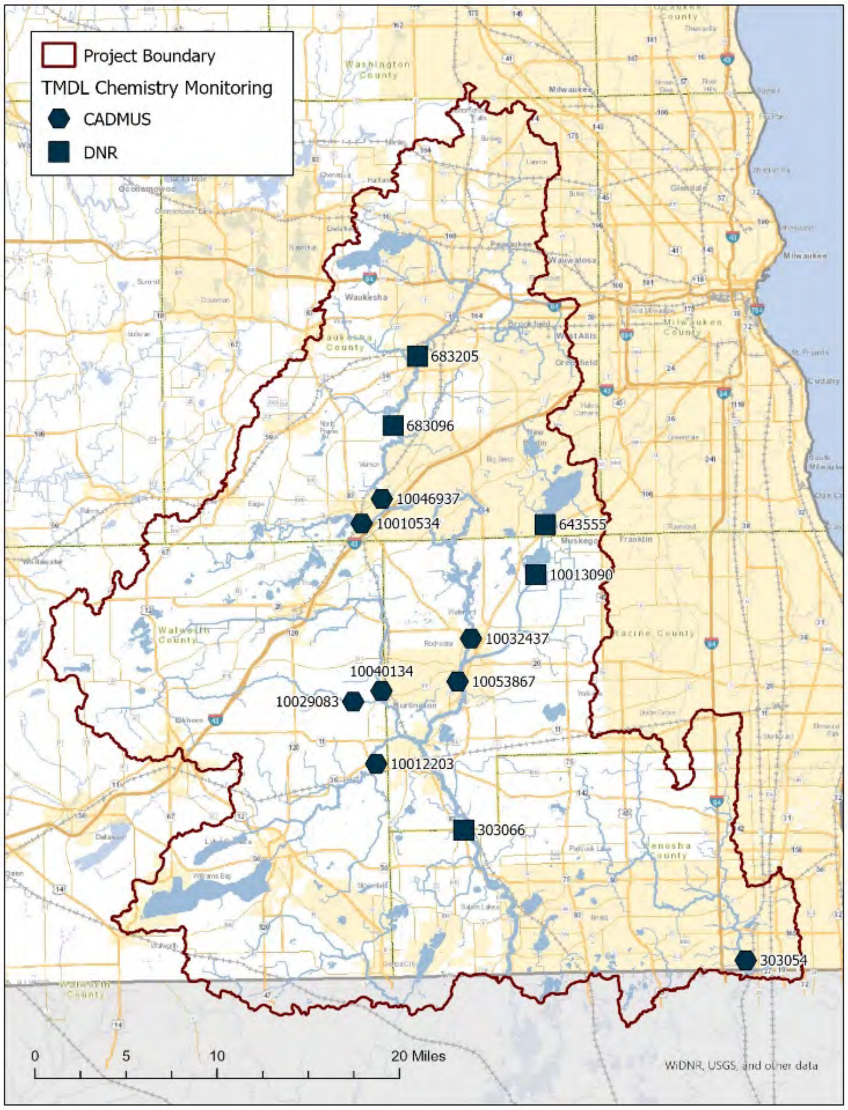
Fox Illinois River TMDL Chemistry Monitoring Sites

SWIMS ID	SWIMS Station Name	Monitoring Entity	Chemistry Parameters
683205	Fox River - Ds Sunset Dr Bridge (Waukesha)	DNR	TP, TSS
683096	Fox River at Cth I Bridge	DNR	TP, TSS, TN, DOP, NO3, NH4
10046937	Fox River at CTH ES	Cadmus	TP, TSS, DOP
303066	Fox River (Il) - Nr New Munster Cthjb	DNR	TP, TSS, TN, DOP, NO3, NH4
10032437	Fox River at STH 20/30 Waterford	Cadmus	TP, TSS, DOP
10053867	Fox River at Case Eagle Park Bridge[1]	Cadmus	TP, TSS, DOP
10010534	Mukwonago River (1) - Upstream of HWY 83	Cadmus	TP, TSS, DOP
643555	Muskego (Big Muskego) Lake - Outlet Near Wind Lake	DNR	TP, TSS
10013090	Wind Lake Canal_Wind Lake Upstream To Ceasars Dam	DNR	TP, TSS
10040134	Honey Creek at CTH DD/Academy Rd	Cadmus	TP, TSS, DOP
10029083	Sugar Creek at Potter Road	Cadmus	TP, TSS, DOP
10012203	White River - 10 M Upstream Of Hwy 36	Cadmus	TP, TSS, DOP
303054	Des Plaines River at Cth ML	Cadmus	TP, TSS, DOP

1. The Fox River at Case Eagle Park replaced an original monitoring site at Fox River above Rochester Dam at Highway D (10021230) due to unsatisfactory conditions at the original site.

Parameters: DOP = Dissolved orthophosphate, NH4 = Ammonium, NH3 = Nitrate, TN = Total Nitrogen, TP = Total Phosphorus, TSS = Total Suspended Solids

FIGURE 4.1
Fox Illinois River TMDL Chemistry Monitoring Locations



4.2.2. Stage and Flow

Stage and flow monitoring data were also collected during the monitoring period. The Department collected periodic flow measurements and continuous stage data at five sites and periodic flow data at four sites. The sites with only flow measurements were located near gages maintained by the USGS that had stage data available. A summary of the stage and flow monitoring sites is provided in Table 4.2, and the location of each site is provided in Figure 4.2.

TABLE 4.2

Fox Illinois Rivers TMDL Stage and Flow Monitoring Sites

Stage and Flow Measurement Location	Stage data	Flow Data
Fox River at Cth I	DNR	DNR
Fox River at CTH ES	DNR	DNR
Honey Creek at Academy Road	DNR	DNR
Sugar Creek at Potter Road	DNR	DNR
White River at Hwy 36	DNR	DNR
Fox River downstream of Waterford Dam	USGS	DNR
Fox River downstream of Rochester Dam	USGS	DNR
Muskego Canal at Muskego Dam Road	USGS	DNR
Wind Lake Outlet at South Wind Lake Road	USGS	DNR

FIGURE 4.2

Fox Illinois River TMDL Stage and Flow Monitoring Locations

4.3. Continuous Flow Estimation

Model calibration required datasets with continuous flow estimates. Continuous flow datasets were available from sites with USGS flow monitoring, but the datasets had to be estimated at all other sites. Two methods were used to establish continuous flow estimates, and the two methods are described in the following sections.

4.3.1. Stage-Discharge Relationships

Rating curves developed using a stage-discharge relationship use continuous stage data and periodic flow measurements to estimate continuous flows. Stage and discharge data at all monitoring locations were reviewed to determine where and when stage-discharge relationships could be developed. Use of stage-discharge to estimate continuous flow was determined to be appropriate at five sites: Honey Creek, Sugar Creek, White River, Muskego Lake, and Wind Lake.

At the five sites, stage-discharge pairs were fit using an exponential curve using methods detailed in a paper by Hamilton and others (Hamilton, Watson, & Pike, 2019). The standard form of the equation is provided in Equation 4.1.

$$Q = C_0(H - e)^B \qquad \text{Equation 4.1}$$

In the equation, discharge (Q) depends on a coefficient (C_0), an offset (e), the stage (H), and an exponent (B). The offset is an adjustment that approximates the stage at which the discharge is equal to zero. The coefficient and exponent define the shape of the stage-discharge relationship. The value of all equations can be estimated based on physical properties of the stream at which the curve is being developed. Detailed information about the development of the rating curves is provided in a separate report (Wisconsin Department of Natural Resources, 2024b)

Two of sites utilizing the stage-discharge relationship—Muskego Lake and Wind Lake—were located at the outlet of lakes that are controlled by dams. The dams were operated to ensure a minimum water level at different points during the year. As a result, no flow was released through the dam into the downstream channels. Stage data both upstream and downstream of the dam were available at the two sites. The stage data along with flow measurements in the downstream channels were used to predict when no flow was being released from the lakes. During these periods, flow in the downstream channel was set to zero. Additional details about the determination of these periods aree described in a separate report (Wisconsin Department of Natural Resources, 2024b).

4.3.2. Linear Regression Relationships

Developing reliable stage-discharge estimates at three sites—Fox River at CTH I, Fox River at Waterford, and Fox River at Rochester—was not possible with available data. For the Fox River at CTH I, issues with the continuous stage monitoring limited the number of days available for generating the estimates. At the Fox River at Waterford and Fox River at Rochester, the stage is impacted by the presence of dams, so an accurate stage-discharge estimate could not be established.

Continuous discharge data from USGS gages near the Fox River sites were available. The USGS data were paired with the periodic flow measurements collected at the sites to develop a relationship between flows at the USGS stations and flows at the monitoring sites of interest. The relationship was applied to the USGS flow data to generate continuous flow measurements at the three sites. More information about the methods and the results is provided in a separate report (Wisconsin Department of Natural Resources, 2024b).

4.4. Load Estimation

Continuous daily loads for TP and TSS were estimated at each site in the monitoring network. Loads were estimated using a modified version of the Fluxmaster and LOADEST methods developed by USGS (Schwarz, Hoos, Alexander, & Smith, 2006). Details about the modified methods are provided in a separate report (Wisconsin Department of Natural Resources, 2024b) and in Appendix J of the DNR's Northeast Lakeshore TMDL (Wisconsin Department of Natural Resources, 2023c). The continuous daily load estimates were used during the calibration and validation of the SWAT+ model.

4.5. Reservoir Phosphorus Concentrations

Of the 37 lakes and reservoirs represented in the model, 22 had sufficient data to have its impairment status assessed using Wisconsin's Consolidated Assessment and Listing Methodology (Wisconsin Department of Natural Resources, 2024c). The remaining 15 lakes lack sufficient data for an impairment status to be assessed. Lake phosphorus assessments are determined using phosphorus samples from June 1 through September 15. Phosphorus estimates for assessed lakes in the study area were downloaded from the Water Assessment Tracking and Electronic Reporting System (Wisconsin Department of Natural Resources, 2024d). The data also included the TP impairment threshold, which is based on specific lake morphology. When assessed concentrations exceed the TP impairment threshold, the waterbody is listed as impaired. Impairment status is an important consideration when evaluating the accuracy of the watershed model because it can be used to verify whether or not the model is accurately representing the impairment status. A summary of available phosphorus estimates for the 22 lakes are provided in Appendix E.

5. MODEL CALIBRATION AND VALIDATION APPROACH

Once the SWAT+ model was set up using the steps in Sections 2 and 3, the model was run and the results were compared to the calibration datasets described in Section 4. Model parameters were adjusted in a systematic way, detailed below, until the modeled results adequately matched the results generated from the load and flow estimates. The full calibration and validation process is described in the following sections.

5.1. Calibration Software

A number of software options were available to adjust model parameters and calibrate the SWAT+ model. Four software packages were considered for the calibration process: SWAT+ Editor, SWAT+ Toolbox, SWATplus-CUP, and SWATrunR. Table 5.1 provides an overview of the different options and their advantages and disadvantages.

TABLE 5.1

Software Options Available for SWAT+ Model Calibration

Parameter Name	Description	Advantages	Disadvantages
SWAT+ Editor (SWAT Development Team, 2024b)	*A user interface for modifying SWAT+ inputs and running the model*	Same interface used for model setup Simple checks to identify model problems	Lacking automated tools for sensitivity analysis and calibration
SWAT+ Toolbox (Chawanda, 2024)	*SWAT+ Toolbox is a free tool that allows the user to perform sensitivity analyses, calibration and more. The software has been written in C# and is available for the Windows operating system.*	Free Easy-to-use interface Built-in sensitivity analysis and calibration tools	Unstable performance with large model
SWATplus-CUP (Abbaspour, 2022)	*SWATplus-CUP is a program for the calibration of SWAT+ models. The program performs single, behavioral, and multi-objective calibration, validation, sensitivity analysis (one-at-a-time and global), and uncertainty analysis.*	Built-in sensitivity analysis and calibration tools Easy-to-use interface SWAT-CUP widely used by WDNR and others	Paid license required
SWATrunR (Schuerz, 2019)	*SWATrunR integrates your SWAT2012 and SWAT+ projects in R modeling workflows. SWATrunR's key function is to execute SWAT in a project folder located on a hard drive and return simulation results in R.*	Easy-to-use package within R Customizable Efficient model runs using SWAT+ executables	Lacking tools for visualizations and fit statistics

After evaluating the strengths and limitations of the calibration options, SWATrunR was chosen as the primary tool for facilitating the calibration and validation process.

5.1.1. SWATrunR R Package

SWATrunR (Schuerz, 2019) is a package within the R software environment (R Core Team, 2022) that integrates SWAT+ modeling into R modeling workflows. SWATrunR provides a user-friendly approach to control essential model parameters using functions built into the package. The package allows for easily parallel processing, which allows multiple simulations to be performed simultaneously and increases the efficiency of sensitivity analysis and calibration. Specified model output is stored in an R dataframe that facilitates easy processing and evaluation.

Version 0.2.7 of the SWATrunR package was loaded into version 2022.07.2.576 of RStudio (RStudio Team, 2022). Version 60.5.7 of the SWAT+ executable file was used for all model simulations.

5.1.2. SWAT+ Editor and SQLite Studio

After a SWAT+ model is set up, model inputs are stored in a SQLite database (Hipp, 2024). The SWAT+ Editor reads data from the SQLite database and writes .txt files that are utilized by the SWAT+ executable file.

During the calibration of the FOXIL SWAT+ model, some model inputs were adjusted within the SQLite database using Version 3.2.1 of SQLite Studio (Salawa, 2019). Once model inputs were adjusted in the SQLite database, the SWAT+ editor was run to translate the database into usable .txt files.

5.1.3. Text Editors for SWAT+ Input Files

Some parameters were not able to be changed using the calibration framework within SWAT+ and SWATrunR, so the values had to be manually adjusted in the .txt files generated by the SWAT+ editor.

5.2. Sensitivity Analysis

The first step in the model calibration process was determining which model parameters had the biggest impacts on flow, TSS, and TP. To identify the most important parameters, a sensitivity analysis was conducted on a set of 55 parameters that could be adjusted in the SWATrunR software. The 55 parameters were selected based on a literature review conducted during the Department's Wisconsin River Basin TMDL (Wisconsin Department of Natural Resources, 2019) and subsequent TMDL studies.

The sensitivity analysis was performed using Morris' method for parameter screening (Morris, 1991). The method is a one-at-a-time sensitivity analysis which runs the model by adjusting the value of one parameter while keeping all other parameters constant. This approach allows the impact of each parameter tested to be isolated and assessed. The sensitivity analysis approach was adapted from the SWATrunR documentation (Schuerz, 2024) and utilizes the *sensitivity* package in R (Iooss, Veiga, Janon, & others, 2023). Inputs used for the sensitivity analysis and the results are provided in Appendix E. The results were used to guide decisions about which parameters to adjust during the calibration process.

5.3. Calibration and Validation Strategy

Determination of appropriate calibration and validation time periods, assessment of locations with similar hydrologic features, and selection of appropriate model performance statistics were important components of the calibration and validation strategy. The components of the calibration and validation strategy are summarized in the following sections.

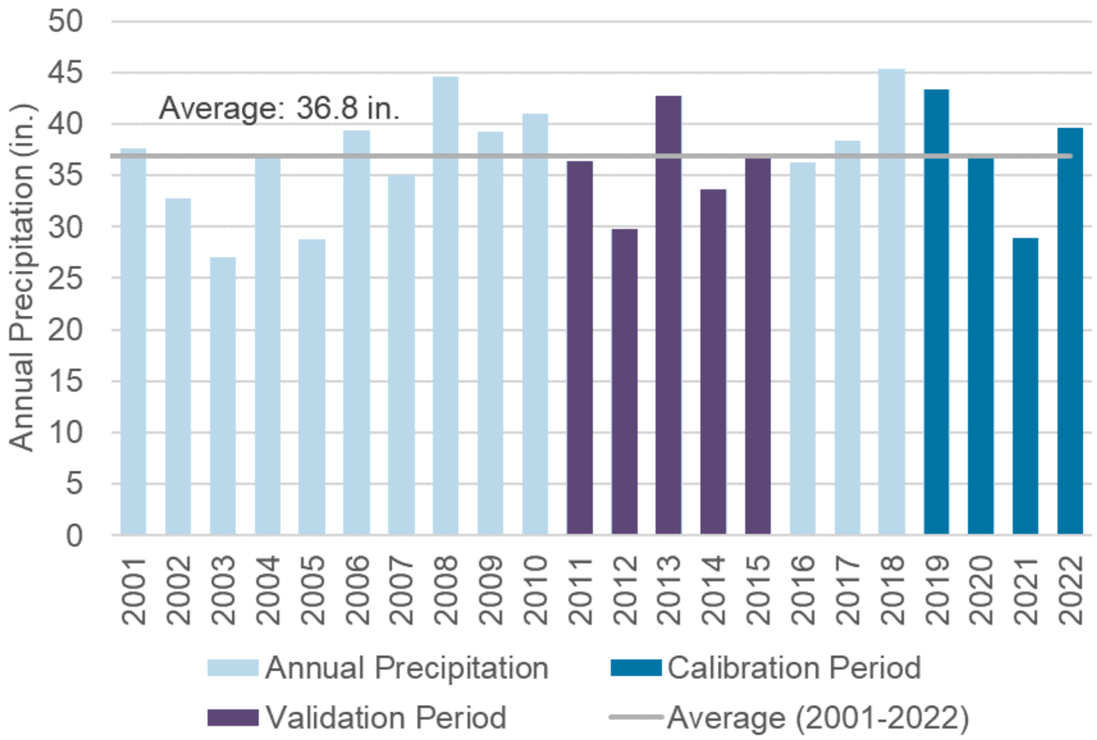
5.3.1. Simulation, Calibration, and Validation Periods

The SWAT+ model was run for 22 years from January 1, 2001, through December 31, 2022. The first ten years of the simulation acted as a warm-up period and allowed the initial conditions of the model to reach equilibrium. Model output from these first ten years was not evaluated for calibration or validation.

The model calibration period encompassed three years from July 1, 2019, through June 30, 2022. These dates were selected because they included three full years that overlapped with the monitoring period. The model validation period encompassed five years from January 1, 2011, through December 31, 2015. These five years were selected for validation because they provided a good representation of precipitation ranges. The validation period included one year with precipitation well below the annual average precipitation (2012), one year with precipitation well above the annual average precipitation (2013), and three years close to the annual average precipitation (2011, 2014, and 2015). The annual precipitation for the entire 22-year model run, and the years used for calibration and validation are shown in Figure 5.1.

FIGURE 5.1

Annual Precipitation in Study Area



5.3.2. Calibration Basins

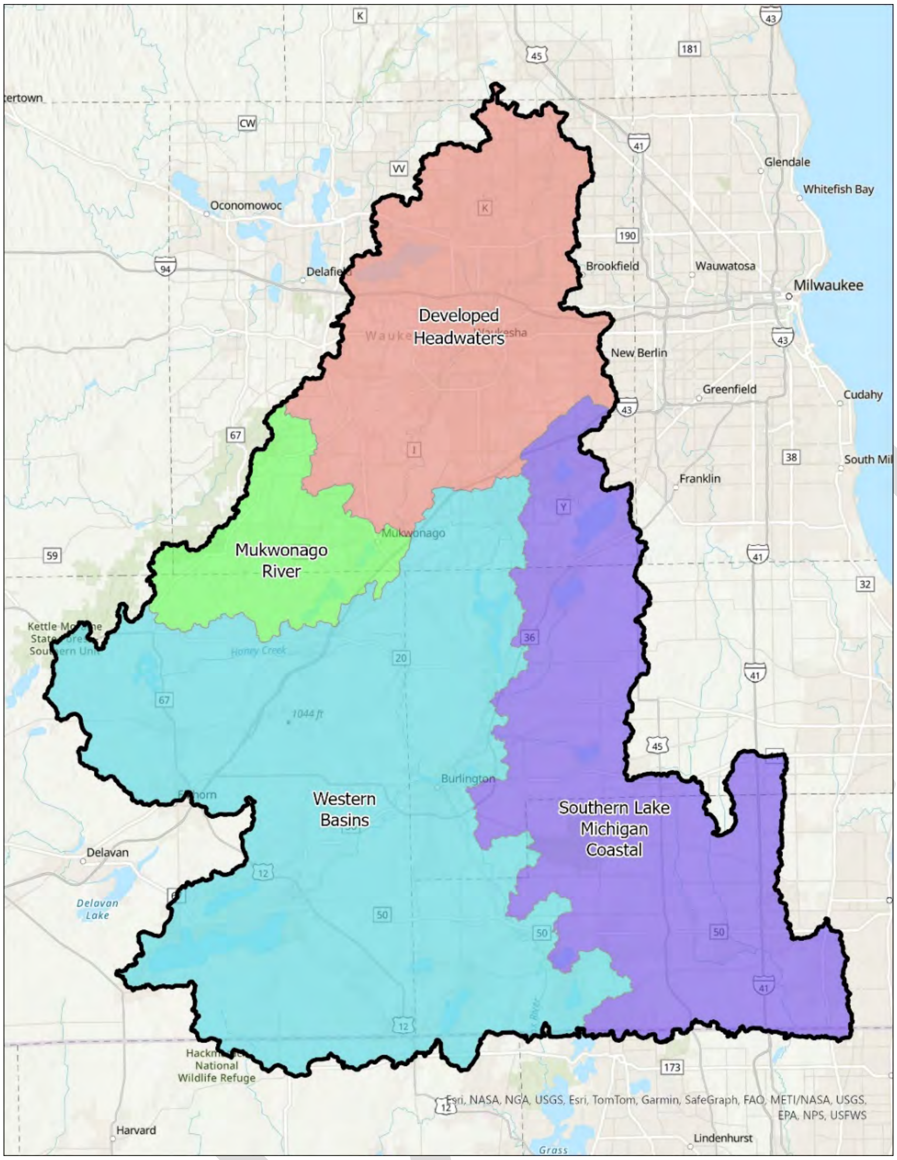
Hydrologic properties of the landscape vary across the FOXIL Basin study area, so the basin was separated into distinct “calibration basins”. Model parameters were independently adjusted for each calibration basin during model calibration. Unique calibration basins were established for runoff parameters and aquifer parameters. A separate set of calibration parameters was also established for the Geneva Lake region. Details of the unique calibration areas are provided below .

5.3.2.1. Runoff

Four distinct calibration basins were established for parameters directly related to runoff. Model parameters were independently adjusted for each of the basins. The basins were delineated for regions with hydrologic properties that are distinct from other areas in the study area. The four basins are shown in Figure 5.2, and they include the following properties:

- *Developed headwaters*: The headwaters of the Fox River are unique within the larger study area because a large portion of the land is urbanized. Land use is generally characterized by low- and high-density urbanized areas with only small areas of agriculture.
- *Mukwonago River*: The Mukwonago River is a uniquely high-quality waterway when compared to other streams and rivers in the region. Land use is characterized by a relatively even split of natural, urbanized, and agricultural lands. The mainstem of the Mukwonago River itself has a notable buffer of forests and wetlands.
- *Western Basins*: The Western Basin are dominated by agriculture, with over 50 percent of the land dedicated to agriculture. The topography in the Western Basins is also more variable when compared to the eastern portion of the study area.
- *Southern Lake Michigan Coastal*: The eastern portion of the study area is within the Southern Lake Michigan Coastal Ecological Landscape (Wisconsin Department of Natural Resources, 2015). The soils are poorly drained, and a significant portion of agriculture in the area utilizes tile drainage. The majority of land is used for agriculture.

FIGURE 5.2
Calibration Basins for Runoff Parameters

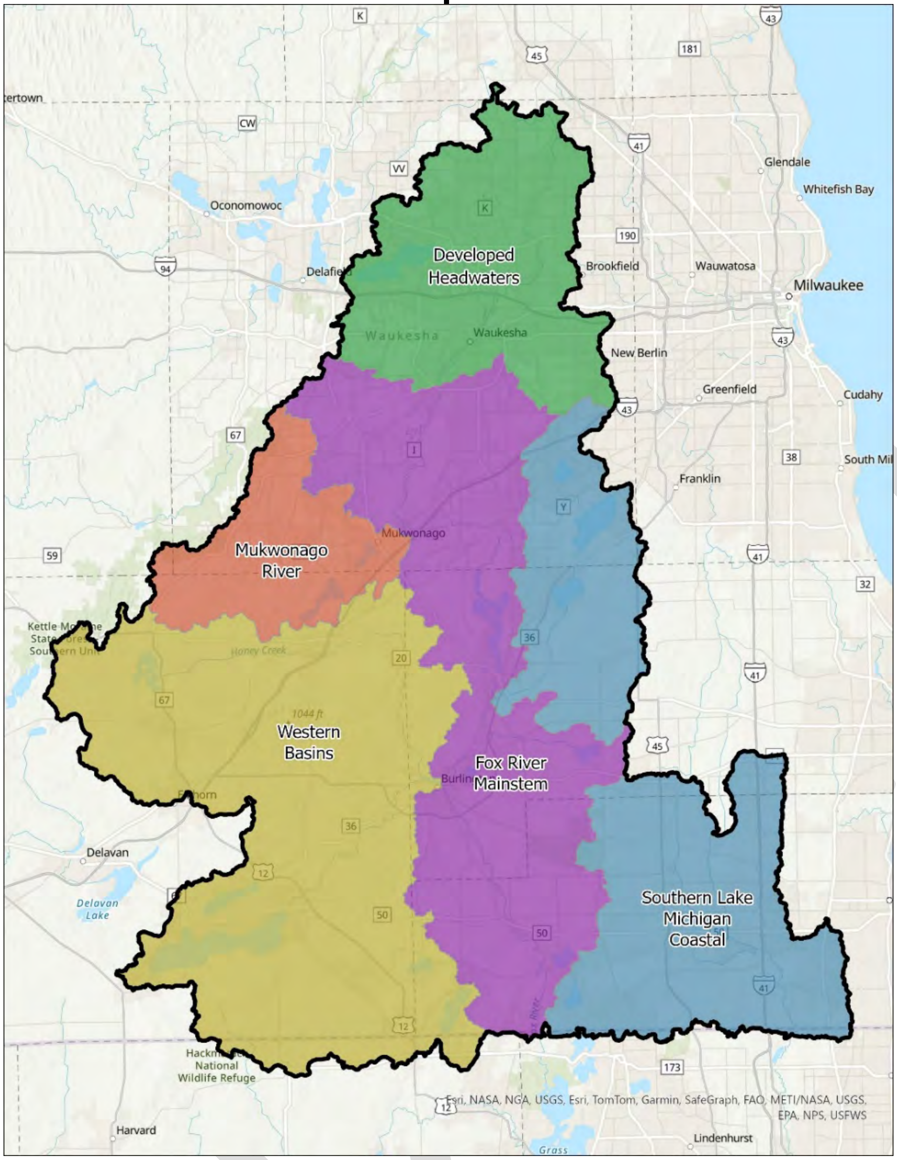


Esri, NASA, NGA, USGS, Esri, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, USFWS

5.3.2.2. Aquifers

During model setup, model aquifers were delineated to align with HUC 10 boundaries. The model aquifers were lumped into five distinct calibration areas. During calibration, aquifer parameters in each of these areas were independently adjusted. The groundwater calibration areas resemble the areas identified for runoff parameters, but an additional calibration area for the mainstem of the Fox River was established. The Fox River Mainstem was assigned its own calibration area because the drainage basin lies within a valley that likely has different aquifer properties than the upland areas. The boundaries of the five aquifer calibration areas are provided in Figure 5.3.

FIGURE 5.3
Calibration Basins for Aquifer Parameters



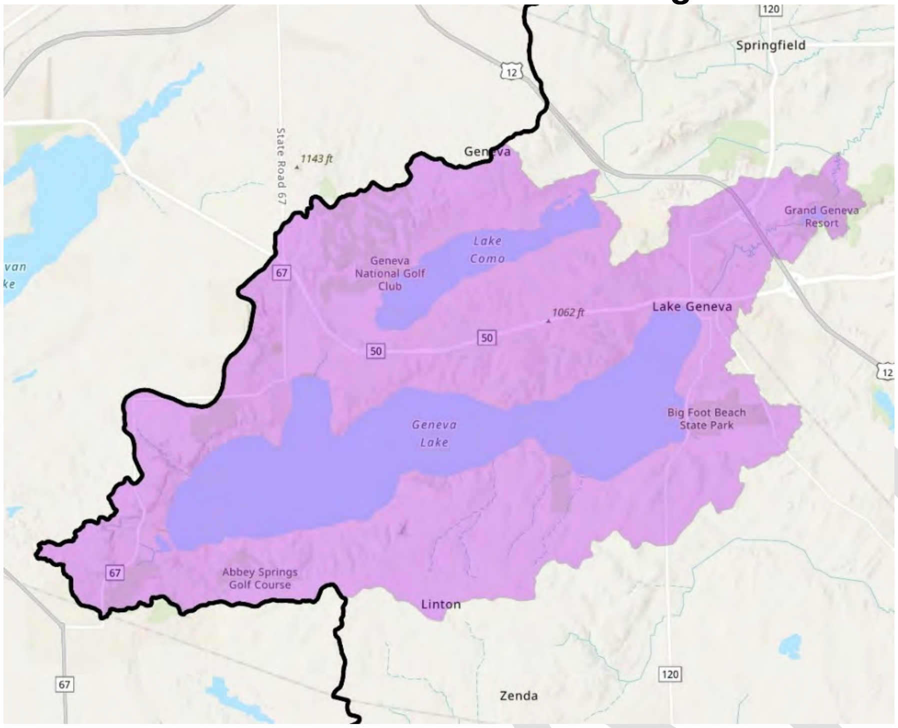
Esri, NASA, NGA, USGS, Esri, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, USFWS

5.3.2.3. Geneva Lake Area

During calibration, a sub-area of the Western Basins was established around Geneva Lake. Geneva Lake is a uniquely large and deep waterbody for the region. Additionally, the land use around the area is characterized by steep terrain and low-density residential development, and it also includes a number of golf courses. Given the unique nature of the area around Geneva Lake, some runoff and aquifer parameters were independently adjusted. The extent of the Geneva Lake sub-calibration basin is shown in Figure 5.4.

FIGURE 5.4

Calibration Basin for Lake Geneva Region



5.3.3. Assessment of Model Fit

To ensure the model was accurately representing reality, statistics to estimate model fit were required. Well established guidelines for evaluating how well models match observations are available in the scientific literature. One of the most common approaches for assessing model fit is described in Moriasi et al. (2007). The approach uses numeric benchmarks for model performance that are applicable to most SWAT models. The numeric criteria used as benchmarks are percent bias (PBIAS), Nash-Sutcliffe efficiency (NSE), and root mean squared error standard deviation ratio (RSR). Only PBIAS and NSE were used for model evaluation in this study. The equation for PBIAS is shown in Equation 5.1, and the equation for NSE is shown in Equation 5.2.

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{sim} - Y_i^{obs}\right) * 100}{\sum_{i=1}^{n} Y_i^{obs}}\right] \qquad \text{Equation 5.1}$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{sim} - Y_i^{obs}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2}\right] \qquad \text{Equation 5.2}$$

In the equations Y_i^{obs} is the *i*th observation of the constituent being evaluated, Y_i^{sim} is the *i*th simulated value for the constituent being evaluated, Y_i^{mean} is the mean of observed data for the constituent being evaluated, an *n* is the total number of observations” (Moriasi, et al., 2007). Moriasi et al. (2007) also provide benchmarks that represent qualitative interpretations of the numeric criteria. The benchmarks are summarized in Table 5.2..

TABLE 5.2

General Performance Ratings for a Monthly Time Step

(from Moriasi, et al., 2007)

		PBIAS (%)		
Performance Rating	NSE	Streamflow	Sediment	N, P
Very good	0.75 < NSE ≤ 1.00	PBIAS < ±10	PBIAS < ±15	PBIAS < ±25
Good	0.65 < NSE ≤ 0.75	±10 ≤ PBIAS < ±15	±15 ≤ PBIAS < ±30	±25 ≤ PBIAS < ±40
Satisfactory	0.50 < NSE ≤ 0.65	±15 ≤ PBIAS < ±25	±30 ≤ PBIAS < ±55	±40 ≤ PBIAS < ±70
Unsatisfactory	NSE ≤ 0.50	PBIAS ≥ ±25	PBIAS ≥ ±55	PBIAS ≥ ±70

5.4. Calibration Approach and Parameter Adjustment

Calibration progressed in four sequential phases: crop growth, streamflow, sediment, and phosphorus. The importance of this progression is described below:

1. Crop Growth: Crop growth was the first model output calibrated. Crop growth was an important first parameter to calibrate because crop growth impacted streamflow via evapotranspiration, sediment and nutrients via residue cover, and phosphorus via nutrient uptake.
2. Streamflow: Streamflow was the second model output calibrated. Streamflow was calibrated before sediment and phosphorus because overland runoff and streamflow impacted sediment and phosphorus transport and delivery.
3. Sediment: Sediment was the third model output calibrated. Sediment was calibrated before phosphorus because sediment transport and delivery impacted phosphorus transport and delivery.
4. Phosphorus: Phosphorus was the final model output calibrated.

Each of the model outputs were calibrated by adjusting relevant model parameters. The following sections describe the model parameters that were adjusted during the calibration process. Additional details about model parameters are available in the SWAT+ Theoretical Documentation (SWAT Development Team, 2024b).

5.4.1. Crop Growth

Parameters that impact plant growth relate to how much biomass can be produced from solar radiation, how much biomass is removed during a harvest operation, optimal temperatures for crop growth, and the development of leaf area. The parameters used to calibrate crop growth are summarized in Table 5.3.

TABLE 5.3

Plant Growth Parameters Adjusted for Calibration

Parameter Name	Parameter Description
bm_e	Biomass-energy ratio
harv_idx	Harvest index for optimal growth conditions
tmp_opt	Optimal temperature for plant growth
tmp_base	Minimum temperature for plant growth
lai_pot	Maximum potential leaf area index

5.4.2. Flow Calibration

Flow calibration was performed using information from the sensitivity analysis, experience from previous SWAT modeling, and automated calibration techniques. General parameters impacting streamflow and runoff were calibrated, but additional calibration for shallow aquifer flow and precipitation falling as snow was also required. The following sections describe the process for flow calibration.

5.4.2.1. Initial Streamflow and Runoff Parameters

Fifteen parameters related to streamflow and runoff were initially identified for calibration. The parameters were selected based on the results of the sensitivity analysis described in Section 5.2.

The initial values of the 15 flow parameters were estimated using a parameter sampling technique described in the documentation for the SWATrunR package (Schuerz, 2024). Below is a brief summary of the methodology:

1. *Definition of Parameter Boundaries*: The most important parameters affecting flow were identified in the sensitivity analysis. The typical and allowable numeric range for these parameters was selected based on the SWAT+ recommendations and experience from previous TMDLs in Wisconsin.
2. *Sampling of values using LHS*: A matrix of values for each parameter to be modeled was created by applying Latin Hypercube Sampling to the range of values specified for each parameter. This method creates a semi-random distribution of values within the specified range. The LHS was performed in R using the *lhs* package (Carnell, 2022).
3. *Running of SWAT+ model*: The SWAT+ model was run for each of the unique parameter combinations created from the LHS. For the initial calibration, 600 model runs were performed. For efficiency, the models were run from January 1, 2014 through December 31, 2022, with the first five years of the model run being used as a warmup period to initialize parameters.
4. *Evaluation of Results*: Calibration statistics for each model run were calculated for each of the model calibration locations. The model runs with the best fit for each of the calibration sites were identified, and the values of the model parameters associated with the model runs were reviewed to determine an approximate range of most representative values for each of the model parameters.

The ranges determined from the parameter sampling were used as a baseline for further model calibration. Values for each parameter in each calibration basin were adjusted to ensure the best possible fit of model results to the calibration data. The fifteen parameters selected for initial streamflow calibration are summarized in Table 5.4.

TABLE 5.4

Initial Parameters Adjusted for Streamflow Calibration

Parameter Name	Parameter Description
esco	Soil evaporation compensation factor
epco	Plant uptake compensation factor
awc	Available water capacity of the soil layer
cn2	Curve number at antecdent moisture condition II
cn3_swf	Soil water factor for curve number at antecedent moisture condition III
latq_co	Lateral flow coefficient
soil_k	Saturated hydraulic conductivity of the soil layer
petco	Potential evapotranspiration adjustment
perco	Percolation coefficient
alpha	Baseflow alpha factor
surlag	Surface runoff lag coefficient
snomelt_tmp	Snow melt base temperature
canmx	Canopy storage
snomelt_min	Melt factor for snow on December 21
chs	Channel Slope

5.4.2.2. Aquifer Parameters

Although the parameter sampling and subsequent parameter adjustment provided a reasonable starting point for streamflow calibration, additional parameters related to baseflow from the shallow aquifer had to be adjusted. A summary of the aquifer parameters used in the calibration is provided in Table 5.5.

TABLE 5.5

Aquifer Parameters Adjusted for Calibration

Parameter Name	Parameter Description
flo_min	Threshold depth from surface to water table for groundwater flow to occur
dep_bot	Depth from mid-slope surface to bottom of aquifer
revap_min	Threshold depth from surface to water table for revap to occur
revap_co	Revap coefficient
deep_seep	Recharge to deep aquifer

5.4.2.3. Snow Parameters

The timing and distribution of streamflow estimated by the SWAT+ model during the winter and spring required refinement. Parameters related to snowfall and snow melt were incorporated into the calibration, and the parameters used are summarized in Table 5.6.

TABLE 5.6

Snow-related Parameters Adjusted for Calibration

Parameter Name	Parameter Description
tmp_lag	Snowpack temperature lag factor
snow_h2o	Minimum snow water content that corresponds to 100% snow cover
snofall_tmp	Snowfall temperature
snomelt_max	Melt factor for snow on June 21
cn_froz	Parameter for frozen soil adjustment on infiltration/runoff

5.4.3. Sediment Calibration

Once flows were calibrated, model parameters related to sediment were adjusted to ensure modeled sediment yield matched sediment yield predicted by the site-specific load model. The results of the sensitivity analysis described in Section 5.2 were used to identify model parameters impacting sediment yield. For sediment yield, not all model parameters were able to be automatically adjusted using SWATrunR, so many parameters for sediment calibration required manual calibration. The manual calibration involved adjusting values in the model SQLite database and adjusting values in the model's input .txt files. A summary of the parameters used for sediment calibration are provided in Table 5.7. Parameters that required manual adjustment are identified in the table with an asterisk.

TABLE 5.7

Sediment Parameters Adjusted for Calibration

Parameter Name	Parameter Description
usle_k	USLE equation soil erodibility (K) factor for the top layer
rock	Rock fragment content of the soil layer
adj_pkrt_sed*	Peak rate adjustment for sediment routing in the main channel
slp_len*	Tributary slope length
bed_load*	Percent of sediment entering the channel that is bed material
ov_mann*	Overland Manning's n
cons_prac*	Conservation practice
biomix	Biological mixing efficiency
rsd_init*	Initial residue cover
yrs_init*	Age of plant at start of simulation
rsd_decay*	Minimum daily residue decay
plnt_decomp*	Plant residue decomposition coefficient
rsd_pctcov*	Residue factor for percent cover equation
rsd_covfac*	Residue factor for surface cover equation
bm_dieoff*	Above-ground biomass that dies off at dormancy

5.4.4. Phosphorus Calibration

Once sediment was calibrated, model parameters related to phosphorus were adjusted. Similar to sediment, most parameters affecting phosphorus were not able to be automatically adjusted and required manual calibration using the SQLite database and the input .txt files. A list of the parameters used for phosphorus calibration is provided in Table 5.8. Parameters that required manual calibration are indicated with an asterisk.

TABLE 5.8

Phosphorus Parameters Adjusted for Calibration

Parameter Name	Parameter Description
p_avail*	Phosphorus availability index
p_soil*	Phosphorus soil partitioning coefficient
p_perc*	Phosphorus percolation coefficient
p_uptake*	Phosphorus uptake distribution parameter
lat_orgp	Organic phosphorus in the base flow
ero_grp	Phosphorus enrichment ratio
frac_p_xyz*	Normal fraction of phosphorus in plant at different life stages
pltp_stl*	Organic P settling rate in the channel at 20 degrees C
ptl_p*	Channel organic P concentration
ben_disp*	Benthos source rate for dissolved P in reach

5.4.5. Reservoir Calibration

Throughout the calibration process for streamflow, sediment, and phosphorus, reservoir parameters were also adjusted. Initial parameter values for reservoirs were estimated based on reservoir characteristics such as area and depth. When necessary, reservoir parameters were adjusted during the respective calibration steps. A list of reservoir parameters adjusted during the calibration process is provided in Table 5.9.

TABLE 5.9

Reservoir Parameters Adjusted for Calibration

Calibration Group	Parameter Name	Parameter Description
Flow	evap_co	Lake evaporation coefficient
	days	Reservoir drawdown days
Sediment	sed_amt	Equilibrium sediment concentration in water body
	stl_vel	Sediment settling velocity
Phosphorus	p_conc_min	Minimum phosphorus concentration for settling
	mid_p_stl	Phosphorus settling rate during the mid-year nutrient settling period
	p_stl	Phosphorus settling rate outside the mid-year nutrient settling period

5.5. Final Model Parameter Values

The final values for parameters adjusted during the calibration and validation process are provided in Appendix F. The results of the model calibration are described in the following sections.

6. MODEL CALIBRATION AND VALIDATION PERFORMANCE

The model calibration described in Section 5 proceeded until the model outputs adequately (see Section 5.3.3 for explanation of overall thresholds) represented site-specific loads and flows generated during the creation of calibration and validation datasets. The following sections summarize the performance of the final calibrated and validated model.

6.1. Crop Yields

The crop yields reported by NASS for the model period (2011-2022) were compared to the crop yield estimated by SWAT+ to ensure the model was appropriately representing crop growth. A summary of the final crop yield results is provided in Table 6.1. The yield for the crops simulated in the model are all within seven percent (7%) of the yields reported by NASS, which was deemed to be sufficient for the purposes of the calibration. Figures showing the annual comparison of estimated and reported crop yields are provided in Appendix G.

TABLE 6.1

Comparison of SWAT+ and NASS Crop Yields

Crop Name	SWAT+ Yield (Mg/ha)	NASS Yield (Mg/ha)	% Difference
Corn	9.6	9.0	7%
Corn silage	15.9	15.2	4%
Soybean	2.7	2.8	-4%
Alfalfa, hay	6.0	6.4	-6%
Winter wheat	4.3	4.3	-1%

6.2. Streamflow

Model output for streamflow at 13 monitoring stations were compared to the calibration and validation datasets described in Section 4. The Fox River site at County Highway ES was not used for calibration of the model due to the challenges in developing a continuous flow record. Additionally, validation was not possible at the sites that did not have continuous USGS monitoring because no data were available for the validation period of 2011 through 2015.

A summary of the performance metrics for streamflow calibration and validation is provided in Table 6.2. The table includes values for Nash-Sutcliffe Efficiency (NSE) and percent bias (PBIAS). Based on the guidance in Moriasi et al. (2007), statistics were calculated using monthly average streamflow. The colors in the table correspond to the categorical groupings outlined in Moriasi et al. (2007) for streamflow. Time series plots for each calibration and validation site are provided in Appendix H. The plots show flows generated by the rating curve or regression models versus flows predcited by the SWAT+ model.

TABLE 6.2

Performance Metrics for Streamflow Calibration and Validation

	Calibration		Validation	
Calibration Site	NSE	PBIAS	NSE	PBIAS
Fox River at Waukesha	0.89	-2.0	0.92	4.6
Fox River at CTH I	0.92	-6.2	0.93	0.1
Mukwonago River	0.84	1.1	0.49	14.1
Fox River at Waterford	0.94	-5.1	0.84	2.4
Muskego Lake	0.88	0.8		
Wind Lake	0.66	-1.1		
Fox River at Rochester Dam	0.91	-9.8	0.91	0.3
Honey Creek	0.74	-7.6		
Sugar Creek	0.72	1.1		
Lake Geneva	0.71	-13.0	0.52	12.8
White River	0.80	-14.6		
Fox River at New Munster	0.95	2.2	0.90	7.7
Des Plaines River	0.88	-0.9	0.83	12.1

Performance Metrics	Very Good	Good	Satisfactory	Not Satisfactory

For the calibration period, the performance of the model at the 13 sites was classified as *very good* or *good* for both NSE and PBIAS. For the validation period, NSE performance was *very good* at six sites, *satisfactory* at the Lake Geneva Outlet, and *unsatisfactory* for the Mukwonago River. The *unsatisfactory* value of the NSE at the Mukwonago River (0.49) was close to the threshold for *satisfactory*. Additionally, the PBIAS for the validation period were all *very good* or *good*. Overall, the model performed well and accurately represented streamflow.

6.3. Sediment Yield

Model output for sediment yield at 10 monitoring stations were compared to the calibration and validation datasets described in Section 4. The Fox River site at County Highway ES was not used for calibration of the model due to the challenges in developing a continuous flow record. Calibration data were not available at the four sites immediately downstream of dams (Mukwonago River, Muskego Lake, Wind Lake, Lake Geneva) because either sufficient sediment data were not available or a reasonable load estimation was not able to be calculated. Three sites had sufficient long-term sediment and flow datasets for model validation.

A summary of the performance metrics for sediment yield calibration and validation is provided in Table 6.3. The table includes values for Nash-Sutcliffe Efficiency (NSE) and percent bias (PBIAS). Based on the guidance in Moriasi et al. (2007), statistics were calculated using monthly average sediment yield. The colors in the table correspond to the categorical groupings outlined in Moriasi et al. (2007) for sediment yield. Time series plots for each calibration and validation site are provided in Appendix H. The plots show loads generated by the site-specific load model versus loads predicted by the SWAT+ model.

TABLE 6.3

Performance Metrics for Sediment Calibration and Validation

	Calibration		Validation	
Calibration Site	NSE	PBIAS	NSE	PBIAS
Fox River at Waukesha	0.41	7.5		
Fox River at CTH I	0.43	-23.6	0.71	-10.6
Fox River at Waterford	0.68	-16.9		
Fox River at Rochester Dam	0.67	-18.4	0.85	2.8
Honey Creek	0.84	-4.9		
Sugar Creek	0.69	10.3		
White River	0.85	-10.7		
Fox River at New Munster	0.79	-4.4	0.90	9.7
Des Plaines River	0.81	-7.3		

Performance Metrics	Very Good	Good	Satisfactory	Not Satisfactory

For the calibration period PBIAS performance was *very good* or *good* at all 10 sites. NSE was *very good* or *good* at eight of the 10 sites but was *unsatisfactory* for the two most upstream sites for the Fox River. The headwaters of the Fox River are highly urbanized, and the limitations of the urban sediment routing routines appear to be impacting the timing of sediment delivery more than the overall load. For the validation period, however, NSE and PBAIS for the three validation sites were all *very good* or *good*. Overall, the model performed well and accurately represented sediment yield.

6.4. Total Phosphorus in Streams

Model output for phosphorus yield at 13 monitoring stations were compared to the calibration and validation datasets described in Section 4. The Fox River site at County Highway ES was not used for calibration of the model due to the challenges in developing a continuous flow record. Five sites had sufficient long-term datasets for phosphorus and flow and were available for model validation.

A summary of the performance metrics for phosphorus calibration and validation is provided in Table 6.4. The table includes values for Nash-Sutcliffe Efficiency (NSE) and percent bias (PBIAS). Based on the guidance in Moriasi et al. (2007), statistics were calculated using monthly average phosphorus yield. The colors in the table correspond to the categorical groupings outlined in Moriasi et al. (2007) for phosphorus yield. Time series plots for each calibration and validation site are provided in Appendix H. The plots show loads generated by the site-specific load model versus loads predicted by the SWAT+ model.

TABLE 6.4

Performance Metrics for Phosphorus Calibration and Validation

	Calibration		Validation	
Calibration Site	NSE	PBIAS	NSE	PBIAS
Fox River at Waukesha	0.66	6.9		
Fox River at CTH I	0.67	4.2	0.50	40.1
Mukwonago River	0.36	13.5		
Fox River at Waterford	0.57	24.7		
Muskego Lake	0.86	1.2		
Wind Lake	0.54	24.3		
Fox River at Rochester Dam	0.66	-5.9	0.74	28.9
Honey Creek	0.81	6.8		
Sugar Creek	0.61	19.6		
Lake Geneva	0.30	9.6	0.53	5.9
White River	0.77	-4.8		
Fox River at New Munster	0.79	-0.3	0.80	24.9
Des Plaines River	0.75	-10.2	0.77	3.5

Performance Metrics	Very Good	Good	Satisfactory	Not Satisfactory

For the calibration period, the PBIAS performance was *very good* at all 13 sites. The NSE performance was *very good* or *good* at 8 sites, *satisfactory* at three sites, and *unsatisfactory* at two sites. The locations with *unsatisfactory* performance of NSE were the Mukwonago River and Lake Geneva. The calibration sites for these two locations are located immediately downstream of a large lake or reservoir, so internal phosphorus cycling within the waterbodies may not be sufficiently represented within the model. For the validation period, the PBIAS performance was *very good* at three sites, *good* at one site, and *satisfactory* at one site. The NSE performance was *very good* at two sites, *good* at one site, and *satisfactory* at two sites. Overall, the model performed well and accurately represented phosphorus yield.

6.5. Total Phosphorus in Lakes and Reservoirs

The phosphorus concentration in the 22 lakes and reservoirs with TP assessment data were compared with model outputs to ensure lakes and reservoirs were being accurately represented in the watershed model. The assessment data are based on samples collected between June 1st and September 15th. To evaluate the performance of the SWAT+ model for lakes, the mean concentration from the lake assessment was compared to the average modeled lake phosphorus concentration between June 1st and September 15th.

The concentrations estimated for the assessments are based on the most recently available five years—or in some cases up to 10 years—of data. Lake phosphorus data were not always available through the present year, so some of the data used for the assessments ranged from 2010 through present. The average modeled concentration for the entire model period (2011 through 2022) was calculated, and the two concentration measurements may not always represent the same time ranges. Nonetheless, the concentration calculated for the assessment period and the concentration estimated from the SWAT+ model were compared to ensure they were within the same order of magnitude. Overall, the SWAT+ seems to be accurately characterizing phosphorus loads. The comparison of the assessment data to the SWAT+ model data are available in Appendix H.

7. MODEL RESULTS

One of the primary goals for the SWAT+ model was to quantify the sources of sediment and phosphorus. For nonpoint sources of sediment and phosphorus, the sources were expressed as the total mass or weight of each constituent per unit area. The following sections describe the model results related to sediment and phosphorus yields.

7.1. Pollutant Yields

The total amount of sediment and phosphorus yield per unit area was evaluated for each source area or land use. Yields for sediment were converted from the SWAT+ output of metric tons per hectare to short tons per acre. Yields for phosphorus were converted from the SWAT+ output of kilograms per hectare to pounds per acre. Yields represent delivered loads to the pour point of the subbasin and are not comparable with edge of field or HRU loads which are often higher.

7.2. Spatial Distribution

The model produced estimates of sediment and phosphorus yield by model subbasin. Understanding the spatial distribution of yields was important because it helped identify which portions of the study area were contributing the highest loads. This understanding has implications for future implementation efforts since areas with higher sediment and phosphorus loads can be prioritized and benefit from improved land management practices or other approaches to address nonpoint source pollution.

Average annual sediment yield for the model watersheds is displayed in Figure 7.1. Modeled sediment yield from the landscape was highest along the mainstem of the Fox River and in the White River basin. Modeled sediment yield from the landscape was lowest in the Mukwonago River basin and along the eastern portions of the Fox River and Des Plaines River watersheds. The low sediment yield in the Mukwonago River basin was expected given the high-water quality within the Mukwonago River. The low sediment yield in the eastern portions of the Fox River and Des Plaines River watersheds was likely driven by the very flat slopes in that portion of the study area. The median sediment yield across all model subbasins was 0.028 tons per acre, and the mean sediment yield across all model subbasins was 0.35 tons per acre. A distribution of the yields is provided in Appendix I.

Average annual phosphorus yield for the model subbasins is displayed in Figure 7.2. The characteristics of spatial distribution of phosphorus yield were similar to those related to sediment. The highest modeled phosphorus yields were along the mainstem of the Fox River and within the White River basin. The lowest modeled phosphorus yields were in the Mukwonago River basin and along the eastern portions of the Fox River basin and the Des Plaines River basin. The median phosphorus yield across all model subbasins was 0.29 pounds per acre, and the mean sediment yield across all model subbasins was 0.34 pounds per acre. A distribution of the yields is provided in Appendix I.

FIGURE 7.1

Spatial Distribution of Average Annual Sediment Yield

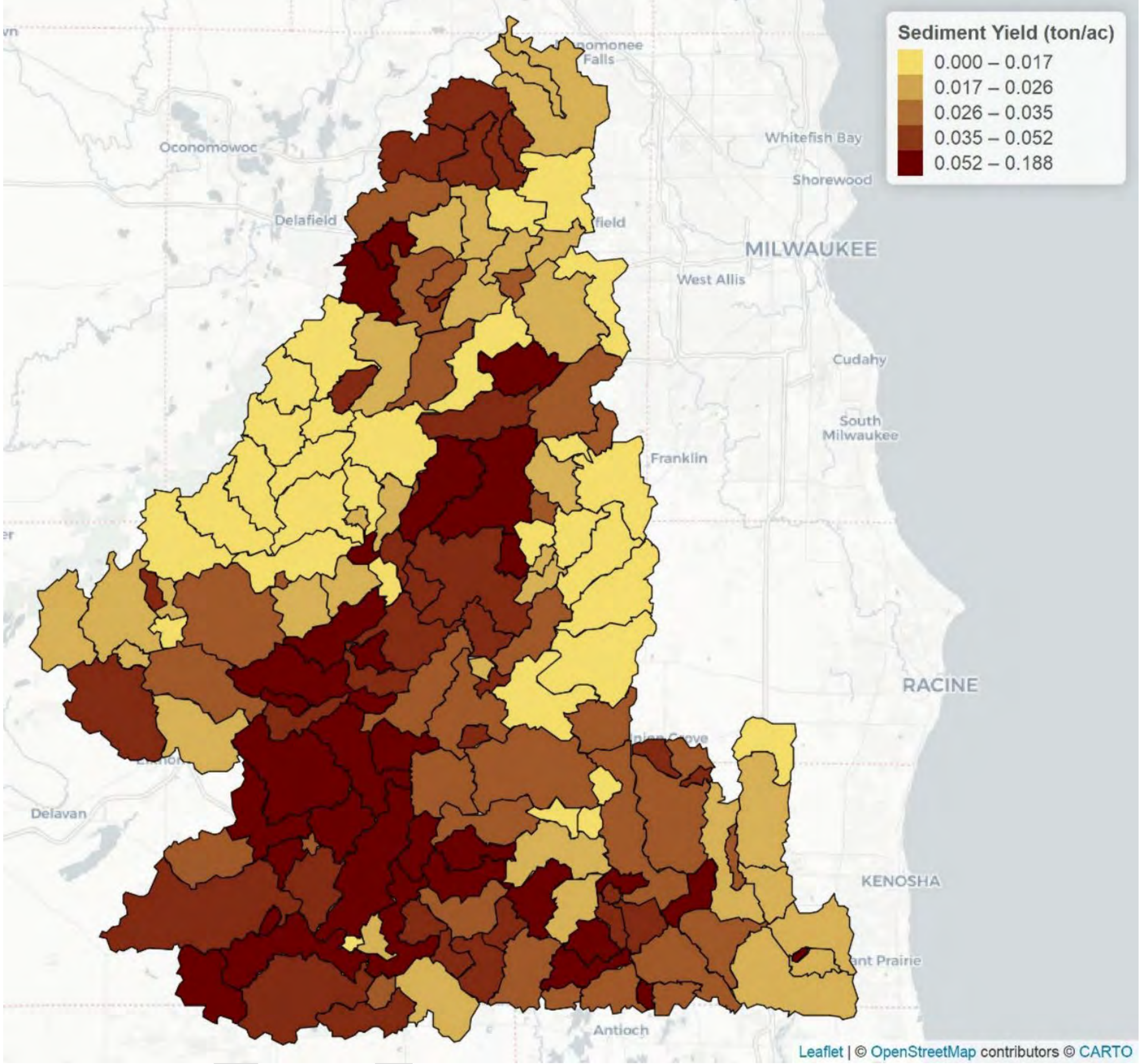
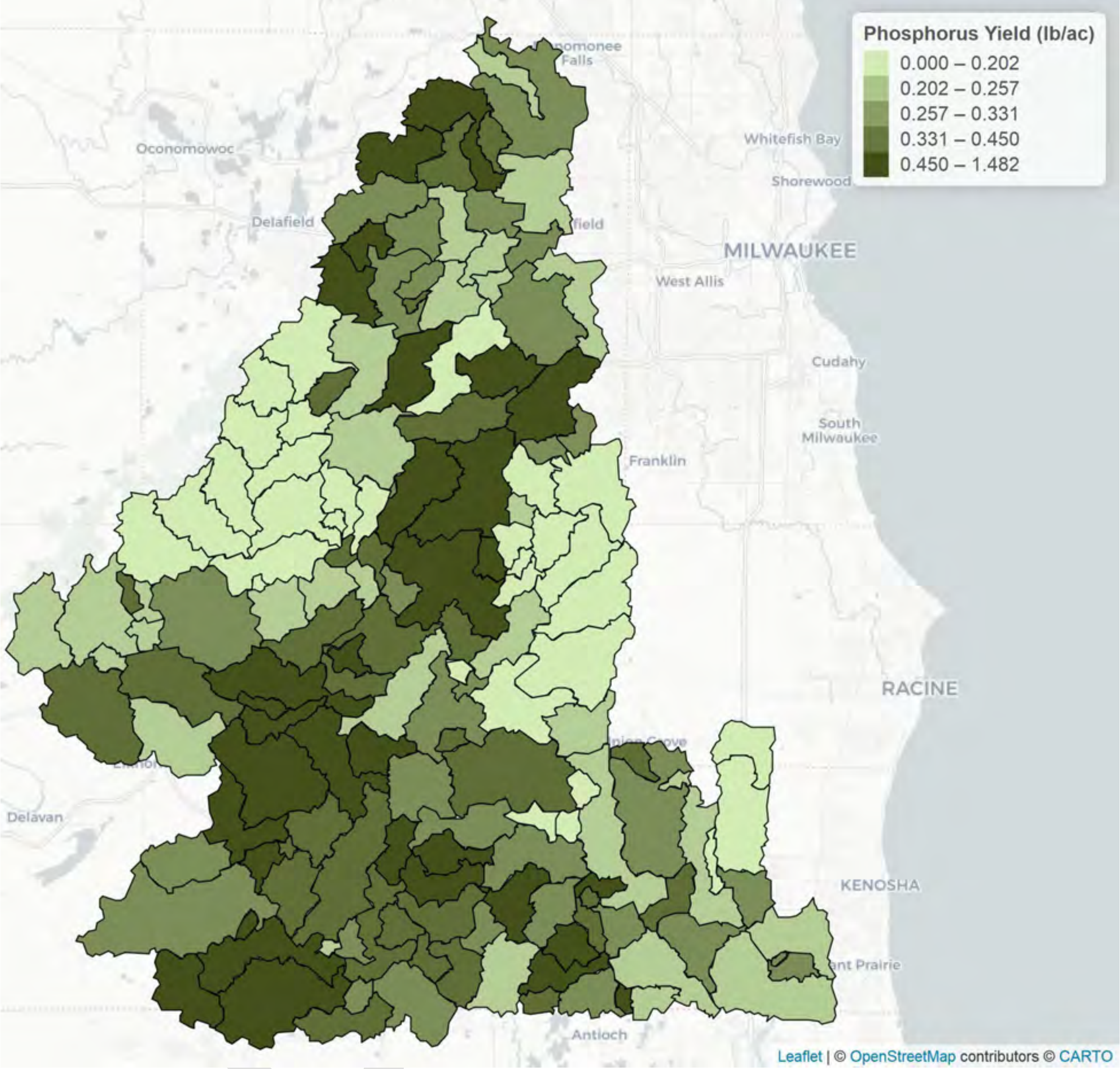


FIGURE 7.2

Spatial Distribution of Average Annual Phosphorus Yield



Leaflet | © OpenStreetMap contributors © CARTO

7.3. Temporal Distribution

Modeled sediment and phosphorus yields were influenced by land use, precipitation, snow cover and frozen ground, vegetative cover, and residue cover. The characteristics varied from year-to-year and month-to-month, so the average sediment and phosphorus yield also varied from year-to-year and month-to-month. In general, sediment and phosphorus yields were lowest in the colder months when snow was present and precipitation was falling as snow. The yields were highest in late spring and early summer when precipitation quantity and intensity was greatest and leaf cover was still being established. Figures showing the month-to-month variation in sediment and phosphorus yields are presented in Appendix I.

7.4. Categorical Distribution

Land use definitions also impacted the sediment, and phosphorus yields through two main mechanisms. First, areas that were classified as developed had higher total runoff than the areas classified as natural. The increase in runoff volume and intensity led to an increase in sediment and phosphorus yield. Additionally, areas planted with crops were affected by tillage and other land-distributing activities that increased sediment and phosphorus yields.

Sediment and phosphorus yield were evaluated for each of the land use classes defined in the model. The land use classes were grouped into three categories: developed, agriculture, and natural. Urban high-density, urban low-density, and developed open-space land classes were grouped into the developed category. In previous TMDLs the grassland and pastureland covers were lumped into a single land use class and assigned to the agricultural category. However, the grassland land class in this study area primarily comprised golf courses or other developed parklands, so the land class was lumped into the developed category. Cash grain, continuous corn, dairy, pasture, and sod land use classes were grouped into the agricultural category. Forest and wetland land use classes were grouped into the natural background category.

For both sediment and phosphorus, agricultural lands had the highest yields, followed by developed and natural lands. Within the agricultural category, the croplands—dairy, continuous corn, and cash grain—produced the highest yield of sediment and phosphorus. Within the developed category, high-density urban developed produced the highest yield of sediment and phosphorus. The modeled average annual sediment yield by land class is provided in Figure 7.3. The modeled average annual phosphorus yield by land use class is provided in Figure 7.4 The figures reflect sediment and phosphorus yield from surface runoff only and do not include loading from subsurface drainage. Additional figures showing the spatial distribution of sediment and phosphorus yield by model watershed are provided in Appendix I.

FIGURE 7.3

Modeled Average Annual Sediment Yield by Land Use Class

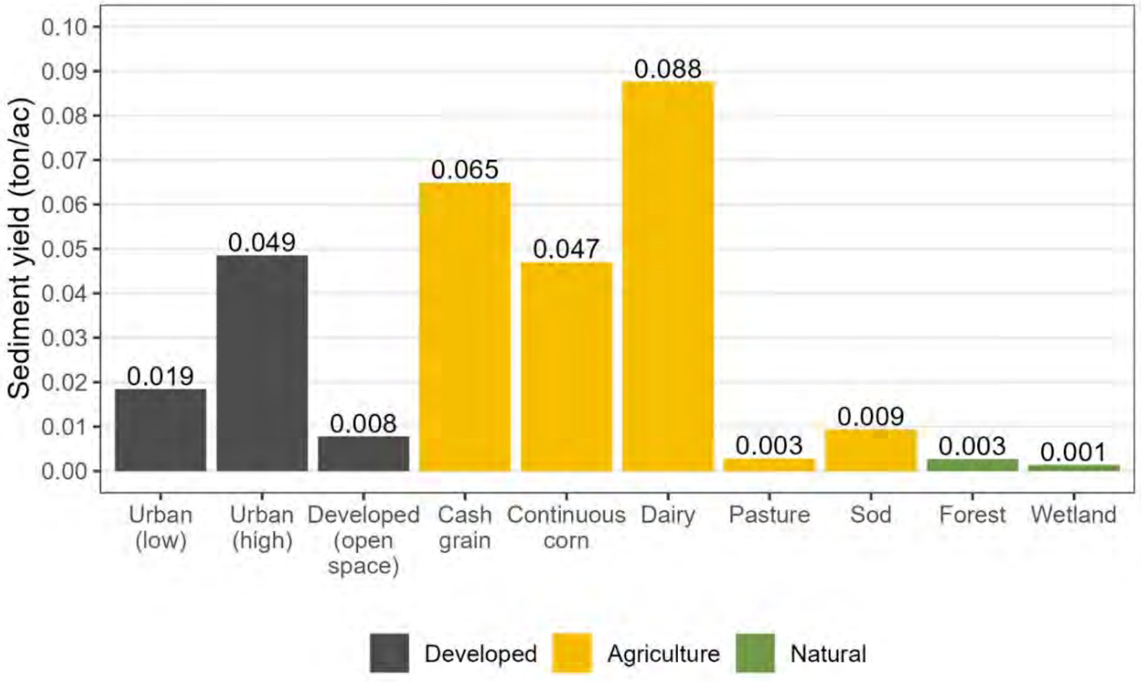
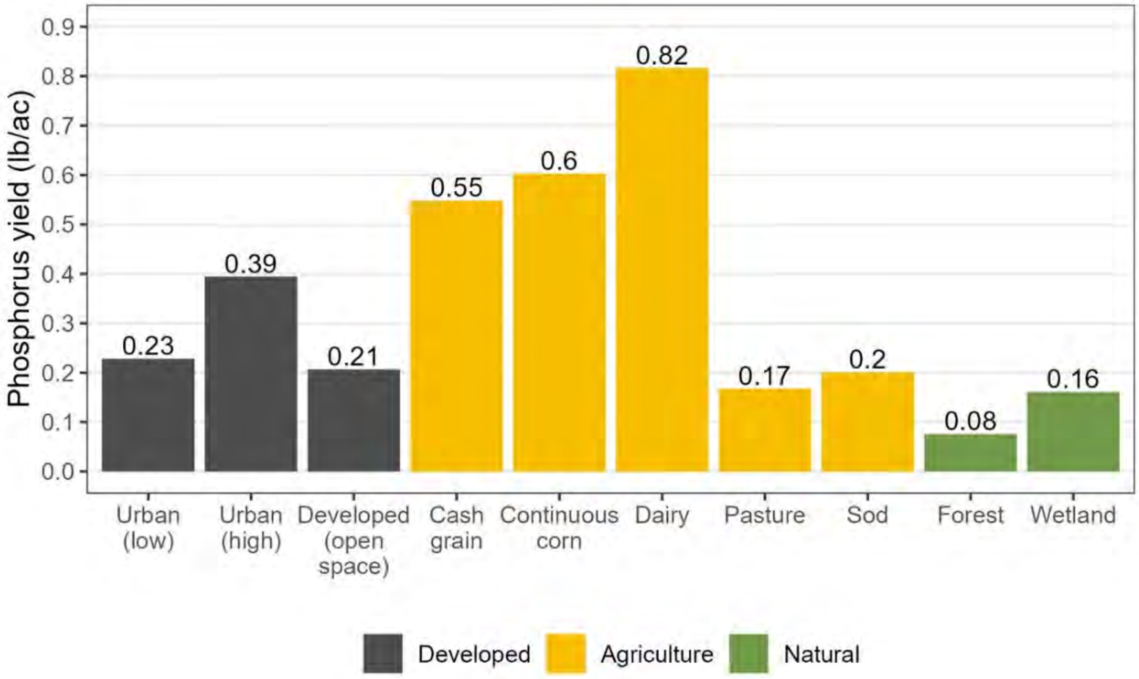


FIGURE 7.4

Modeled Average Annual Phosphorus Yield by Land Use Class



Understanding the distribution of sediment and phosphorus yields by land use category was important for identifying vulnerable areas, but the total contribution of the loads from each land use category was also important. For example, the modeled sediment yield in tons per acre from urbanized areas in the headwaters of the Fox River was similar to other urbanized areas in the study area. However, since most of the land in that area is developed, urban areas contributed over 80 percent of all sediment loads in the area. Conversely, modeled sediment yield from agricultural areas in the headwaters of the Fox River were higher than average; however, since the headwaters of the Fox River have very little agricultural land, the overall contribution of load from agricultural lands in the headwaters is relatively low. Understanding the total contribution from each land use can help guide decisions about how to best address pollutant loading. Figures showing the fraction of sediment load by land use category are provided in Appendix I.

8. SUMMARY

A watershed model for the FOXIL River Basin TMDL study area was required to better understand and characterize flows, sediment loads, and phosphorus loads. SWAT+ was selected for this model because it is widely recognized as an appropriate modeling tool for large watershed projects.

The FOXIL SWAT+ model was configured to estimate streamflow and pollutant loading from 158 unique model subbasins. Within each subbasin unique combinations of land use, slopes, and soils were specified. These combinations, known as hydrologic response units (HRUs), are the basis of the model. Information about point sources, weather, detailed agricultural operations, soil phosphorus, urban areas, reservoirs, and aquifers were also incorporated into the model.

Information about actual streamflow and pollutant loading was required to ensure the model results appropriately represented real conditions. Datasets representing actual streamflow and pollutant loading were developed using monitoring data collected during a monitoring program from late-2019 through 2022. Additional monitoring data were also collected from other reliable sources, such as the USGS.

Parameters in the SWAT+ model were systematically adjusted until the modeled results closely matched the observations. The model was first calibrated to ensure crop growth in the model matched observed crop growth. Next, the performance of the model was evaluated by comparing the modeled results to monitored data at 13 sites. Performance was evaluated for flow, sediment yield, and phosphorus yield. Model parameters were adjusted until a satisfactory fit between modeled results and observations was achieved.

The final model predictions were provided accurate overall results. Calibration and validation statistics that were calculated to assess model performance were primarily classified as good or very good. Given the high model accuracy, the model output can be used to estimate flows and monthly pollutant loads between the years of 2011 and 2022. The model output can also be used to estimate the relative contribution of pollutant loadings by source. These data will be fundamental when load allocations for the FOXIL TMDL are established.

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APPENDIX A

DATASETS FOR HRU DEFINITION

1. DEVELOPMENT OF LAND COVER DATASET FOR ILLINOIS

A land cover dataset for the Illinois portion of the study area had to be developed for the watershed model. The land cover categories in Illinois were defined using the same methodology used to develop the Wiscland 2 database (Wisconsin Department of Natural Resources, 2016). The process used to develop the Illinois land use data are described below:

1. Download 2011 through 2022 Cropland Data Layer (CDL) (United States Department of Agriculture, 2022) for Illinois.
2. Clip Illinois CDL datasets to HUC 12s overlapping the FOXIL TMDL study boundary.
3. Assign crops from CDL to unique categories using the following table:

Crop Category	CDL Code
Non Rotation Crops	0, 63-181, 182-204
Corn	1
Alfalfa	28, 36, 37, 58
Pasture	62, 176, 181
Soy and Grain	4, 5, 21, 22, 23, 24, 25, 27, 29, 30, 39, 205
Potatoes	43
Vegetables	12, 42, 47, 49, 50, 53, 206, 216
Sod	59

4. For each individual pixel in the CDL, define rotation type based on the following logic:

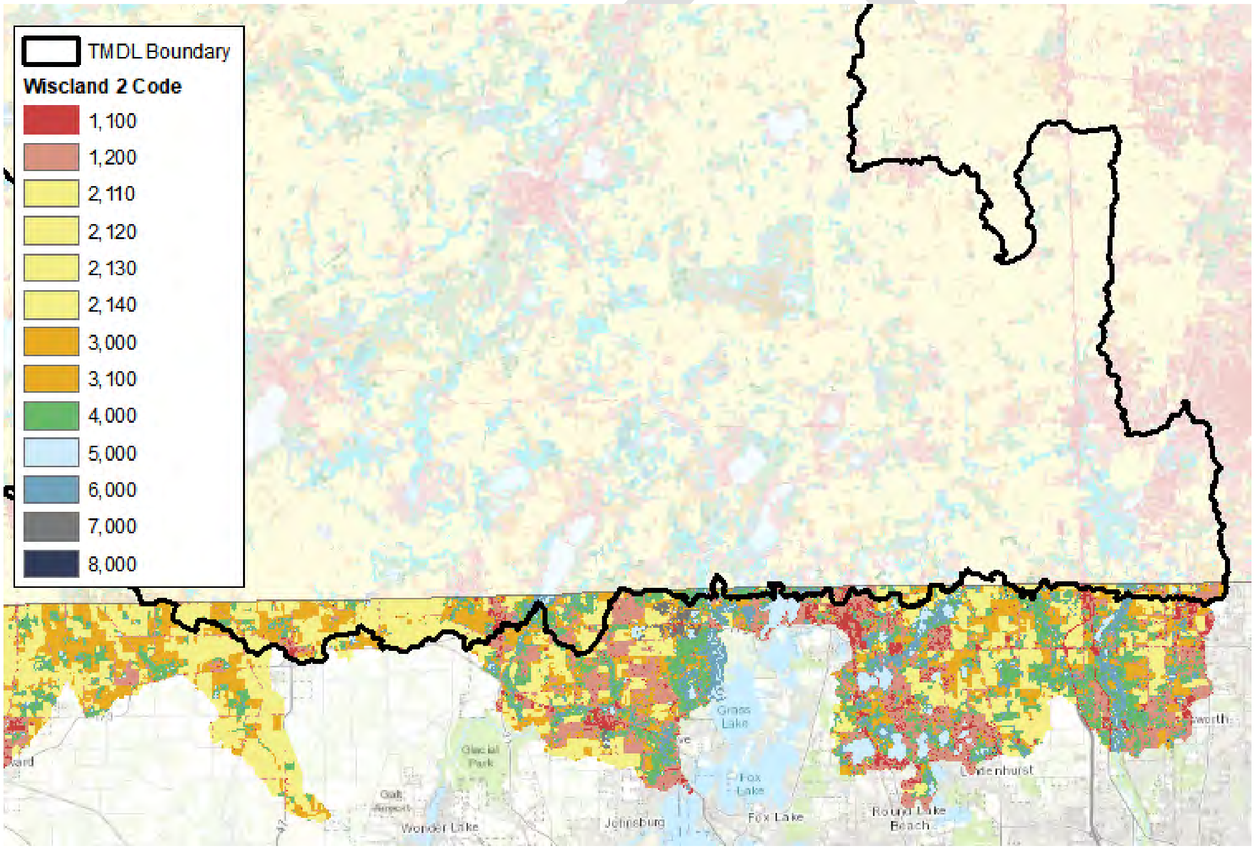
Crop Rotation	Definitions
Continuous Corn	Corn >= 60% of all years Soy and Grain + Potatoes + Vegetables+ Alfalfa + Pasture < 20% of all years
Cash Grain	Corn + Soy and Grain >= 40% of all years Potato + Veggies + Alfalfa + Pasture < 20% of all years
Dairy 1	Alfalfa >= 20% of all years Corn + Soy and Grain >=20% of all years
Dairy Potato	Potato >= 20% of all years Alfalfa >= 20% of all years
Green Vegetables	Potato + Vegetables >= 20% of all years
Pasture	Pasture + Alfalfa >= 40% of all years Corn + Soy and Grain + Potato + Vegetables < 20% of all years
Dairy 2	Alfalfa + Pasture >= 20% of all years
Sod	Sod >= 20% of all years
No Agriculture	None of above conditions met

Note: the table is prioritized based on the position. For example, if the conditions for continuous corn and cash grain are both met, the pixel is only defined as continuous corn because it is higher in the list

5. Download agricultural field boundaries from the Ag. Data Commons (James & Tomer, 2021).
6. Calculate the dominant crop rotation within each field from the Ag Data Commons and assign that entire field to the dominant crop rotation.
7. Convert non-agricultural land uses to Wiscland 2 categories using the 2022 CDL.

Wiscland Category	Wiscland Code	CDL Codes
Forested	4000	141, 142, 143
Wetlands	6000	190, 195
Open Water	5000	111
Grassland	3000	176
Barren	7000	131
Shrubland	8000	152
Developed, High-Intensity	1100	123, 124
Developed, Low-Intensity	1200	121, 122

8. Combine agricultural and non-agricultural datasets to get a Wiscland 2 representation of the Illinois Land Cover.



2. DETERMINATION OF LAND USE THRESHOLD

Agricultural land cover data were refined to include details about rotations and tillage categories. Since the refined datasets decreased the area of each agricultural land cover class classified in SWAT+, a custom method for determining land use threshold was developed. The methods to establish the threshold were adapted from the DNR's Northeast Lakeshore TMDL (Wisconsin Department of Natural Resources, 2023c) and are defined below.

2.1. Assign Rotations and Tillage Combinations to Land Cover Dataset

The Wiscland 2 derived land cover dataset only included generic categories for agricultural land use (dairy rotation, cash grain, and continuous corn). Additional information about the specific land use and land management practices was required for the SWAT+. Information from the agricultural surveys sent to counties (Wisconsin Department of Natural Resources, 2023a) were incorporated into the modified land cover dataset. Details of the process are provided below:

1. Summarized results from the agricultural survey sent to counties to determine all crop rotation and tillage combinations, which are summarized in the following table:

Crop Category	Rotation Category	Tillage Category
Dairy	Dairy 1	Tillage 1
	Dairy 1	Tillage 2
	Dairy 2	Tillage 1
Cash Grain	Cash Grain	Tillage 1
	Cash Grain	Tillage 3
	Cash Grain	Tillage 4
	Cash Grain	Tillage 5
Continuous Corn	Continuous Corn	Tillage 1
	Continuous Corn	Tillage 2

2. Summarized results of the agricultural survey for each county to estimate percent of each rotation for each crop group (dairy, cash grain, continuous corn) by HUC 12, which are summarized in the following tables. Distribute rotation/tillage combination to the respective land use pixels throughout HUC 12 based on the estimates.

Rotation and Tillage for Kenosha County HUC 12s

	Dairy			Cash Grain				Cont. Corn	
HUC 12	D1-T1	D1-T2	D2-T1	CG-1	CG-3	CG-4	CG-5	CC-T1	CC-T3
071200061002	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200061003	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200060802	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200040102	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200061005	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200040103	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200040201	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200061006	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200061001	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200040104	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200040101	0%	100%	0%	0%	0%	0%	100%	50%	50%

Rotation and Tillage for Racine County HUC 12s

	Dairy			Cash Grain				Cont. Corn	
HUC 12	D1-T1	D1-T2	D2-T1	CG-1	CG-3	CG-4	CG-5	CC-T1	CC-T3
071200061002	0%	100%	0%	0%	0%	25%	75%	100%	0%
071200061003	0%	100%	0%	0%	0%	25%	75%	100%	0%
071200060604	50%	50%	0%	0%	0%	25%	75%	100%	0%
071200060704	0%	100%	0%	0%	0%	25%	75%	100%	0%
071200040102	50%	50%	0%	0%	0%	25%	75%	100%	0%
071200060302	50%	50%	0%	0%	0%	25%	75%	100%	0%
071200040103	50%	50%	0%	0%	0%	25%	75%	100%	0%
071200060705	50%	50%	0%	0%	0%	25%	75%	100%	0%
071200060706	0%	100%	0%	0%	0%	25%	75%	100%	0%
071200060304	0%	100%	0%	0%	0%	25%	75%	100%	0%
071200060707	50%	50%	0%	0%	0%	25%	75%	100%	0%
071200060503	30%	70%	0%	0%	0%	25%	75%	100%	0%
071200060303	0%	100%	0%	0%	0%	25%	75%	100%	0%
071200061001	50%	50%	0%	0%	0%	25%	75%	100%	0%
071200040101	50%	50%	0%	0%	0%	25%	75%	100%	0%

Rotation and Tillage for Walworth County HUC 12s

	Dairy			Cash Grain				Cont. Corn	
HUC 12	D1-T1	D1-T2	D2-T1	CG-1	CG-3	CG-4	CG-5	CC-T1	CC-T3
071200060401	0%	0%	100%	35%	65%	0%	0%	100%	0%
071200060402	0%	0%	100%	35%	65%	0%	0%	100%	0%
071200060603	0%	0%	100%	35%	65%	0%	0%	100%	0%
071200060802	0%	0%	100%	35%	65%	0%	0%	100%	0%
071200060604	100%	0%	0%	35%	65%	0%	0%	100%	0%
071200060502	100%	0%	0%	35%	65%	0%	0%	100%	0%
071200060903	0%	0%	100%	35%	65%	0%	0%	100%	0%
071200060801	20%	0%	80%	35%	65%	0%	0%	100%	0%
071200060602	0%	0%	100%	35%	65%	0%	0%	100%	0%
071200060403	50%	0%	50%	35%	65%	0%	0%	100%	0%
071200060601	0%	0%	100%	35%	65%	0%	0%	100%	0%
071200060203	0%	0%	100%	35%	65%	0%	0%	100%	0%
071200060503	100%	0%	0%	35%	65%	0%	0%	100%	0%
071200060202	0%	0%	100%	35%	65%	0%	0%	100%	0%
071200060501	0%	0%	100%	35%	65%	0%	0%	100%	0%
071200060404	0%	0%	100%	35%	65%	0%	0%	100%	0%

Rotation and Tillage for Waukesha County HUC 12s

	Dairy			Cash Grain				Cont. Corn	
HUC 12	D1-T1	D1-T2	D2-T1	CG-1	CG-3	CG-4	CG-5	CC-T1	CC-T3
071200060103	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060101	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060104	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060703	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060704	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060302	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060701	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060301	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060201	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060105	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060304	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060203	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060702	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060202	100%	0%	0%	40%	0%	0%	60%	100%	0%
071200060102	100%	0%	0%	40%	0%	0%	60%	100%	0%

Rotation and Tillage for Additional Wisconsin County HUC 12s

		Dairy			Cash Grain				Cont. Corn	
County	HUC 12	D1-T1	D1-T2	D2-T1	CG-1	CG-3	CG-4	CG-5	CC-T1	CC-T3
Washington	071200060102	100%	0%	0%	40%	0%	0%	60%	100%	0%
Jefferson	071200060202	0%	0%	100%	35%	65%	0%	0%	100%	0%
Milwaukee	071200060302	50%	50%	0%	0%	0%	25%	75%	100%	0%

Rotation and Tillage for Illinois HUC 12s

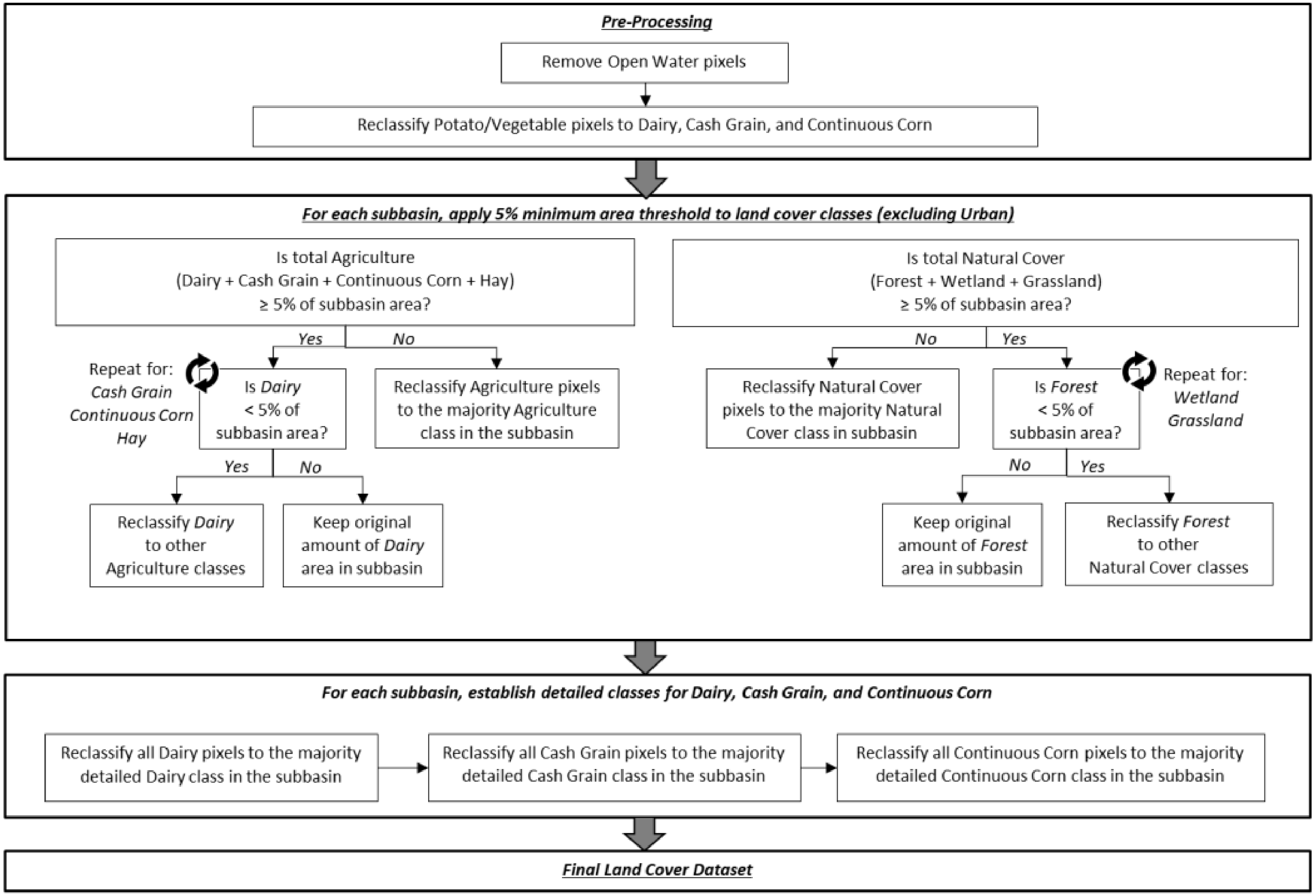
	Dairy			Cash Grain				Cont. Corn	
HUC 12	D1-T1	D1-T2	D2-T1	CG-1	CG-3	CG-4	CG-5	CC-T1	CC-T3
071200061005	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200061006	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200040104	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200040201	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200060802	0%	100%	0%	0%	0%	0%	100%	50%	50%
071200060801	20%	0%	80%	35%	65%	0%	0%	100%	0%
071200060903	0%	0%	100%	35%	65%	0%	0%	100%	0%

3. Randomly distributed pixels for each rotation/tillage combination in each HUC 12 into two categories: Year 1 and Year 4. Year 1 represented the pixels where the first year of the rotation occurred on the first year of the model, and Year 4 represented the pixels where the fourth year of the rotation occurs on the first year of the model. This step was required to create an offset in the rotations (i.e., half of dairy fields will have silage/soybean in a given year, and the other half will have alfalfa).

2.2. Simplify Land Cover Dataset by Applying Area Thresholds

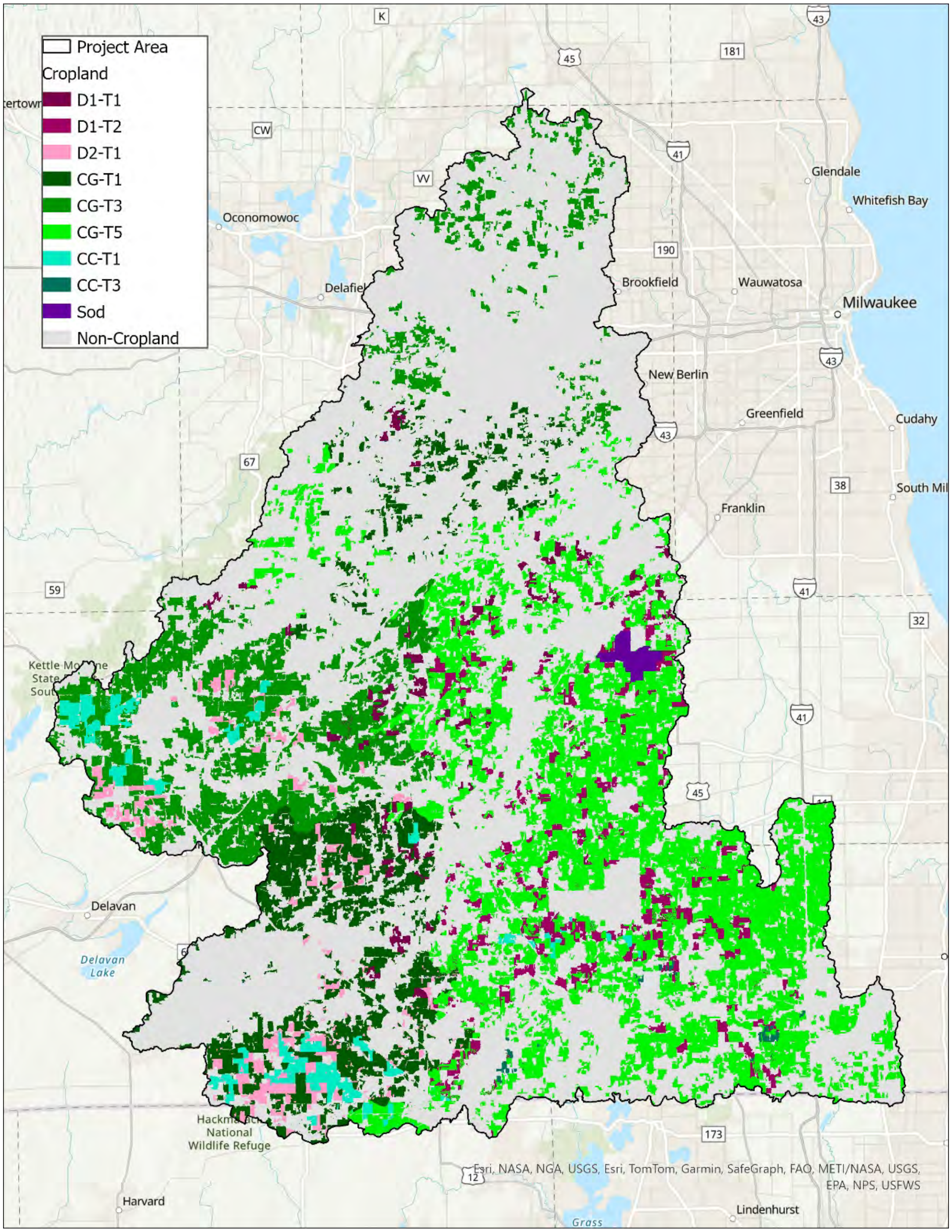
The resulting land cover and land use dataset from the previous section contained detailed information about land cover at a high resolution. An area threshold was established to simplify the land cover datasets and, as previously discussed, reduce the number of HRUs. The method to apply the threshold area was adapted from the DNR's Northeast Lakeshore TMDL (Wisconsin Department of Natural Resources, 2023c). The method used in the modeling appendix of the Northeast Lakeshore TMDL model report and a flowchart explaining the process are reproduced below:

1. Open water was removed from the land cover grid. Within SWAT, runoff volumes and pollutant loads are equal to zero for open water HRUs. Removing open water reduced the total number of HRUs and improved model runtimes.
2. The potato/vegetable class was removed and reclassified according to the proportion of remaining agricultural crop classes in a subbasin (dairy, cash grain, and continuous corn). County LCWDs indicated that potato/vegetable plantings are not prevalent within the study area (Agricultural survey summary).
3. A minimum area threshold for seven major land cover classes (dairy, cash grain, continuous corn, hay, grassland, forest, wetland) was set to 5% of the subbasin area. Within a subbasin, HRUs were only defined for land cover classes that met or exceeded the 5% area threshold. Because small amounts of urban cover can impact runoff and water quality, the developed land cover classes were exempted from the minimum area threshold requirement.
4. Major land cover classes that didn't meet the 5% area threshold were removed from the subbasin and reclassified. Dairy, cash grain, continuous corn pixels were reclassified according to the proportion of remaining agricultural crop classes in the subbasin. For example, if dairy made up 2% of a subbasin, those dairy pixels were reclassified as cash grain and continuous corn according to the proportion of each class in the subbasin. Grassland, forest, and wetland pixels were reclassified according to the proportion of remaining natural classes in the subbasin. For example, if grassland made up 2% of a subbasin, those grassland pixels were reclassified as forest and wetland based on the proportion of each class in the subbasin.
5. If all agricultural classes (dairy, cash grain, continuous corn, or hay) were below the 5% threshold in a subbasin, then the pixels were reclassified to the largest agricultural class in the subbasin. For example, if a watershed contained 1% dairy, 1% cash grain, 2% continuous corn, and 1% hay, then all agricultural pixels were reclassified to continuous corn.
6. If all natural classes (forest, wetland, or grassland) were below the 5% threshold in a subbasin, then then pixels were reclassified to the largest natural class in the subbasin. For example, if a watershed contained 1% grassland, 1% wetland, and 2% forest, then all natural pixels were reclassified to forest.
7. For subbasins with at least 5% dairy cover, one detailed dairy class with unique crop sequence and tillage settings was selected for HRU definition. All dairy pixels were reclassified to the detailed dairy class with the largest area in the subbasin.
8. For subbasins with at least 5% cash grain cover, one detailed cash grain class with unique tillage settings was selected for HRU definition. All cash grain pixels were reclassified to the detailed cash grain class with the largest area in the subbasin.
9. For subbasins with at least 5% continuous corn cover, one detailed continuous corn class with unique tillage settings was selected for HRU definition. All continuous corn pixels were reclassified to the detailed continuous corn class with the largest area in the subbasin.

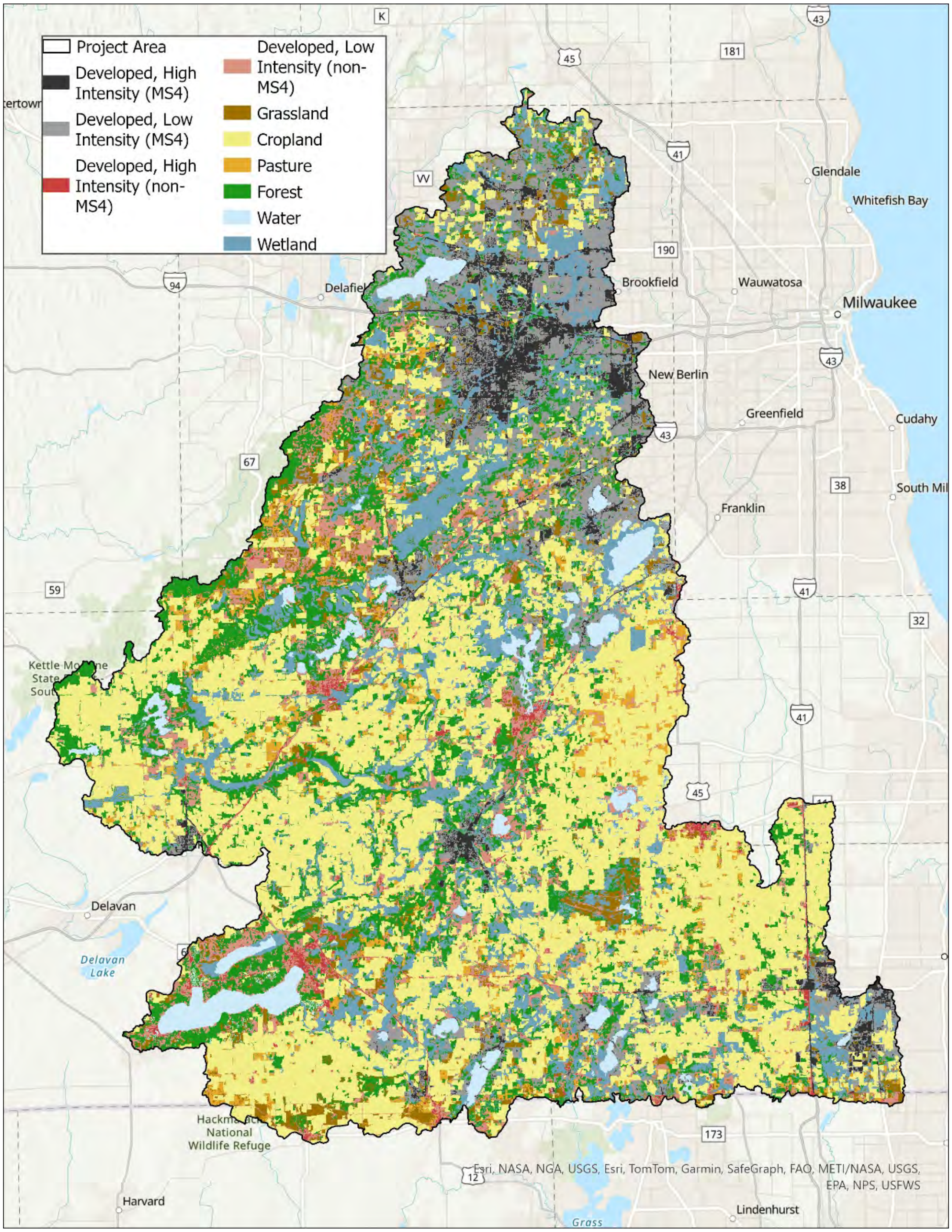

Pre-Processing
Remove Open Water pixels
Reclassify Potato/Vegetable pixels to Dairy, Cash Grain, and Continuous Corn
For each subbasin, apply 5% minimum area threshold to land cover classes (excluding Urban)
Is total Agriculture (Dairy + Cash Grain + Continuous Corn + Hay) ≥ 5% of subbasin area?
Yes
No
Repeat for: Cash Grain Continuous Corn Hay
Is Dairy < 5% of subbasin area?
Reclassify Agriculture pixels to the majority Agriculture class in the subbasin
Yes
No
Reclassify Dairy to other Agriculture classes
Keep original amount of Dairy area in subbasin
Is total Natural Cover (Forest + Wetland + Grassland) ≥ 5% of subbasin area?
No
Yes
Reclassify Natural Cover pixels to the majority Natural Cover class in subbasin
Is Forest < 5% of subbasin area?
Repeat for: Wetland Grassland
No
Yes
Keep original amount of Forest area in subbasin
Reclassify Forest to other Natural Cover classes
For each subbasin, establish detailed classes for Dairy, Cash Grain, and Continuous Corn
Reclassify all Dairy pixels to the majority detailed Dairy class in the subbasin
Reclassify all Cash Grain pixels to the majority detailed Cash Grain class in the subbasin
Reclassify all Continuous Corn pixels to the majority detailed Continuous Corn class in the subbasin
Final Land Cover Dataset

Once the final land cover and land use dataset was completed, it was incorporated into the SWAT+ model setup in QSWAT+. Some adjustments were made to the land use categories based on model calibration and a reevaluation of the agricultural surveys. Details about the final land use and land cover data used in the SWAT+ model are provided in the following figures. The first figure shows the different cropland rotation and tillage groups, and the second figure shows the overall land cover. The table that follows the figures shows the percentage of each land use and land cover category for each county.

Cropland Rotations and Tillage Groups for the SWAT+ Model



Final Land Cover and Tillage Groups in the Study Area



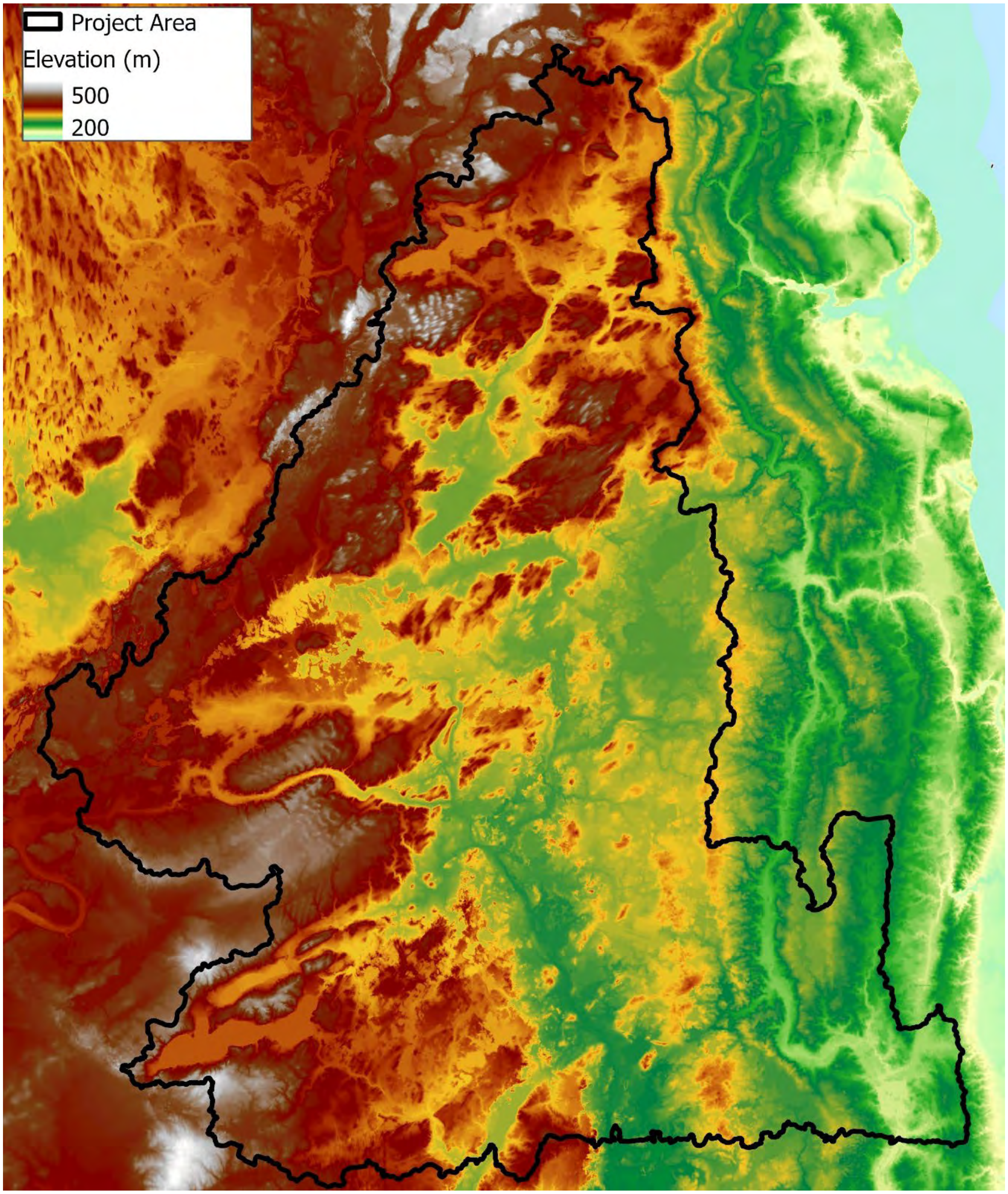
Land Use and Land Cover in the Study Area by County

Land Use Category	Kenosha	Racine	Walworth	Waukesha	Illinois	Jefferson	Milwaukee	Washington
Permitted MS4, high density	3%	1%	0%	8%	0%	0%	0%	0%
Permitted MS4, low density	6%	3%	1%	24%	0%	0%	0%	0%
Non-permitted urban, high density	1%	1%	1%	0%	3%	0%	15%	1%
Non-permitted urban, low density	6%	8%	7%	6%	12%	4%	27%	28%
Grassland	4%	1%	3%	7%	20%	0%	6%	2%
Continuous Corn, Tillage 1	1%	0%	4%	0%	4%	0%	0%	0%
Continuous Corn, Tillage 3	1%	0%	0%	0%	0%	0%	0%	0%
Cash Grain, Tillage 1	0%	0%	15%	4%	11%	0%	0%	0%
Cash Grain, Tillage 3	0%	0%	22%	6%	0%	27%	0%	22%
Cash Grain, Tillage 5	42%	42%	1%	6%	22%	0%	22%	0%
Dairy, Tillage 1	0%	1%	2%	1%	0%	0%	4%	0%
Dairy, Tillage 2	6%	7%	0%	0%	0%	0%	0%	0%
Dairy 2, Tillage 1	0%	0%	5%	0%	5%	0%	0%	0%
Pasture	4%	4%	4%	2%	6%	11%	0%	0%
Sod	0%	2%	0%	0%	0%	0%	0%	0%
Forest	11%	13%	18%	14%	11%	58%	0%	23%
Wetland	13%	12%	11%	18%	4%	0%	19%	24%
Water	3%	4%	5%	3%	1%	0%	7%	0%
Total Area (acres)	**139,842**	**112,254**	**211,797**	**212,963**	**13,521**	**954**	**265**	**186**

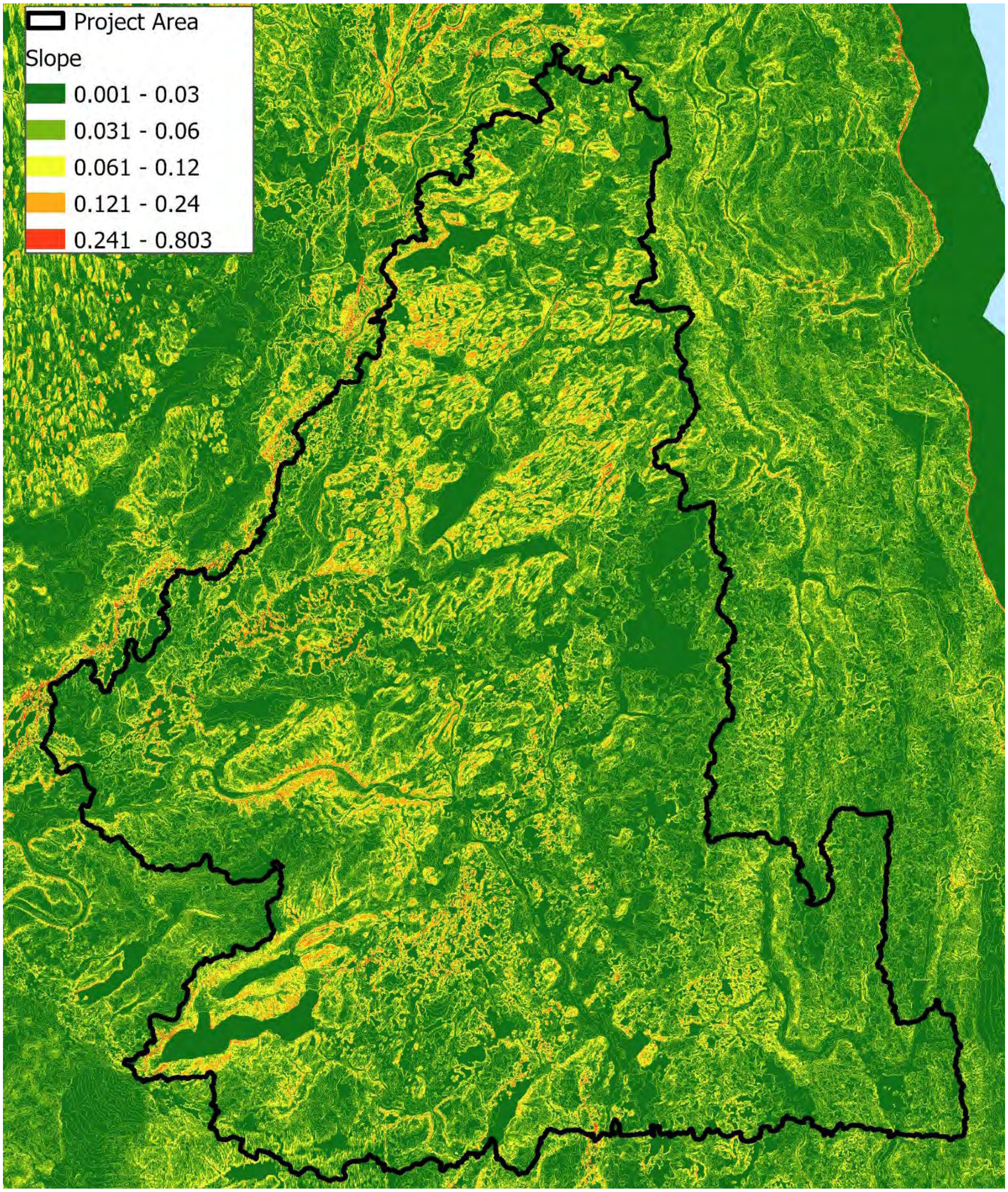
3. EVALUATION OF TOPOGRAPHY AND SLOPE

Topography and slope were also important inputs for the SWAT+ model. The 30-meter DEM (Wisconsin Department of Natural Resources, 2019) was used for the model setup in QSWAT+. QSWAT+ automatically calculated slopes throughout the basin and for each HRU. The following figures show the elevations from the 30-meter DEM and the slopes calculated by QSWAT+.

Elevations from 30-meter DEM



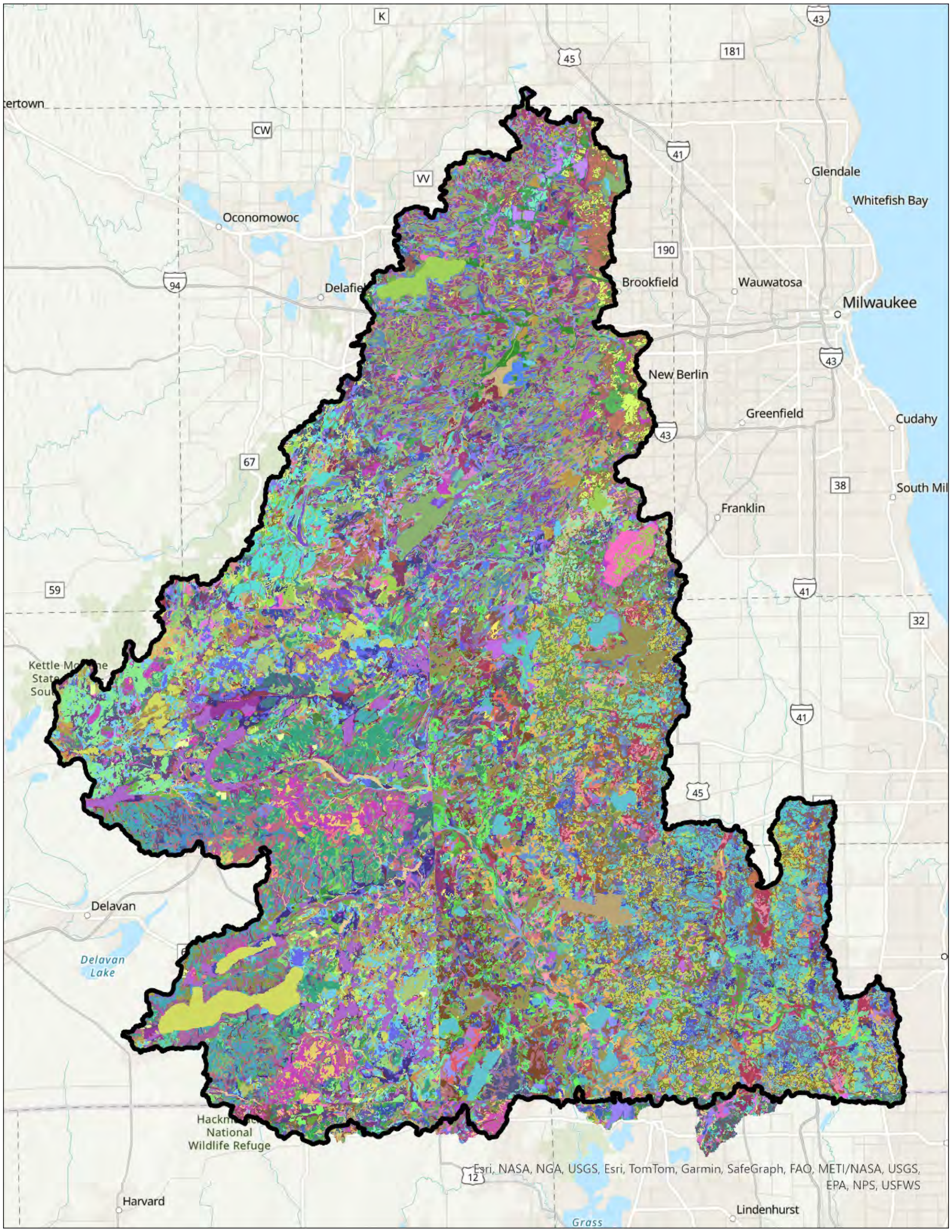
Slopes Calculated by QSWAT+



4. INCORPORATION OF SSURGO SOILS DATA

The SSURGO soil classifications were incorporated into the SWAT+ model for HRU definition. The following figure shows the different map units in the study area. Each unique color in the figure represents a unique map unit.

SSURGO Soil Map Units



Esri, NASA, NGA, USGS, Esri, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, USFWS

APPENDIX B

PERMITTED POINT SOURCES

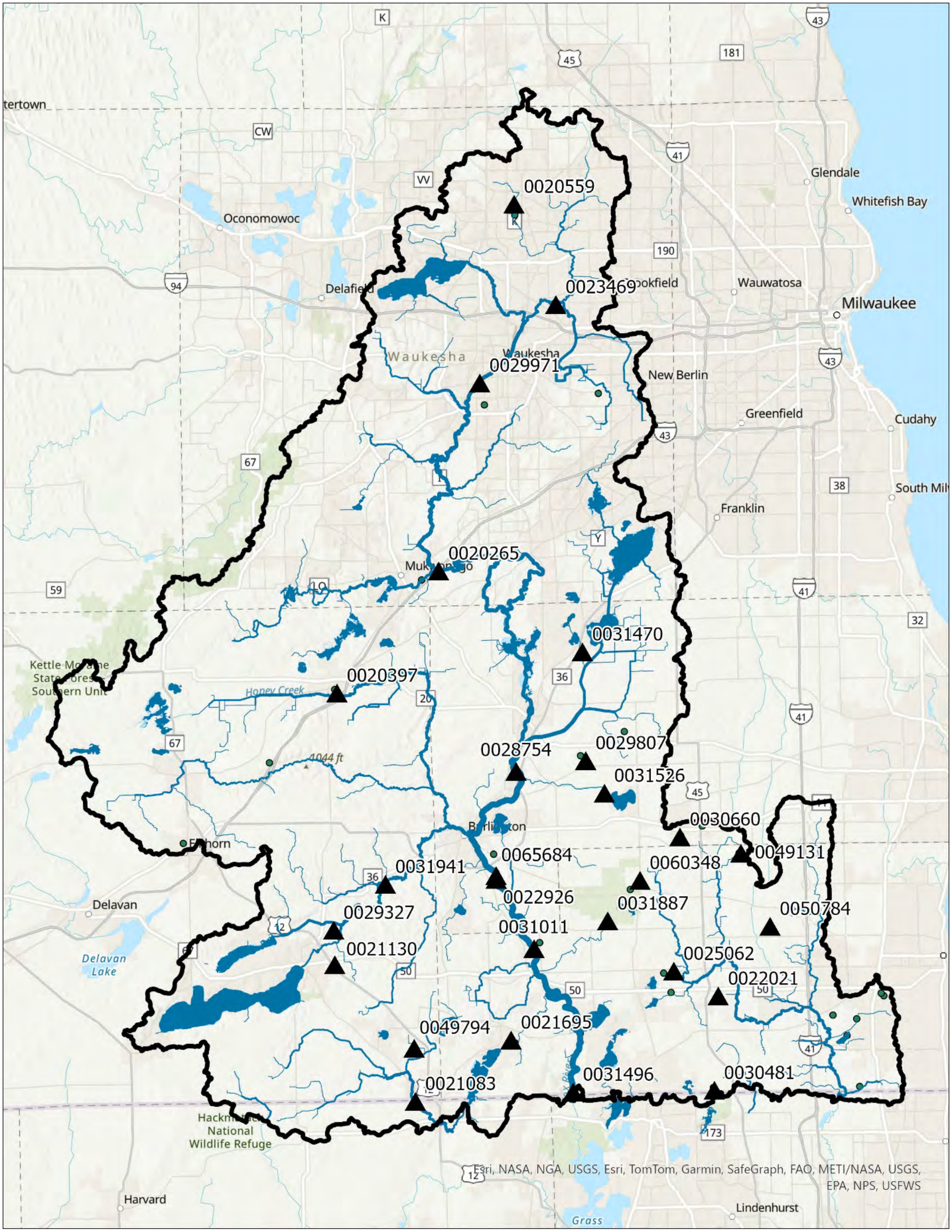
TABLE B.1

Facilities in Study Area with WPDES Permits

WDPES Permit Number	Permittee Name
0065684	Applied Material Solutions Inc Burlington
0060348	Brighton Dale Links WWTP
0022021	Bristol Utility District 1
0022926	Burlington Water Pollution Control
0023469	City of Brookfield
0029971	City of Waukesha
0031526	Eagle Lake Sewer Utility
0020397	East Troy Village
0030660	Fonks Home Center, Inc. - Hickory Haven
0029327	Grand Geneva Resort & Spa
0050784	Kenosha Beef International
0021130	Lake Geneva Wastewater Treatment Plant
0029807	Lakeview Neurological Rehab Center-Midwest
0031941	Lyons Sanitary District No. 2
0030481	MHC Rainbow Lake
0031470	Town of Norway Sanitary District #1
0021695	Twin Lakes Village
0049794	Village of Bloomfield
0021083	Village of Genoa City
0020265	Village of Mukwonago
0025062	Village of Paddock Lake
0031496	Village of Salem Lakes
0020559	Village of Sussex
0028754	Western Racine County Sewerage District
0031011	Wheatland Estates MHC
0031887	WI DNR Richard Bong Recreation Area
0049131	Wisconsin Electric Power Co - Tn of Paris

FIGURE B.1

Map of Facilities with WPDES Permits



Esri, NASA, NGA, USGS, Esri, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, USFWS

TABLE B.2

Stormwater Permits in Study Area

Permit Number	Permit Name
S050059	Root River Group MS4 Permit
S050075	Storm Water Municipal General Permit
S050105	Upper Fox River Watershed Group MS4 Permit
S065404	Menomonee River Watershed-Based MS4 Permit

TABLE B.3

Municipalities in Study Area with MS4 Permits

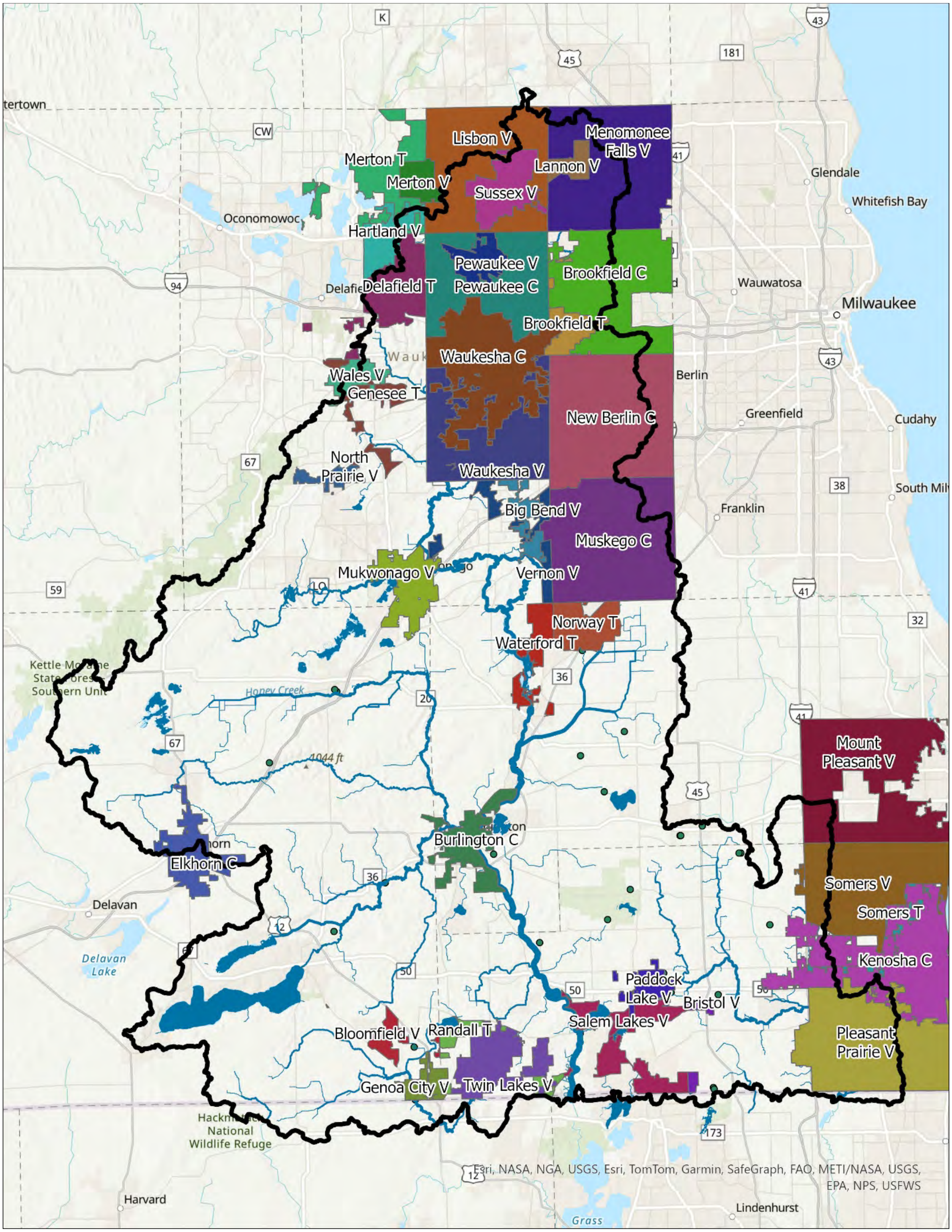
Entity Type[1]	Entity Name	Permit #
C	New Berlin	S050059
V	Big Bend	S050075
V	Bloomfield	S050075
V	Bristol	S050075
C	Burlington	S050075
C	Elkhorn	S050075
T	Genesee	S050075
V	Genoa City	S050075
V	Hartland	S050075
C	Kenosha	S050075
Cn	Kenosha	S050075
V	Lannon	S050075
T	Merton	S050075
V	Mukwonago	S050075
C	Muskego	S050075
V	North Prairie	S050075
T	Norway	S050075
V	Paddock Lake	S050075
V	Pleasant Prairie	S050075
Cn	Racine	S050075
T	Randall	S050075
V	Salem Lakes	S050075
V	Twin Lakes	S050075
V	Vernon	S050075
V	Wales	S050075
T	Waterford	S050075
Cn	Waukesha	S050075

Entity Type[1]	Entity Name	Permit #
T	Brookfield	S050105
T	Delafield	S050105
T	Lisbon	S050105
C	Pewaukee	S050105
V	Pewaukee	S050105
V	Sussex	S050105
C	Waukesha	S050105
C	Brookfield	S065404
V	Menomonee Falls	S065404

C: City, V: Village, T: Town, Cn: County

TABLE B.2

Permitted MS4 Boundaries in the Study Area



APPENDIX C

AGRICULTURAL MANAGEMENT TABLES IN SWAT

TABLE C.1

Land Use and Land Management Practices for Crop Rotations

Land use & management	Year	Month	Day	Operation	Details
Dairy 1, Tillage 1	1	3	15	Tillage	Field cultivator
	1	4	14	Fertilizer	Manure
	1	4	15	Tillage	Field cultivator
	1	5	15	Plant	Corn silage
	1	9	15	Harvest	Corn silage
	1	11	1	Fertilizer	Manure
	1	11	2	Tillage	Chisel plow
	2	3	15	Tillage	Field cultivator
	2	4	14	Fertilizer	Manure
	2	4	15	Tillage	Field cultivator
	2	5	15	Plant	Corn silage
	2	9	15	Harvest	Corn silage
	2	11	1	Fertilizer	Manure
	2	11	2	Tillage	Chisel plow
	3	3	15	Tillage	Field cultivator
	3	4	14	Fertilizer	Manure
	3	4	15	Tillage	Field cultivator
	3	5	25	Plant	Soybeans
	3	10	15	Harvest	Soybeans
	3	10	16	Tillage	Chisel plow
	3	10	17	Plant	Winter wheat
	4	7	15	Harvest	Winter wheat
	4	7	16	Fertilizer	Manure
	4	7	17	Tillage	Chisel plow
	4	7	18	Plant	Alfalfa
	4	11	1	Harvest	Alfalfa
	5	5	20	Harvest	Alfalfa
	5	6	25	Harvest	Alfalfa
	5	7	30	Harvest	Alfalfa
	5	9	5	Harvest	Alfalfa
	6	5	20	Harvest	Alfalfa
	6	6	30	Harvest	Alfalfa
	6	7	30	Harvest	Alfalfa
	6	9	5	Harvest	Alfalfa
Dairy 1, Tillage 2	1	4	14	Fertilizer	Manure
	1	4	15	Tillage	Field cultivator
	1	5	15	Plant	Corn silage
	1	9	15	Harvest	Corn silage

Land use & management	Year	Month	Day	Operation	Details
	1	11	1	Fertilizer	Manure
	1	11	2	Tillage	Vertical tillage
	2	4	14	Fertilizer	Manure
	2	4	15	Tillage	Field cultivator
	2	5	15	Plant	Corn silage
	2	9	15	Harvest	Corn silage
	2	11	1	Fertilizer	Manure
	2	11	2	Tillage	Vertical tillage
	3	4	14	Fertilizer	Manure
	3	4	15	Tillage	Field cultivator
	3	5	25	Plant	Soybeans
	3	10	15	Harvest	Soybeans
	3	10	16	Tillage	Vertical tillage
	3	10	17	Plant	Winter wheat
	4	7	15	Harvest	Winter wheat
	4	7	16	Fertilizer	Manure
	4	7	17	Tillage	Vertical tillage
	4	7	18	Plant	Alfalfa
	4	11	1	Harvest	Alfalfa
	5	5	20	Harvest	Alfalfa
	5	6	25	Harvest	Alfalfa
	5	7	30	Harvest	Alfalfa
	5	9	5	Harvest	Alfalfa
	6	5	20	Harvest	Alfalfa
	6	6	30	Harvest	Alfalfa
	6	7	30	Harvest	Alfalfa
	6	9	5	Harvest	Alfalfa
Dairy 2, Tillage 1	1	3	15	Tillage	Field cultivator
	1	4	14	Fertilizer	Manure
	1	4	15	Tillage	Field cultivator
	1	5	15	Plant	Corn silage
	1	9	15	Harvest	Corn silage
	1	11	1	Fertilizer	Manure
	1	11	2	Tillage	Chisel plow
	2	3	15	Tillage	Field cultivator
	2	4	14	Fertilizer	Manure
	2	4	15	Tillage	Field cultivator
	2	5	15	Plant	Corn silage
	2	9	15	Harvest	Corn silage
	2	11	1	Fertilizer	Manure

Land use & management	Year	Month	Day	Operation	Details
	2	11	2	Tillage	Chisel plow
	3	3	15	Tillage	Field cultivator
	3	4	14	Fertilizer	Manure
	3	4	15	Tillage	Field cultivator
	3	5	15	Plant	Corn silage
	3	9	15	Harvest	Corn silage
	3	11	1	Fertilizer	Manure
	3	11	2	Tillage	Chisel plow
	4	3	15	Tillage	Field cultivator
	4	4	14	Fertilizer	Manure
	4	4	15	Tillage	Field cultivator
	4	5	15	Plant	Alfalfa
	4	7	30	Harvest	Alfalfa
	4	9	5	Harvest	Alfalfa
	5	5	20	Harvest	Alfalfa
	5	6	25	Harvest	Alfalfa
	5	7	30	Harvest	Alfalfa
	5	9	5	Harvest	Alfalfa
	6	5	20	Harvest	Alfalfa
	6	6	30	Harvest	Alfalfa
	6	7	30	Harvest	Alfalfa
	6	9	5	Harvest	Alfalfa
Cash Grain, Tillage 1	1	3	15	Tillage	Field cultivator
	1	4	30	Fertilizer	Chemical fertilizer
	1	5	1	Tillage	Field cultivator
	1	5	15	Plant	Corn silage
	1	6	30	Fertilizer	Chemical fertilizer
	1	11	1	Harvest	Corn silage
	1	11	15	Tillage	Chisel plow
	2	3	15	Tillage	Field cultivator
	2	4	30	Fertilizer	Chemical fertilizer
	2	5	1	Tillage	Field cultivator
	2	5	15	Plant	Soybeans
	2	6	30	Fertilizer	Chemical fertilizer
	2	10	15	Harvest	Soybeans
	2	11	1	Tillage	Chisel plow
	3	3	15	Tillage	Field cultivator

Land use & management	Year	Month	Day	Operation	Details
	3	4	30	Fertilizer	Chemical fertilizer
	3	5	1	Tillage	Field cultivator
	3	5	15	Plant	Corn silage
	3	6	30	Fertilizer	Chemical fertilizer
	3	11	1	Harvest	Corn silage
	3	11	15	Tillage	Chisel plow
	4	3	15	Tillage	Field cultivator
	4	4	30	Fertilizer	Chemical fertilizer
	4	5	1	Tillage	Field cultivator
	4	5	15	Plant	Soybeans
	4	6	30	Fertilizer	Chemical fertilizer
	4	10	15	Harvest	Soybeans
	4	11	1	Tillage	Chisel plow
	5	3	15	Tillage	Field cultivator
	5	4	30	Fertilizer	Chemical fertilizer
	5	5	1	Tillage	Field cultivator
	5	5	15	Plant	Corn silage
	5	6	30	Fertilizer	Chemical fertilizer
	5	11	1	Harvest	Corn silage
	5	11	15	Tillage	Chisel plow
	6	3	15	Tillage	Field cultivator
	6	4	30	Fertilizer	Chemical fertilizer
	6	5	1	Tillage	Field cultivator
	6	5	15	Plant	Soybeans
	6	6	30	Fertilizer	Chemical fertilizer
	6	10	15	Harvest	Soybeans
	6	11	1	Tillage	Chisel plow
Cash Grain, Tillage 3	1	4	30	Fertilizer	Chemical fertilizer
	1	5	1	Tillage	Vertical tillage
	1	5	15	Plant	Corn silage
	1	6	30	Fertilizer	Chemical fertilizer
	1	11	1	Harvest	Corn silage

Land use & management	Year	Month	Day	Operation	Details
	2	4	30	Fertilizer	Chemical fertilizer
	2	5	1	Tillage	Vertical tillage
	2	5	15	Plant	Soybeans
	2	6	30	Fertilizer	Chemical fertilizer
	2	10	15	Harvest	Soybeans
	3	4	30	Fertilizer	Chemical fertilizer
	3	5	1	Tillage	Vertical tillage
	3	5	15	Plant	Corn silage
	3	6	30	Fertilizer	Chemical fertilizer
	3	11	1	Harvest	Corn silage
	4	4	30	Fertilizer	Chemical fertilizer
	4	5	1	Tillage	Vertical tillage
	4	5	15	Plant	Soybeans
	4	6	30	Fertilizer	Chemical fertilizer
	4	10	15	Harvest	Soybeans
	5	4	30	Fertilizer	Chemical fertilizer
	5	5	1	Tillage	Vertical tillage
	5	5	15	Plant	Corn silage
	5	6	30	Fertilizer	Chemical fertilizer
	5	11	1	Harvest	Corn silage
	6	4	30	Fertilizer	Chemical fertilizer
	6	5	1	Tillage	Vertical tillage
	6	5	15	Plant	Soybeans
	6	6	30	Fertilizer	Chemical fertilizer
	6	10	15	Harvest	Soybeans
Cash Grain, Tillage 5	1	4	30	Fertilizer	Chemical fertilizer
	1	5	1	Tillage	Field cultivator
	1	5	15	Plant	Corn silage
	1	6	30	Fertilizer	Chemical fertilizer
	1	11	1	Harvest	Corn silage
	1	11	15	Tillage	Vertical tillage

Land use & management	Year	Month	Day	Operation	Details
	2	4	30	Fertilizer	Chemical fertilizer
	2	5	1	Tillage	Field cultivator
	2	5	15	Plant	Soybeans
	2	6	30	Fertilizer	Chemical fertilizer
	2	10	15	Harvest	Soybeans
	2	11	1	Tillage	Vertical tillage
	2	4	30	Fertilizer	Chemical fertilizer
	3	5	1	Tillage	Field cultivator
	3	5	15	Plant	Corn silage
	3	6	30	Fertilizer	Chemical fertilizer
	3	11	1	Harvest	Corn silage
	3	11	15	Tillage	Vertical tillage
	4	4	30	Fertilizer	Chemical fertilizer
	4	5	1	Tillage	Field cultivator
	4	5	15	Plant	Soybeans
	4	6	30	Fertilizer	Chemical fertilizer
	4	10	15	Harvest	Soybeans
	4	11	1	Tillage	Vertical tillage
	5	4	30	Fertilizer	Chemical fertilizer
	5	5	1	Tillage	Field cultivator
	5	5	15	Plant	Corn silage
	5	6	30	Fertilizer	Chemical fertilizer
	5	11	1	Harvest	Corn silage
	5	11	15	Tillage	Vertical tillage
	6	4	30	Fertilizer	Chemical fertilizer
	6	5	1	Tillage	Field cultivator
	6	5	15	Plant	Soybeans
	6	6	30	Fertilizer	Chemical fertilizer
	6	10	15	Harvest	Soybeans
	6	11	1	Tillage	Vertical tillage
Continuous Corn, Tillage 1	1	3	15	Tillage	Field cultivator
	1	4	30	Fertilizer	Chemical fertilizer

Land use & management	Year	Month	Day	Operation	Details
	1	5	1	Tillage	Field cultivator
	1	5	15	Plant	Corn silage
	1	6	30	Fertilizer	Chemical fertilizer
	1	11	1	Harvest	Corn silage
	1	11	15	Tillage	Chisel plow
Continuous Corn, Tillage 3	1	4	30	Fertilizer	Chemical fertilizer
	1	5	1	Tillage	Vertical tillage
	1	5	15	Plant	Corn silage
	1	6	30	Fertilizer	Chemical fertilizer
	1	11	1	Harvest	Corn silage
Sod	1	9	14	Harvest	Bluegrass
	1	9	15	Tillage	Moldboard plow
	1	10	1	Fertilizer	Chemical fertilizer
	1	10	14	Tillage	Field cultivator
	1	10	15	Plant	Bluegrass

APPENDIX D

LAKES INCLUDED IN SWAT+ MODEL

TABLE D.1

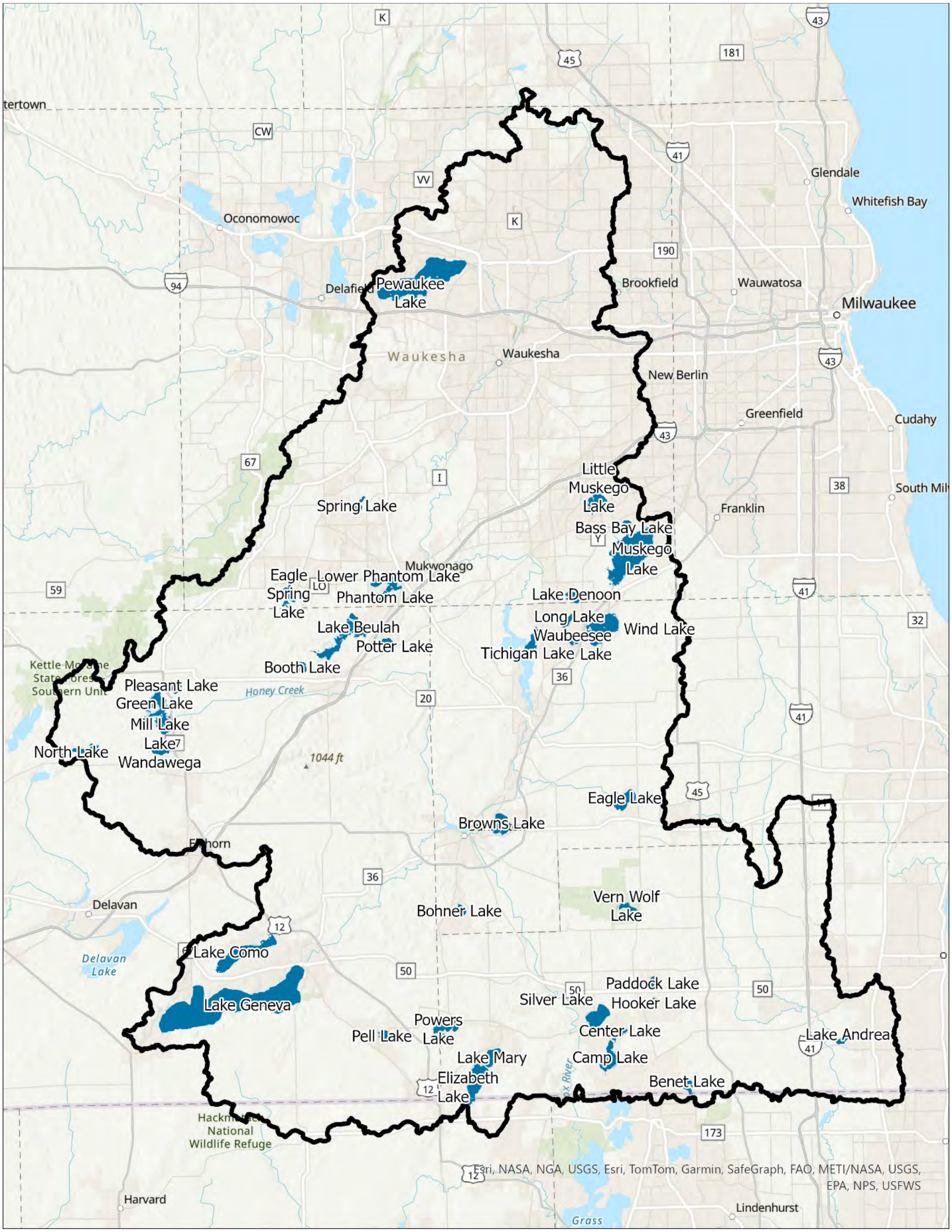
Table of Lakes and Reservoirs Included in the FOXIL SWAT+ Model

Lake Name	WBIC	Area (ac)	Volume (ac-ft)
Bass Bay Lake	763200	638	6,900
Benet Lake & Lake Shangrila	734800	105	553
Bohner Lake	750800	255	935
Booth Lake	740400	113	1,376
Browns Lake	750300	130	1,281
Camp Lake	747100	464	460
Center Lake	747300	459	7,453
Eagle Lake	759800	5,262	320,984
Eagle Spring Lake	768600	135	1,243
Elizabeth Lake	742800	162	1,304
Hooker Lake	738400	129	2,450
Lake Andrea	733850	936	8,995
Lake Beulah	766600	396	3,135
Lake Como	757900	88	770
Lake Denoon	761300	104	290
Lake Geneva	758300	433	1,555
Lake Mary	743000	155	1,910
Lake Wandawega	740700	506	7,170
Lauderdale Lakes[1]		119	480
Little Muskego Lake	762700	311	1,127
Long Lake	761100	834	14,279
Lower Phantom Lake	765800	129	1,136
Muskego Lake	762400	102	1,224
North Lake	741200	2,493	36,863
Paddock Lake	737900	158	600
Pell Lake	743600	2,260	7,000
Pewaukee Lake	772000	100	1,164
Phantom Lake	766000	461	2,328
Pleasant Lake	741500	310	2,798
Potter Lake	753800	834	5,500
Powers Lake	744200	107	1,154
Silver Lake	747900	86	314
Spring Lake	770600	186	748
Tichigan Lake	763600	515	3,267
Vern Wolf Lake	739100	279	5,859
Waubeesee Lake	760900	946	4,033
Wind Lake	761700	162	2,940

1. Lauderdale Lakes (Pleasant Lake, Green Lake, Mill Lake) modeled as a single lake

FIGURE D.1

Map of Lakes and Reservoirs Included in the FOXIL SWAT+ Model



APPENDIX E

SUPPLEMENTAL CALIBRATION DATASETS

TABLE E.1

Average Annual Crop Yield from 2011 to 2022

Crop	NASS Units	Average NASS Yield	Moisture Content (%)	Unit Conversion Factor	SWAT+ Units (Mg/ha)
Alfalfa, hay	short tons/acre, dry	2.9	0	0.45	6.37
Corn	bushels/acre	168.7	15.5	15.9	8.97
Corn silage	short tons/acre, moist	19.6	65	0.45	15.21
Soybean	bushels/acre	48.8	13	14.9	2.85
Winter wheat	bushels/acre	73.2	12.5	14.9	4.30

TABLE E.2

Phosphorus Assessments for Lakes and Reservoirs

		GSM TP Concentration (μg/L)	
Lake Name	WBIC	TP Threshold	Monitored (WATERS)
Pewaukee Lake	772000	30	17
Spring Lake	770600	20	11
Eagle Spring Lake	768600	40	17
Booth Lake	740400	20	14
Lake Beulah	766600	15	15
Lower Phantom Lake	765800	40	16
Tichigan Lake	763600	30	27
Little Muskego Lake	762700	30	16
Lake Denoon	761300	20	28
Waubeesee Lake	760900	30	19
Wind Lake	761700	30	32
Eagle Lake	759800	40	134
Pleasant Lake	741500	30	13
Lake Geneva	758300	15	12
Bohner Lake	750800	30	20
Browns Lake	750300	30	20
Silver Lake	747900	30	21
Powers Lake	744200	30	16
Lake Mary	743000	30	16
Benet Lake & Lake Shangrila	734800	30	53
Paddock Lake	737900	30	17
Hooker Lake	738400	30	39

APPENDIX F

SENSITIVITY ANALYSIS INPUTS AND RESULTS

TABLE F.1

Model Parameters Tested for Sensitivity Analysis

SWAT+ Parameter	Parameter Location[1]	Description	Low	High	Adj[2].
alpha	aqu	Baseflow alpha factor	0	1	u
flo_min	aqu	Threshold of shallow groundwater for return flow	0	10	u
revap_co	aqu	Groundwater revap coefficient	0.02	0.2	u
deep_seep	aqu	Deep aquifer percolation factor	0	1	u
revap_min	aqu	Threshold of shallow groundwater for revap	0	500	u
sp_yld	aqu	Specific yield for shallow aquifer	0.05	0.5	u
dep_bot	aqu	Depth-mid-slope to bottom of aquifer	1	50	u
surlag	bsn	Surface runoff lag coefficient	0	15	u
cn2	hru	Curve number	-25	25	r
esco	hru	Soil evaporation compensation factor	0	1	u
slope	hru	HRU slope	-75	75	r
biomix	hru	Biological mixing efficiency	0	1	u
canmx	hru	Maximum canopy storage	0	100	u
epco	hru	Plant uptake compensation factor	0	1	u
snofall_tmp	hru	Snowfall temperature	-10	5	u
snomelt_tmp	hru	Snowmelt temperature	-2	20	u
snomelt_lag	hru	Snow pack temperature lag factor	0.01	1	u
snomelt_min	hru	Melt factor for snow on June 21	0	10	u
snomelt_max	hru	Melt factor for snow on December 21	0	10	u
cn3_swf	hru	Soil water at CN3	0	1	u
lat_ttime	hru	Exponential of the lateral flow travel time	0.5	180	u
petco	hru	Coefficient related to radiation used in PET equation	0.7	1.3	u
perco	hru	Percoloation coefficient; adjusts soil moisture for perc to occur	0	1	u
chn	rte	Channel Manning's N	0.01	0.5	u
cov	rte	Channel cover factor, erodibility	0	1	u
cherod	rte	Channel erodibility by month	0	1	u
awc	sol	Soil available water capacity	-50	50	r
k	sol	Soil hydraulic conductivity	-50	50	r
alb	sol	Soil albedo	-20	20	r
bd	sol	Soil bulk density	-50	20	r
evlai	bsn	Evaporation from LAI	0	10	u
evrch	bsn	Evaporation reach coefficient	0.5	1	u
chw	rte	Average channel width	-50	50	r
chd	rte	Average channel depth	-50	50	r

SWAT+ Parameter	Parameter Location[1]	Description	Low	High	Adj[2].
slope_len	hru	Slope length	-75	75	r
ovn	hru	Overland manning's	-75	75	r
lat_len	hru	Length of lateral flow	1	150	u
latq_co	hru	Lateral flow coefficient	0	1	u
tile_dep	hru	Depth to tile drain	10	2000	u
tile_dtime	hru	Time to drain soil to field capacity	10	72	u
tile_lag	hru	Drain tile lag time	10	100	u
tile_rad	hru	Effective radius of drains	3	40	u
tile_dist	hru	Distance between two drain tiles	7600	30000	u
tile_latk	hru	Multiplication factor to determine lateral ksat	0.01	4	u
crk	sol	Crack volume of soil profile	0	1	u
z	sol	Depth of soil layer	-50	25	r
k	sol	Saturated hydraulic conductivity	-50	50	r
clay	sol	Clay content of the soil layer	-50	50	r
chs	rte	Channel slope	-75	150	r
chk	rte	Effective hydraulic conductivity of channel alluvium	0.01	500	u
bf_max	aqu	Baseflow rate at which all streams linked to an aquifer receive groundwater flow	0.1	2	u
dep_wt_init	aqu	Initial depth to water table	5	50	u
flo_dist	aqu	Average flow distance to stream	5	300	u
flo_init_mm	aqu	Initial groundwater flow	0.01	5	u
lai_pot	plt	Maximum potential leaf area index	0.01	12	u
harv_idx	plt	Harvest index	0.01	0.95	u

1. Input file in SWAT+. aqu: Aquifer, bsn: Basin, hru: HRU, plt: Plant, rte: Routing unit, sol: Soil
2. r: Value adjusted relative to current (%), u: Value adjusted uniformly

TABLE F.2

Results of Sensitivity Analysis

Rank	Flow Volume	Peak Flow	Sediment	Sediment P	Soluble P
1	cn2	surlag	cov	cn2	chk
2	dep_bot	cn2	chs	surlag	cn2
3	petco	petco	perco	biomix	chw
4	perco	dep_bot	latq_co	chk	z
5	esco	cov	chk	z	biomix
6	flo_min	chs	chw	chs	petco
7	latq_co	snomelt_min	lat_len	chw	bd
8	snomelt_min	cn3_swf	cherod	perco	cn3_swf
9	awc	alpha	surlag	petco	chs
10	alpha	perco	esco	snomelt_min	snomelt_min

APPENDIX G

FINAL CALIBRATED MODEL PARAMETERS

TABLE G.1

Plant Growth Calibration Parameters

Crop	Parameter	Default SWAT+ Value	Calibrated Value
corn	bm_e	40	34
	harv_idx	0.55	0.5
csil	harv_idx	0.55	0.6
	tmp_opt	25	24
	tmp_base	8	6
	lai_pot	4	4.5
soyb	harv_idx	0.31	0.28
alfa	tmp_base	4	3
	bm_e	20	22
wwht	tmp_base	0	1
	tmp_opt	18	18

TABLE G.2

Model Calibration Initialization Parameters

Parameter	Parameter Type	Locations Applied	Change Type	Change Value	SWAT+ Default	SWAT+ Rec.	File Changed
flo_min	Aquifer	All	Absolute	10	5	0 to 10	aquifer.aqu
cn_froz	Runoff	All	Absolute	0.00001	0.000862	None listed	parameters.bsn
sw_init	Runoff	All	Absolute	0.5	0	0 to 1	parameters.bsn
ch_s	Runoff	Mainstem	Percent	-50			hyd-sed-lte.cha
	Runoff	Mukwonago	Percent	50			
	Runoff	West Basins	Percent	-50			
tmp_lag	Snow	All	Absolute	0.25	1	0 to 1	snow.sno
snow_h2o	Snow	All	Absolute	25	1	0 to 500	snow.sno
sed	Sediment	All	Absolute	varies			om_water.ini

TABLE G.3
Plant Community Calibration Initialization Parameters

Parameter	Locations Applied	Change Type	Change Value	SWAT+ Default	SWAT+ Rec.	File Changed
rsd_init	frsd	Absolute	8000	10000	0 to 10000	plant.ini
	wetl	Absolute	12000	10000	0 to 10000	
	crops	Absolute	4000	10000	0 to 10000	
	urbn, gras	Absolute	10000	10000	0 to 10000	
	past	Absolute	12000	10000	0 to 10000	
yrs_init	frsd, past, gras, urbn	Absolute	10			plant.ini
	wetl	Absolute	30			
plt_name	gras_comm	Absolute	past			plant.ini
	urb_comm	Absolute	urbn_cool			
plnt_com	name: all urban	Absolute	urb_comm			landuse.lum
cn2	name: gras_lum	Absolute	open_p	Varies	35 to 98	landuse.lum
	name: past_lum	Absolute	pastg_f	Varies	35 to 98	
	name: sodt_lum	Absolute	fal_bare	Varies	35 to 98	

TABLE G.4
Global Flow Calibration Parameters

Parameter	Locations Applied	Change Type	Change Value	SWAT+ Default	SWAT+ Rec.	Change Location
surlag.bsn	All	Absolute	0.15	4	1 to 24	R script
awc.sol	All	Relative	0.03	SSURGO	0 to 1	R script
canmx.hru	Landuse: non-frsd	Absolute	1	1	None listed	R script
	Landuse: frsd	Absolute	5	1	None listed	
k.sol	All	Relative	0.12	SSURGO	0 to 2000	R script
	sod	Absolute	0.32	SSURGO	0 to 2000	

TABLE G.5

Basin-Specific Flow Calibration Parameters

			Calibration Basin[1]						
Parameter	Locations Applied	Change Type	DHW	MR	WB	SLMC	SWAT+ Default	SWAT+ Rec.	Change Location
cn2.hru	Non-Urban	Percent	15	10	15	10	Varies	35 to 98	R script
	Urban	Percent	3	0	5	3	Varies	35 to 98	R script
cn3_swf.hru	All	Absolute	0.6	0.95	0.2	0.4	0.95	0 to 1	R script
esco.hru	All	Absolute	0.3	0.25	0.3	0.5	0.95	0 to 1	R script
epco.hru	All	Absolute	0.6	0.2	0.6	0.8	0.5	0 to 1	R script
petco.hru	All	Absolute	0.85	0.85	0.85	0.85	1	None listed	R script
perco.hru	All	Absolute	1	0.9	0.9	1	0.9	0 to 1	R script
latq_co.hru	All	Absolute	0.6	0.1	0.8	1	1	None listed	R script
snomelt_tmp.hru	All	Absolute	2.25	1.5	2	1.5	0.5	-5 to 5	R script
snofall_tmp.hru	All	Absolute	2	3	2	2	1	-5 to 5	R script
snomelt_min.hru	All	Absolute	4	3	2	2	4.5	0 to 10	R script
snomelt_max.hru	All	Absolute	5	5	4	8	4.5	0 to 10	R script

1. DHW: Developed Headwaters; MR: Mukwonago River; WB: Western Basins; SLMC: Southern Lake Michigan Coastal

TABLE G.6

Aquifer-Specific Flow Calibration Parameters

			Calibration Basin[1]							
Parameter	Locations Applied	Change Type	DHW	MR	WB	FRM	SLMC	SWAT+ Default	SWAT+ Rec.	Change Location
dep_bot.aqu	All	Absolute	10	10	Input	5	10	10	0 to 10	R script
alpha.aqu	All	Absolute	0.15	0.0025	0.01	0.01	0.25	0.048	0 to 1	R script
revap_min.aqu	All	Absolute				2.5		5	0 to 10	R script
deep_seep.aqu	All	Absolute				0		0.05	0 to 1	R script
revap_co.aqu	All	Absolute				0.01		0.02	0.02 to 0.2	R script

1. DHW: Developed Headwaters; MR: Mukwonago River; WB: Western Basins; Fox River Mainstem; SLMC: Southern Lake Michigan Coastal

TABLE G.7

Geneva Lake Flow Calibration Parameters

Parameter	Parameter Type	Locations Applied	Change Type	Change Value	SWAT+ Default	SWAT+ Rec.	Change Location
cn2.hru	Runoff	Forest	Absolute	85	Varies	35 to 98	R script
cn2.hru	Runoff	Urban LD	Absolute	92	Varies	35 to 98	R script
dep_bot.hru	Aquifer	Aquifer 7	Percent	50	6	0 to 10	R script
alpha.aqu	Aquifer	Aquifer 7	Absolute	0.002	0.01	0 to 1	R script
revap_min.aqu	Aquifer	Aquifer 7	Absolute	2.5	5	0 to 10	R script
deep_seep.aqu	Aquifer	Aquifer 7	Absolute	0	0.05	0 to 1	R script
revap_co.aqu	Aquifer	Aquifer 7	Absolute	0.01	0.02	0.02 to 0.2	R script

TABLE G.8

Global Sediment Calibration Parameters

Parameter	Locations Applied	Change Type	Change Value	SWAT+ Default	SWAT+ Rec.	Change Location	File Changed
usle_k.sol	All	Percent	50	SSURGO	0 to 0.65	R script	
rock.sol	All	Absolute	0	SSURGO	0 to 100	R script	
adj_pkrt_sed	All	Absolute	8	1	0 to 2	Input file	parameters.bsn
slp_len	toportu####	Absolute	0	50	None listed	Input file	topopgraphy.hyd
bed_load	All outside of Muk	Absolute	0	0.5	None listed	Input file	hyd-sed-lte.cha
ov_mann	name: sodt_lum	Absolute	fallow_nores			Input file	landuse.lum
	name: gras_lum	Absolute	shortgrass				
	name: past_lum	Absolute	shortgrass				
cons_prac	Tiled areas, urban areas	Absolute	contour_farming			Input file	landuse.lum
biomix.hru	Non-Urban	Absolute	0.35	0.2	None listed	R script	
	Urban	Absolute	0	0.2	None listed		
rsd_decay	All	Absolute	0.005	0.01	0 to 0.05	Input file	parameters.bsn
plnt_decomp	plt_name: urbn_cool	Absolute	0.001	0.05	0.01 to 0.099	Input file	plants.plt
rsd_pctcov		Absolute	1	0.5	None listed		
rsd_covfac		Absolute	0.04	0.07	None listed		
uslec_min		Absolute	0.1	0.003	0.001 to 0.5		
hu_lai_decl		Absolute	0.99	0.8			
dlai_rate		Absolute	0.1	0			
lai_pot	plt_name: past	Absolute	3	4	0.5 to 10	Input file	plants.plt
rsd_covfac		Absolute	0.04	0.07	None listed		
bm_dieoff		Absolute	0	0.1	0 to 1		
rsd_pctcov	plt_name: blug	Absolute	0.05	0.53	None listed	Input file	plants.plt
rsd_covfac		Absolute	0.005	0.028	None listed		
urban	urld_lum, ms4l_lum	Absolute	urld			Input file	landuse.lum
	urhd_lum, ms4h_lum	Absolute	urmd				

TABLE G.9

Global Phosphorus Calibration Parameters

Parameter	Locations Applied	Change Type	Change Value	SWAT+ Default	SWAT+ Rec.	Change Location	File Changed
soil_p	All	Absolute	1	0		Input file	codes.bsn
p_avail	All	Absolute	0.15	0.4	0.01 to 0.7	Input file	parameters.bsn
p_soil	All	Absolute	500	175	100 to 200	Input file	parameters.bsn
p_perc	All	Absolute	10	10	10 to 17.5	Input file	parameters.bsn
p_uptake	All	Absolute	100	20	0 to 100	Input file	parameters.bsn
lat_orgp.hru	SLMC	Absolute	100	0	0 to 200	R script	
erogrp.hru	Urban	Absolute	1	Calculated		R script	
	Mukwonago	Absolute	2	Calculated		R script	
	Honey Creek	Absolute	2	Calculated		R script	
frac_p_em frac_p_50 frac_p_mat	past	Absolute	0.002 0.001 0.001	0.008 0.0032 0.0019		Input file	plants.plt
frac_p_em frac_p_50 frac_p_mat	urbn_cool	Absolute	0.0084 0.0032 0.0019	0.0099 0.0022 0.0019		Input file	plants.plt
pltp_stl	All	Absolute	0.001	0.05	0.001 to 0.1	Input file	nutrients.cha
pltp_solp	All	Absolute	0.01	0.35	0.01 to 0.7	Input file	nutrients.cha
ptl_p	All	Absolute	0.1	0	0 to 100	Input file	nutrients.cha
ben_disp	All	Absolute	0	0.05	0.001 to 0.1	Input file	nutrients.cha

TABLE G.10

Reservoir Flow Calibration Parameters

Parameter	Locations Applied	Change Type	Change Value	SWAT+ Default	SWAT+ Rec.	File Changed
evap_co	res0902, res1004, pnd9001	Absolute	0.65	0.6		hydrology.res
evap_co	res1401	Absolute	0.7	0.6		hydrology.res
evap_co	res2601	Absolute	0.45	0.6		hydrology.res
drawdown days	drawdown_days_1	Absolute	1			res_rel.dtl
drawdown days	drawdown_days_2	Absolute	2			
drawdown days	drawdown_days_5	Absolute	5			

TABLE G.11

Reservoir Sediment Calibration Parameters

Parameter	Locations Applied	Change Type	Change Value	SWAT+ Default	SWAT+ Rec.	File Changed
sed_amt	sedres1	Absolute	100	1	1 to 5000	sediment.res
d50		Absolute	0.5	10	None listed	
carbon		Absolute	0.4	0	None listed	
bd		Absolute	0.5	0	None listed	
stl_vel		Absolute	0	1	None listed	

TABLE G.12

Reservoir Phosphorus Calibration Parameters

Parameter	Locations Applied	Change Type	Change Value	SWAT + Default	SWAT+ Rec.	File Changed
mid_p_stl	nutres1	Absolute	20	10	2 to 20	nutrients.res
p_stl		Absolute	20	10	2 to 20	
p_conc_min		Absolute	0.001	0.01		
mid_p_stl	nutres1a	Absolute	20	10	2 to 20	nutrients.res
p_stl		Absolute	20	10	2 to 20	
p_conc_min		Absolute	0	0.01		
mid_p_stl	nutres2	Absolute	70	10	2 to 20	nutrients.res
p_stl		Absolute	70	10	2 to 20	
p_conc_min		Absolute	0.001	0.01		
mid_p_stl	nutres3	Absolute	250	10	2 to 20	nutrients.res
p_stl		Absolute	250	10	2 to 20	
p_conc_min		Absolute	0.001	0.01		
mid_p_stl	nutres4	Absolute	1000	10	2 to 20	nutrients.res
p_stl		Absolute	1000	10	2 to 20	
p_conc_min		Absolute	0	0.01		
mid_p_stl	nutres5	Absolute	1000	10	2 to 20	nutrients.res
p_stl		Absolute	2500	10	2 to 20	
p_conc_min		Absolute	0	0.01		

TABLE G.13

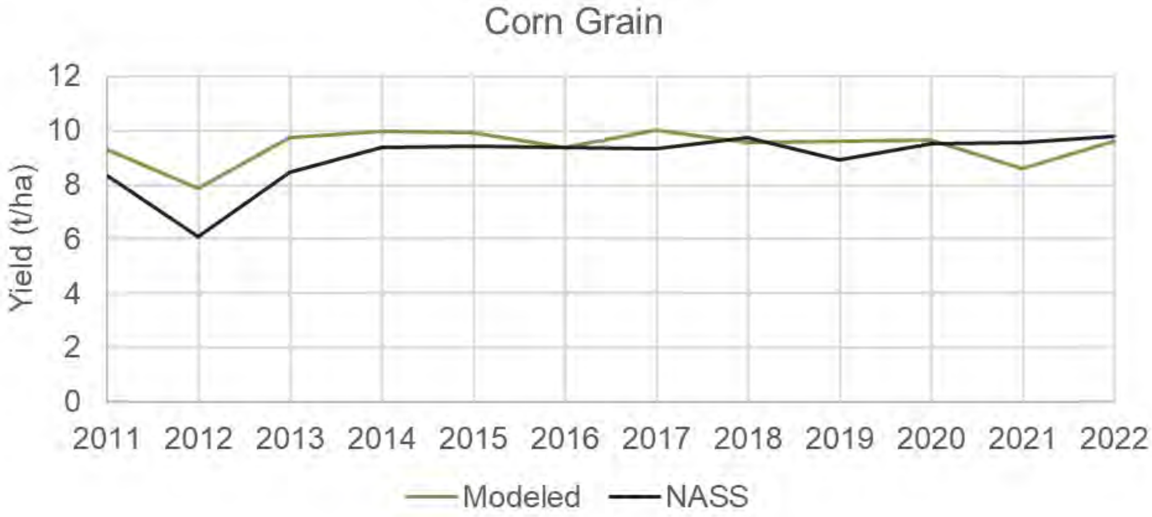
Reservoir and Lake Calibration Parameter Assignment

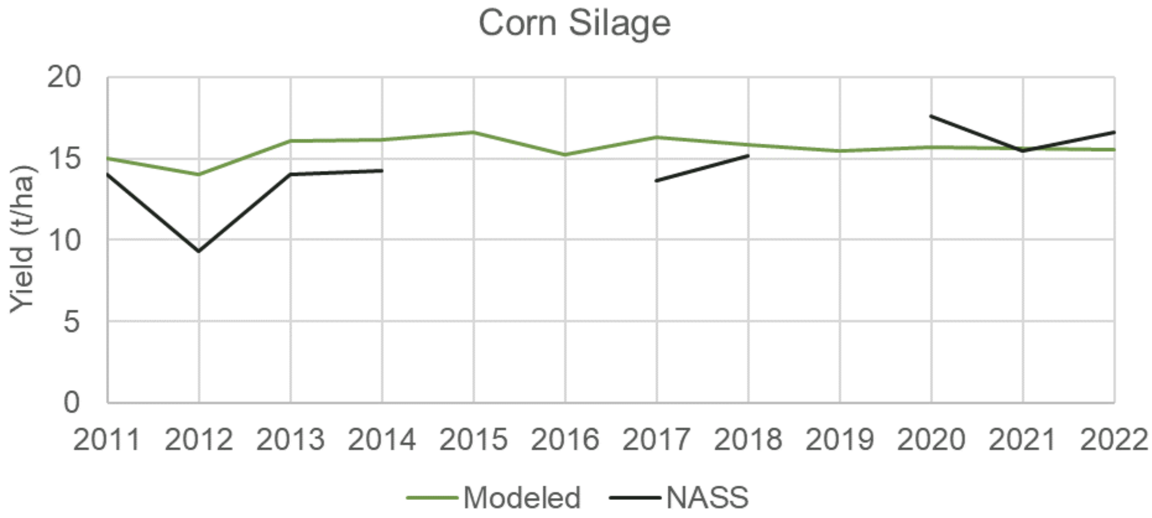
Lake Name	SWAT+ ID	Reservoir Release	Sediment Parameters	Phosphorus Parameters
Pewaukee Lake	res0103	drawdown_days_5	sedres1	nutres3
Spring Lake	pnd0500	drawdown_days_1	sedres1	nutres4
Eagle Spring Lake	res0902	drawdown_days_1	sedres1	nutres4
Booth Lake	pnd1000	drawdown_days_1	sedres1	nutres1
Lake Beulah	res1001	drawdown_days_1	sedres1	nutres2
Phantom Lake	pnd1002	drawdown_days_1	sedres1	nutres2
Lower Phantom Lake	res1004	drawdown_days_2	sedres1	nutres5
Tichigan Lake	pnd1200	drawdown_days_1	sedres1	nutres2
Little Muskego Lake	pnd1300	drawdown_days_1	sedres1	nutres4
Bass Bay Lake	pnd1400	drawdown_days_1	sedres1	nutres3
Muskego Lake	res1401	drawdown_days_5	sedres1	nutres3
Lake Denoon	pnd1600	drawdown_days_1	sedres1	nutres2
Long Lake	pnd1601	drawdown_days_1	sedres1	nutres3
Waubeesee Lake	res1602	drawdown_days_1	sedres1	nutres2
Wind Lake	res1604	drawdown_days_5	sedres1	nutres3
Eagle Lake	pnd1700	drawdown_days_1	sedres1	nutres1
Pleasant Lake	pnd1900	drawdown_days_1	sedres1	nutres3
Lauderdale Lakes	pnd1902	drawdown_days_5	sedres1	nutres3
Potter Lake	pnd2100	drawdown_days_1	sedres1	nutres2
Lake Wandawega	pnd2300	drawdown_days_1	sedres1	nutres3
Lake Como	res2500	drawdown_days_1	sedres1	nutres2
Lake Geneva	res2601	drawdown_days_5	sedres1	nutres1
Pell Lake	pnd2800	drawdown_days_1	sedres1	nutres2
Bohner Lake	pnd2900	drawdown_days_1	sedres1	nutres4
Browns Lake	pnd3000	drawdown_days_1	sedres1	nutres2
Silver Lake	pnd3202	drawdown_days_1	sedres1	nutres4
North Lake	pnd4000	drawdown_days_1	sedres1	nutres3
Powers Lake	pnd6100	drawdown_days_5	sedres1	nutres2
Lake Mary	pnd6105	drawdown_days_5	sedres1	nutres3
Elizabeth Lake	res6106	drawdown_days_5	sedres1	nutres3
Center Lake	pnd7000	drawdown_days_1	sedres1	nutres3
Camp Lake	res7001	drawdown_days_1	sedres1	nutres3
Benet Lake & Lake Shangrila	pnd8000	drawdown_days_1	sedres1	nutres2
Vern Wolf Lake	pnd9001	drawdown_days_1	sedres1	nutres2
Paddock Lake	pnd9003	drawdown_days_1	sedres1	nutres3
Hooker Lake	pnd9004	drawdown_days_1	sedres1	nutres2
Lake Andrea	pnd9300	drawdown_days_1	sedres1	nutres2

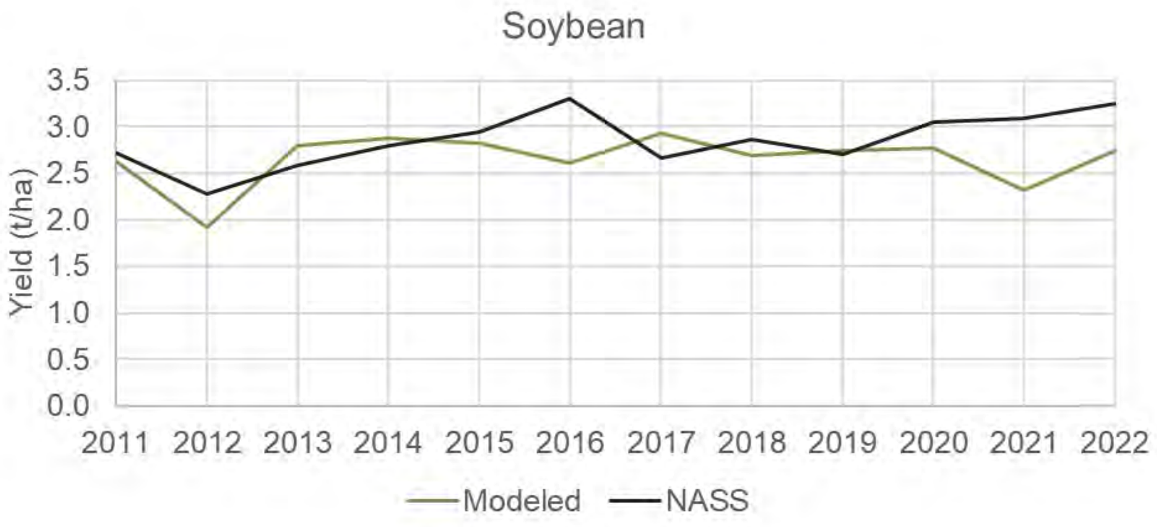
APPENDIX H

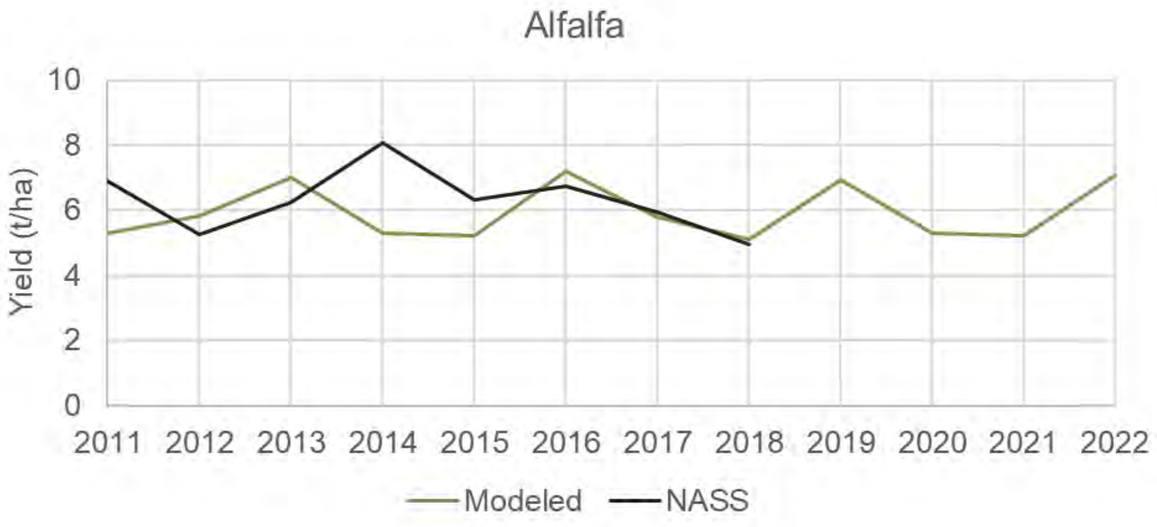
SWAT+ MODEL CALIBRATION AND VALIDATION RESULTS

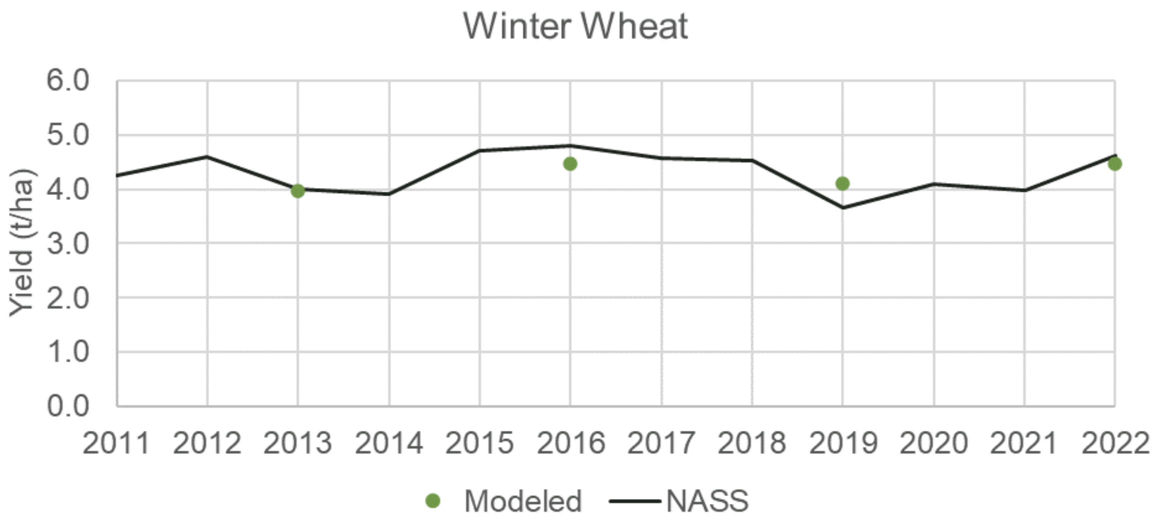
1. CROP GROWTH CALIBRATION



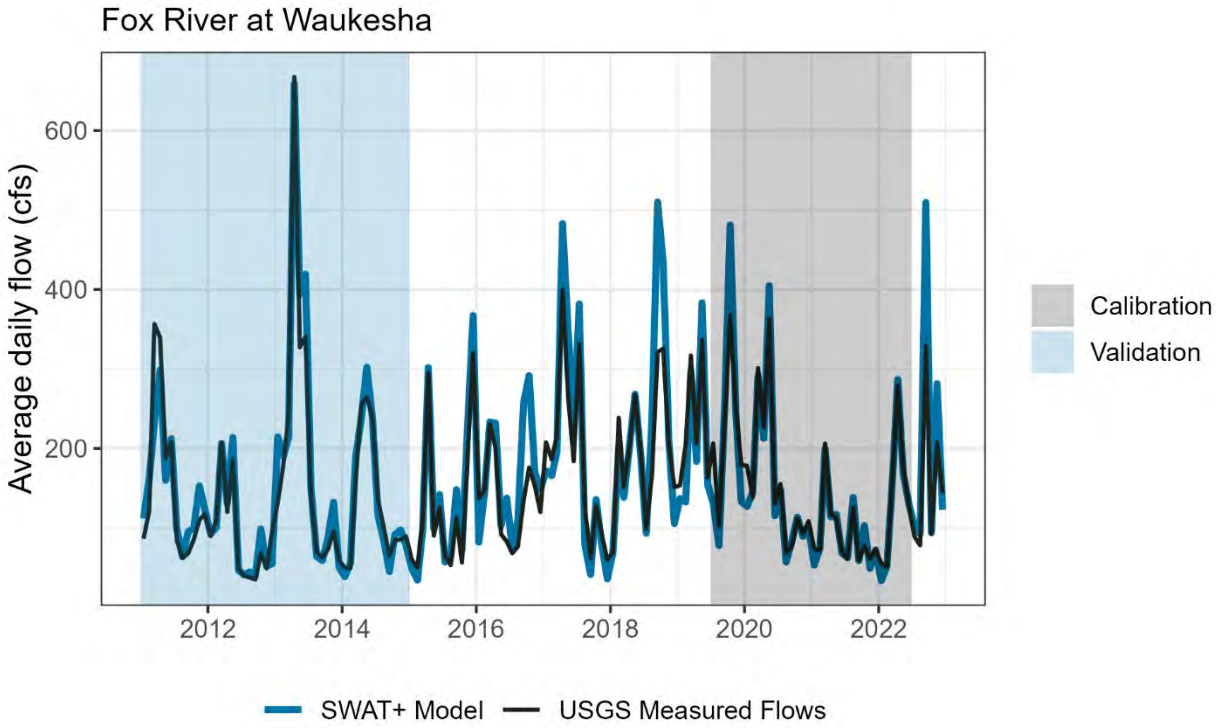


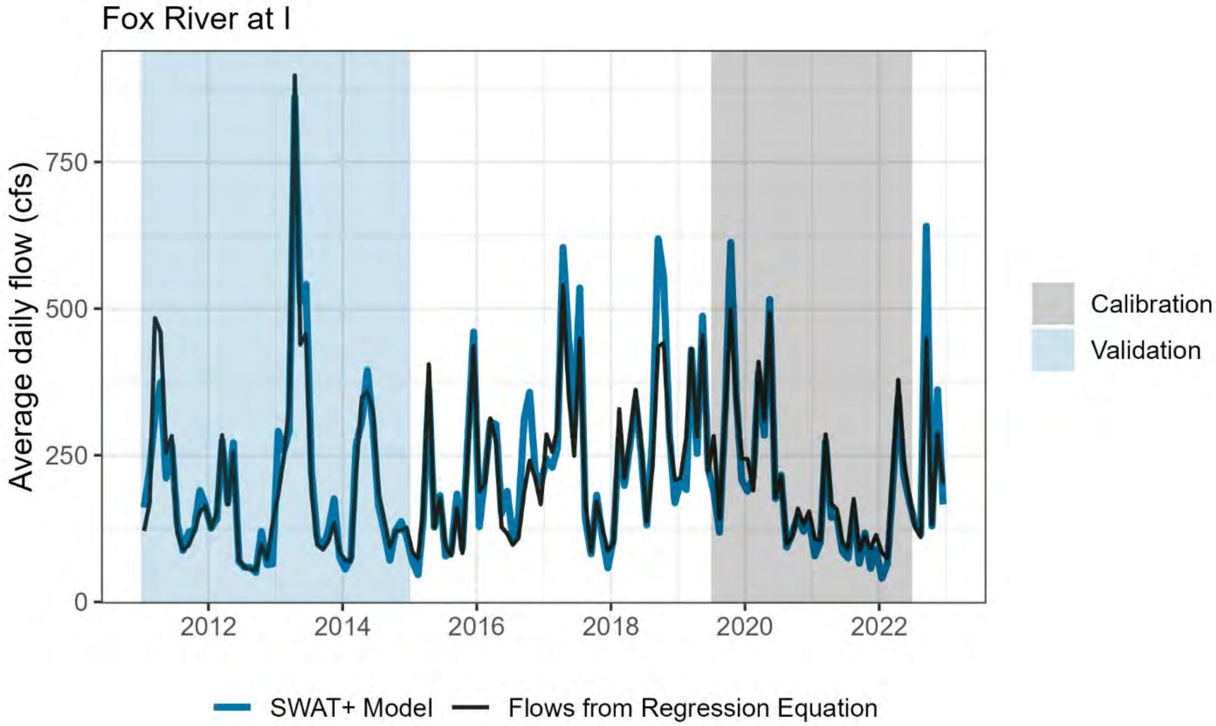

Soybean
Yield (t/ha)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Modeled
NASS

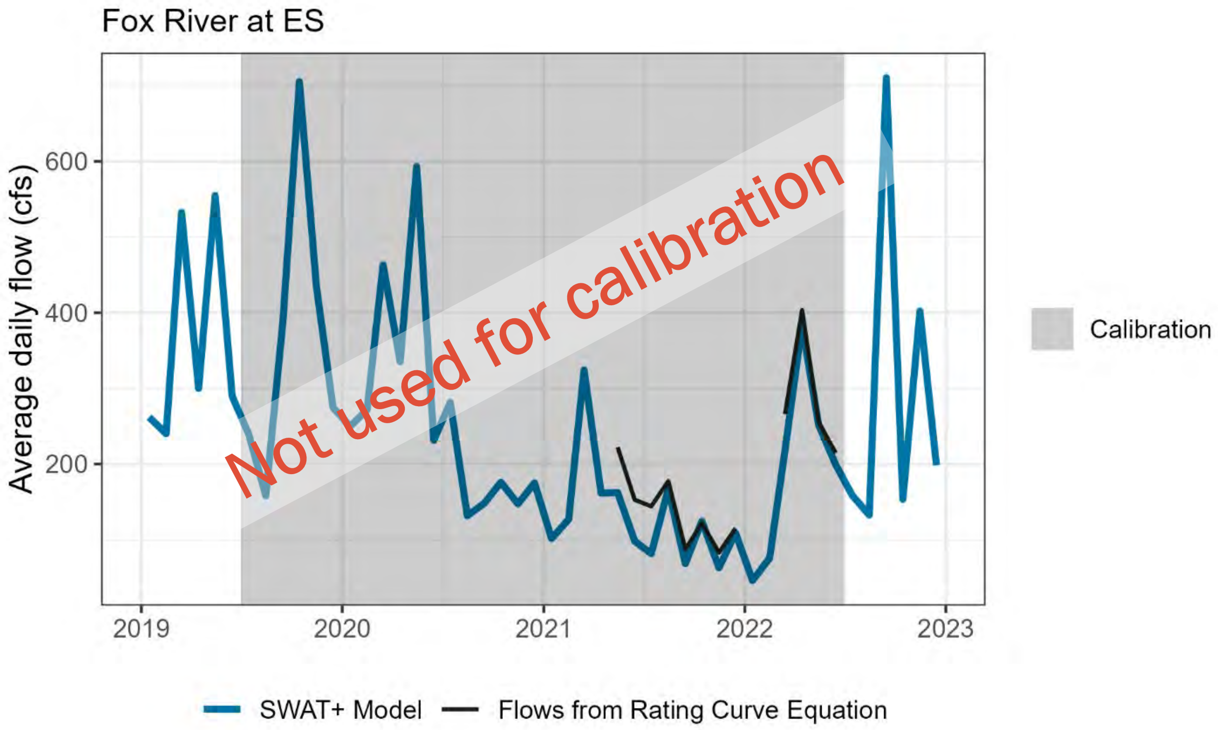

Alfalfa
Yield (t/ha)
10
8
6
4
2
0
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Modeled
NASS

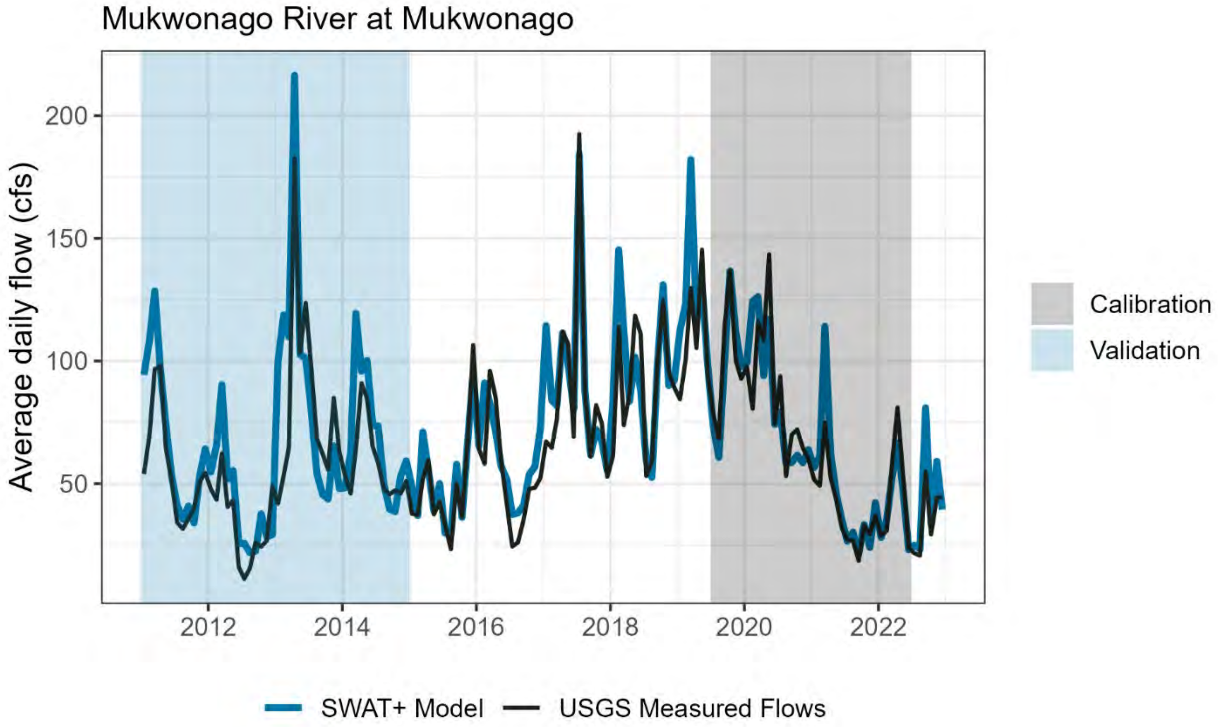

Winter Wheat
Yield (t/ha)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Modeled
NASS

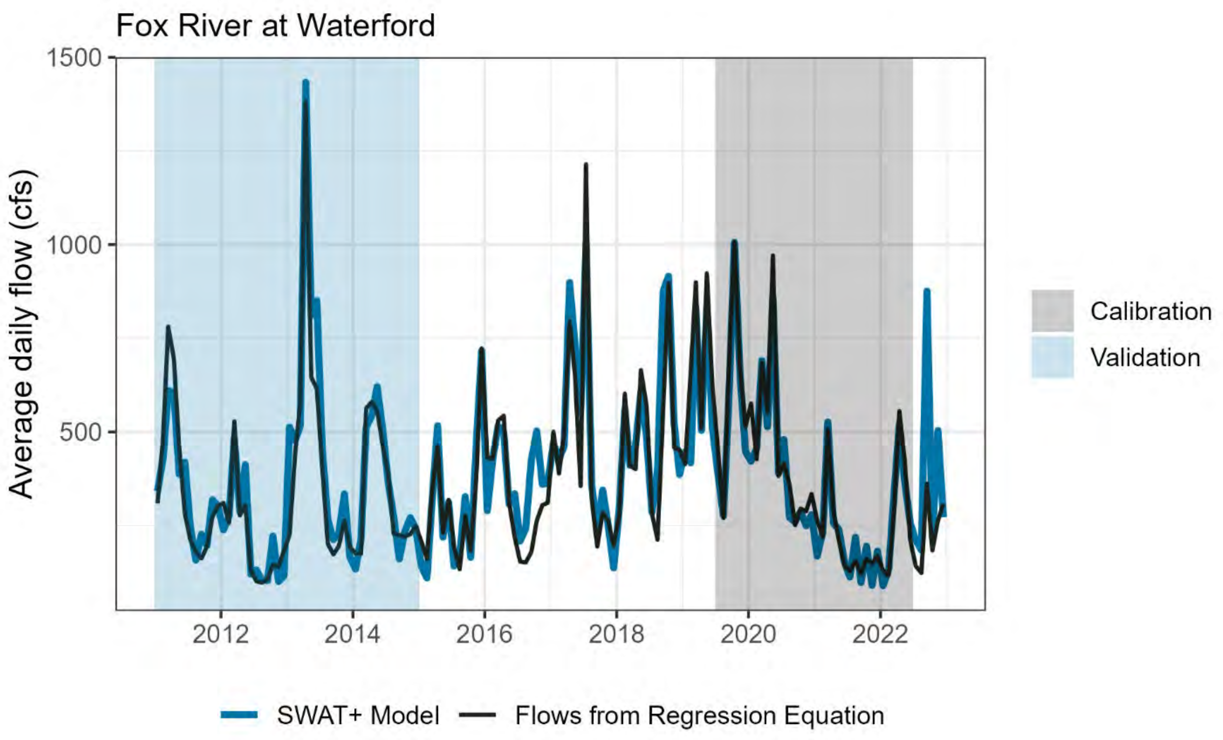
2. FLOW CALIBRATION AND VALIDATION

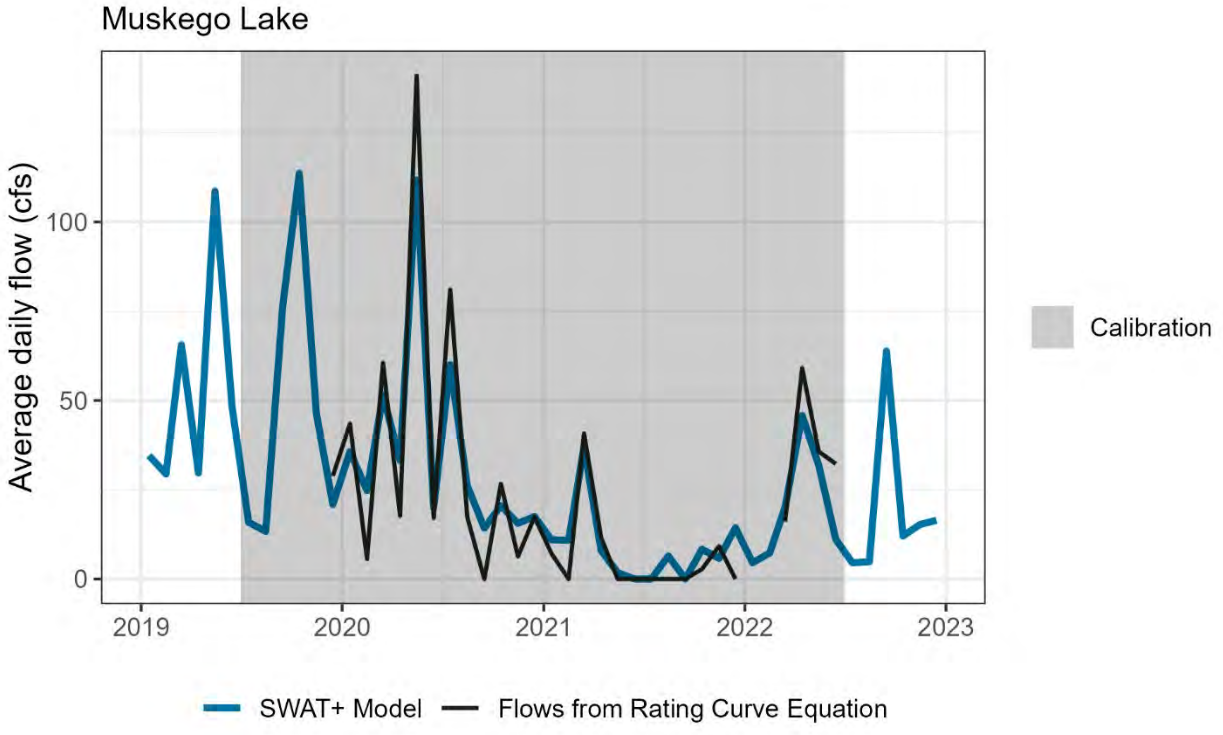

Fox River at Waukesha

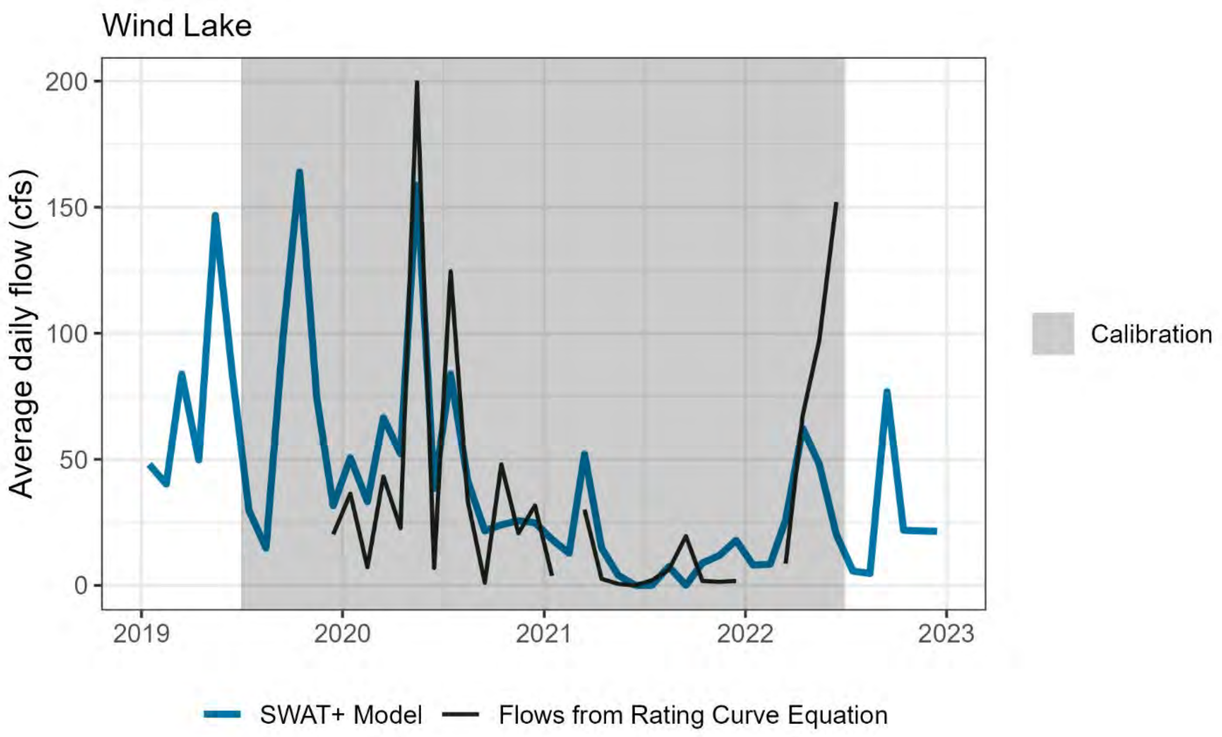

Fox River at I

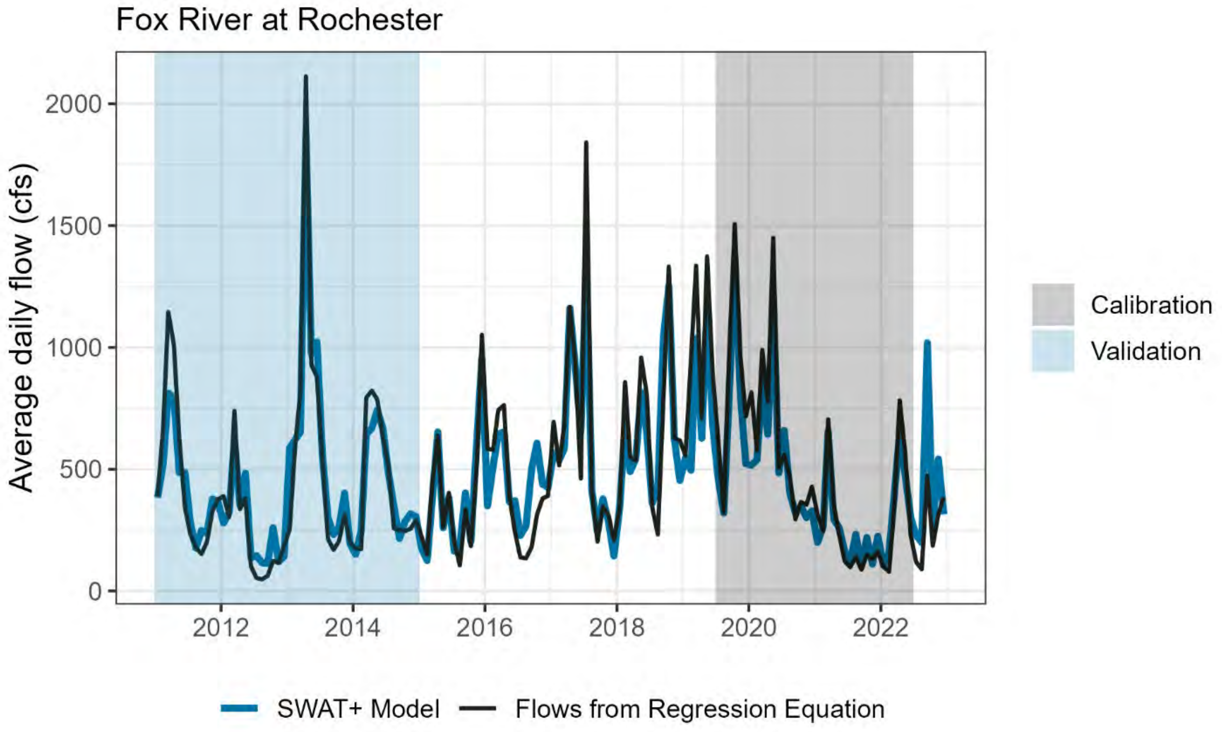

Fox River at ES
Average daily flow (cfs)
600
400
200
2019
2020
2021
2022
2023
Not used for calibration
Calibration
SWAT+ Model
Flows from Rating Curve Equation

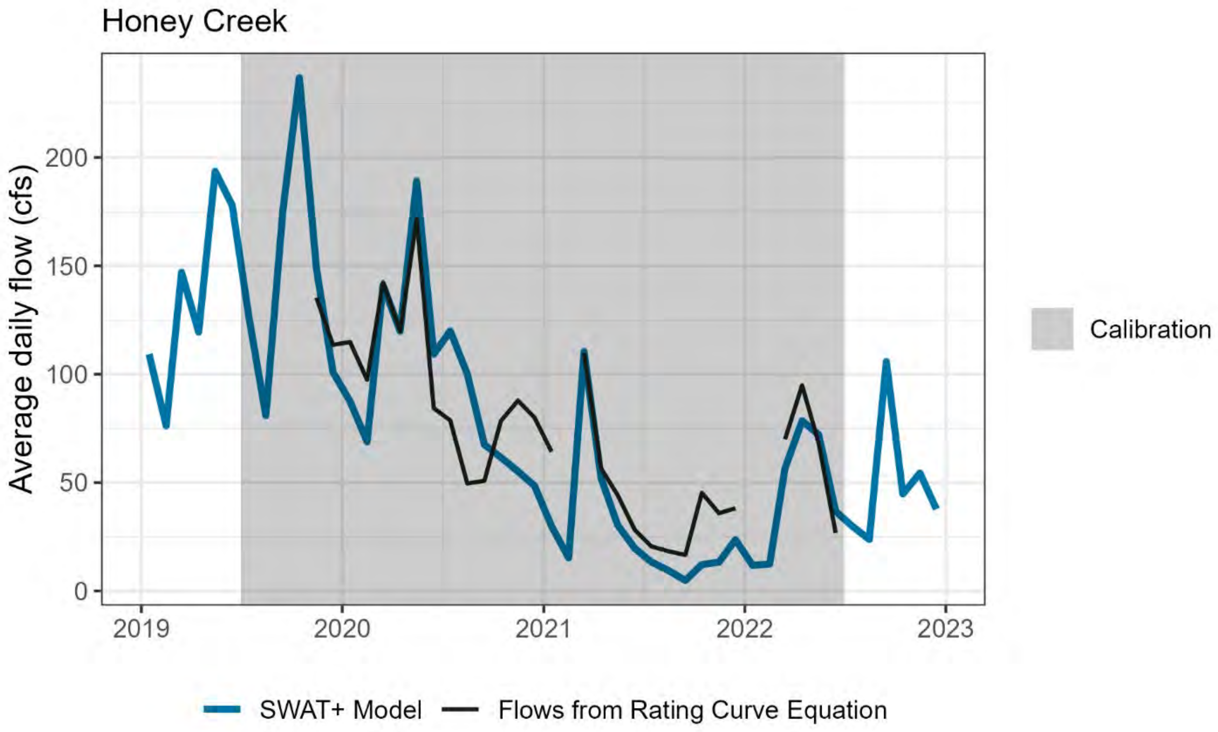

Mukwonago River at Mukwonago
Average daily flow (cfs)
200
150
100
50
2012
2014
2016
2018
2020
2022
Calibration
Validation
SWAT+ Model
USGS Measured Flows

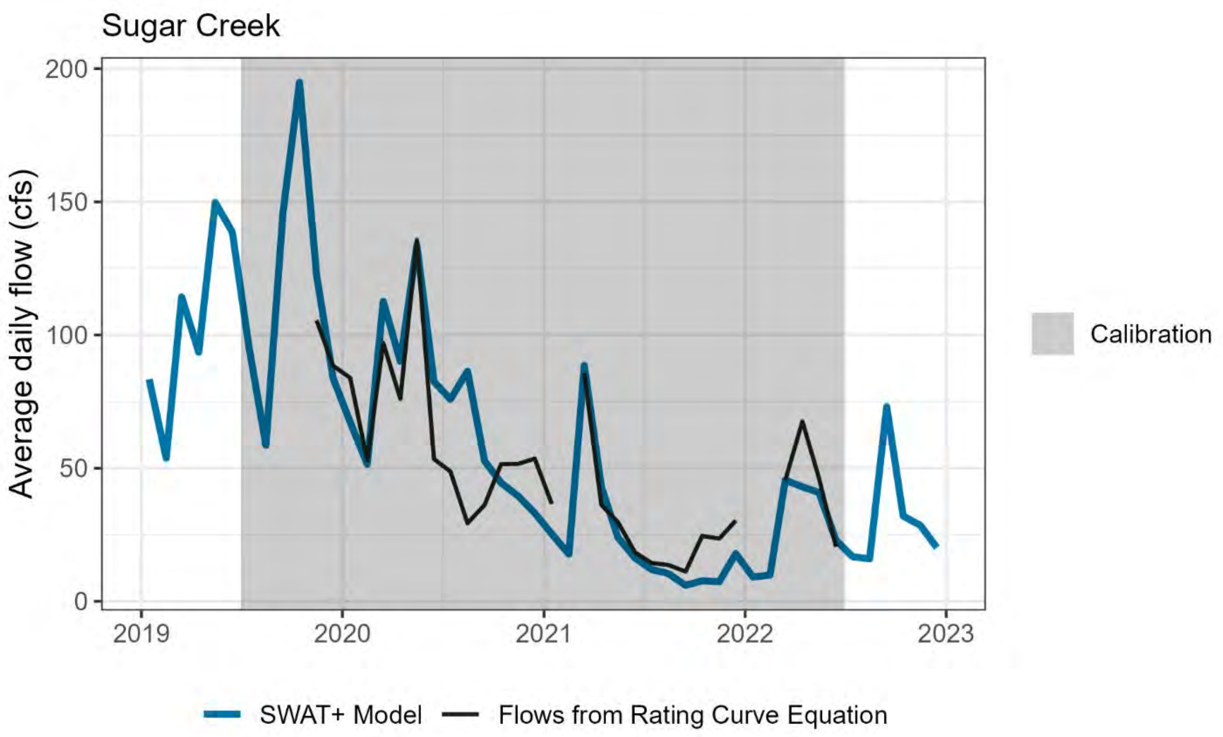

Fox River at Waterford
Average daily flow (cfs)
1500
1000
500
2012
2014
2016
2018
2020
2022
Calibration
Validation
SWAT+ Model
Flows from Regression Equation


Muskego Lake
Average daily flow (cfs)
100
50
0
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Flows from Rating Curve Equation

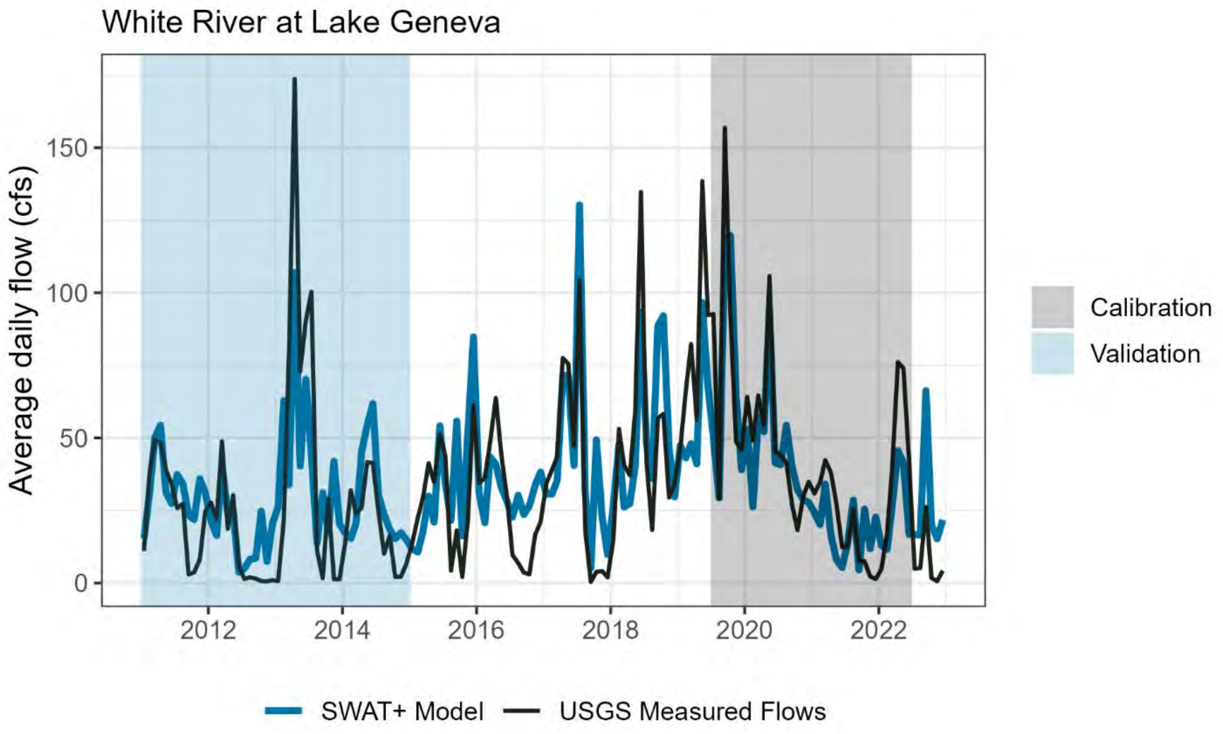

Wind Lake
Average daily flow (cfs)
200
150
100
50
0
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Flows from Rating Curve Equation


Fox River at Rochester
Average daily flow (cfs)
2000
1500
1000
500
0
2012
2014
2016
2018
2020
2022
Calibration
Validation
SWAT+ Model
Flows from Regression Equation

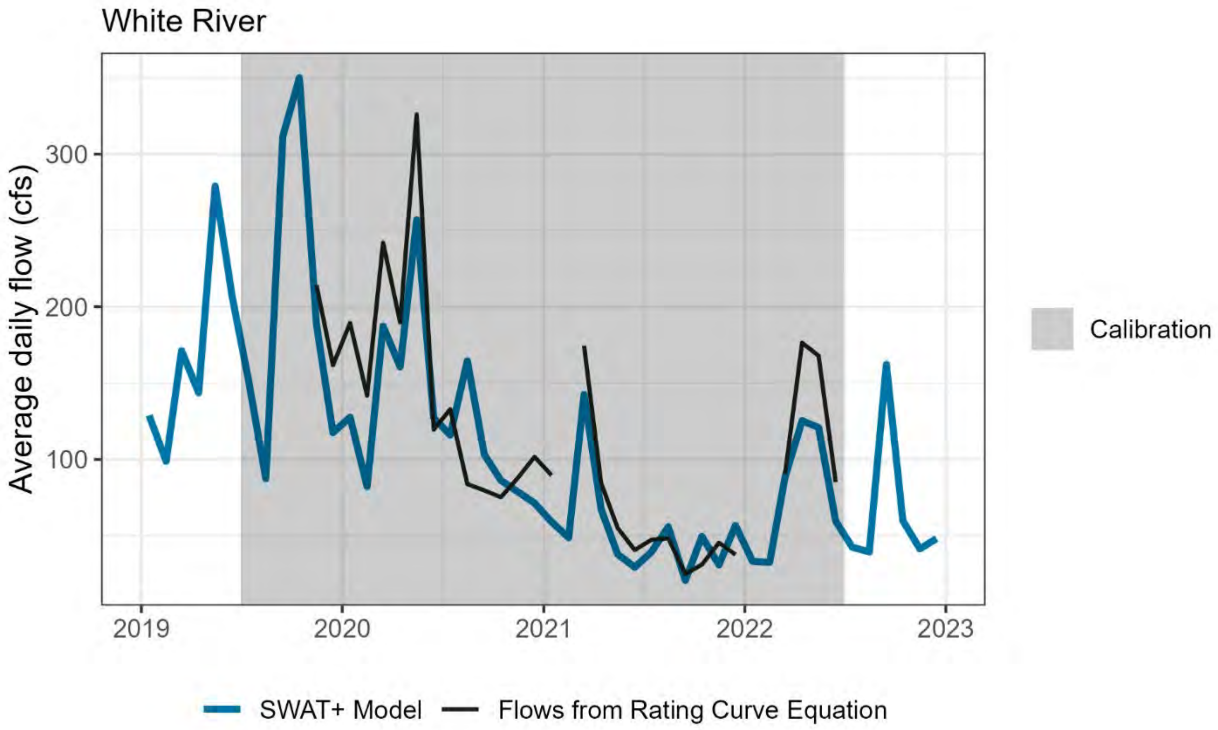

Honey Creek
Average daily flow (cfs)
0
50
100
150
200
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Flows from Rating Curve Equation

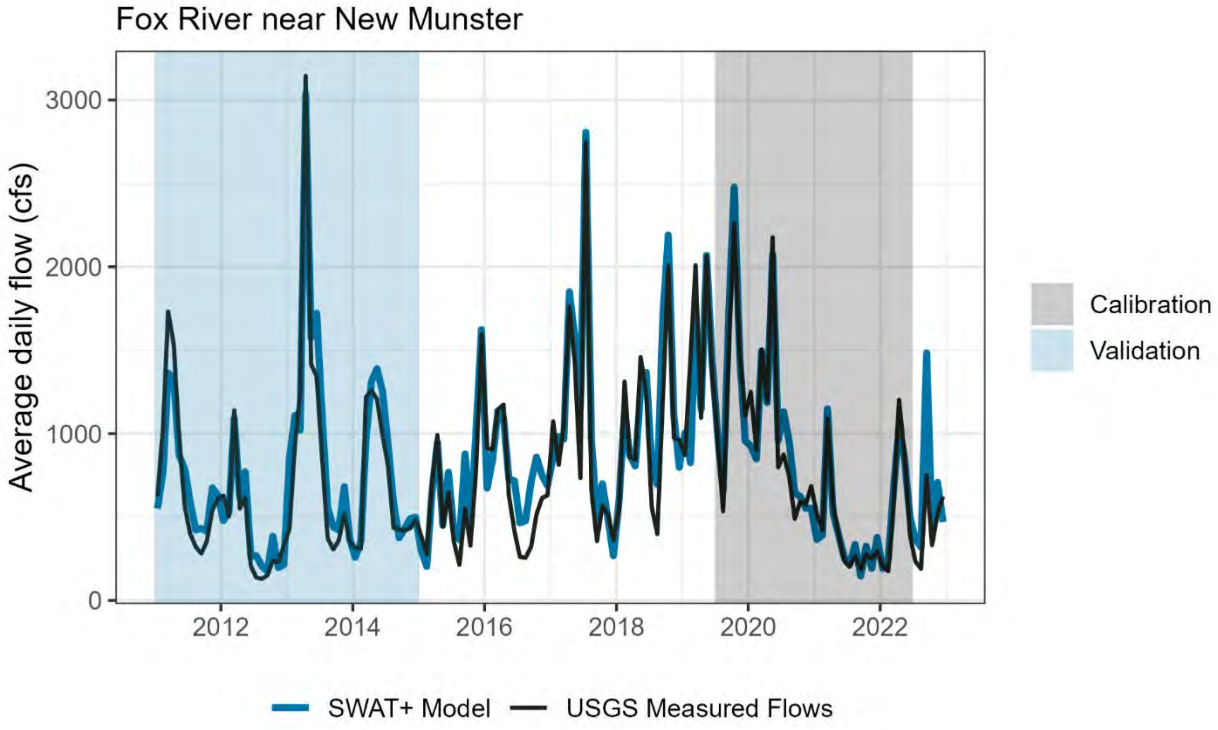


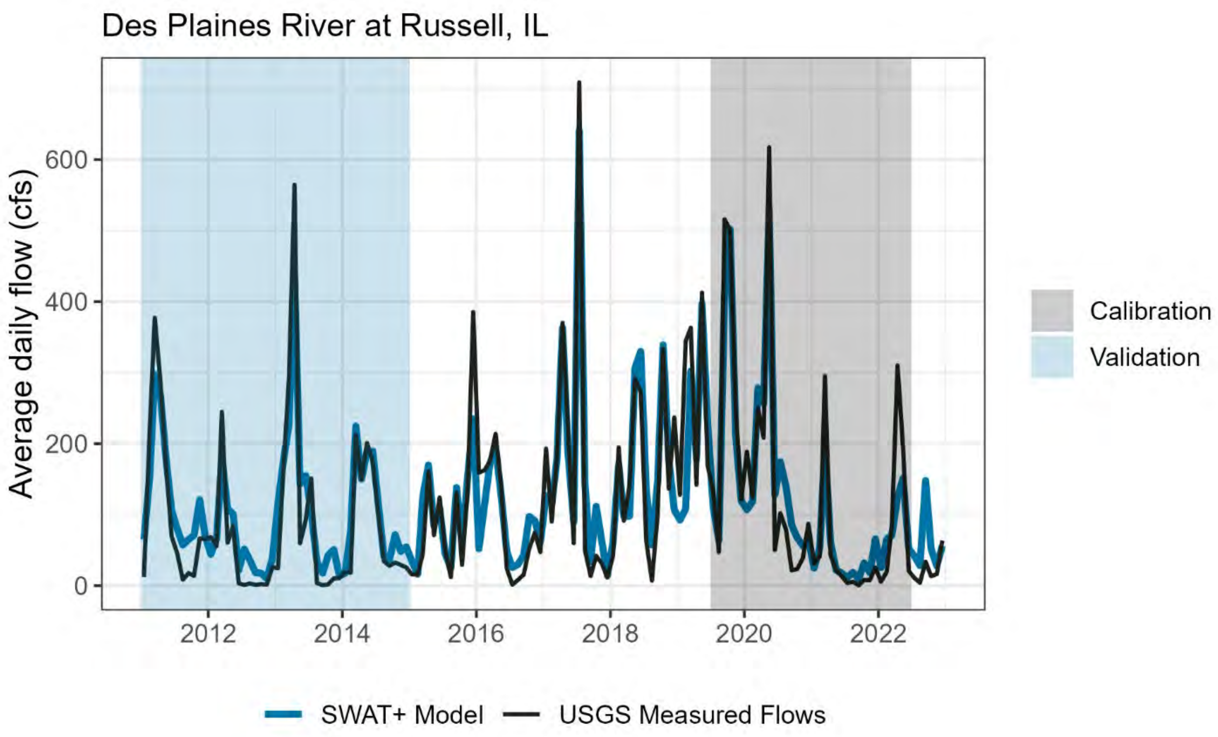
Sugar Creek



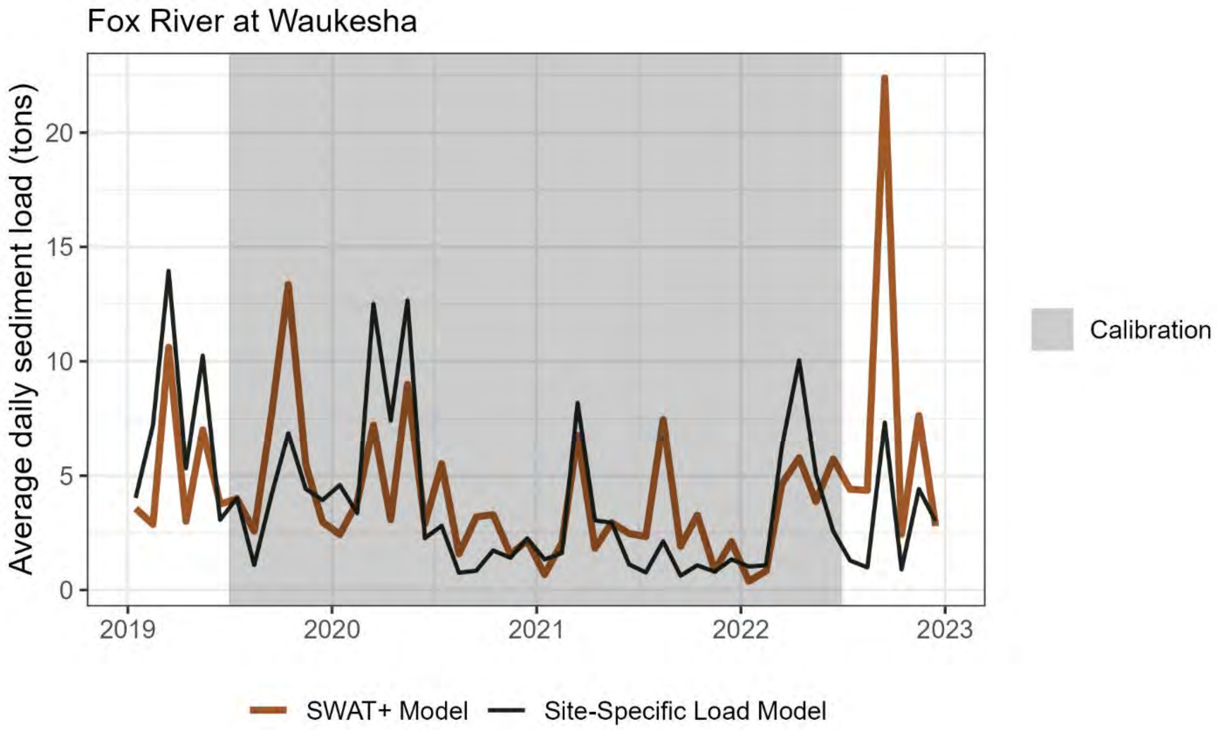
White River at Lake Geneva

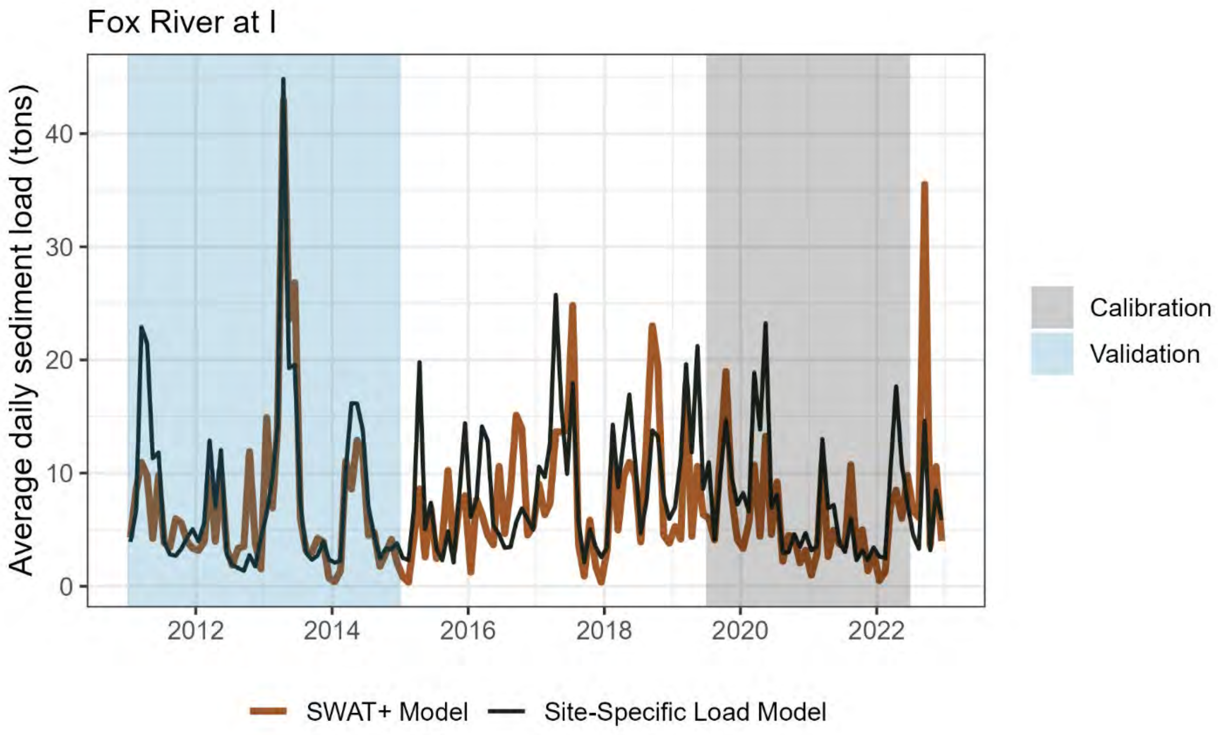

White River
Average daily flow (cfs)
300
200
100
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Flows from Rating Curve Equation

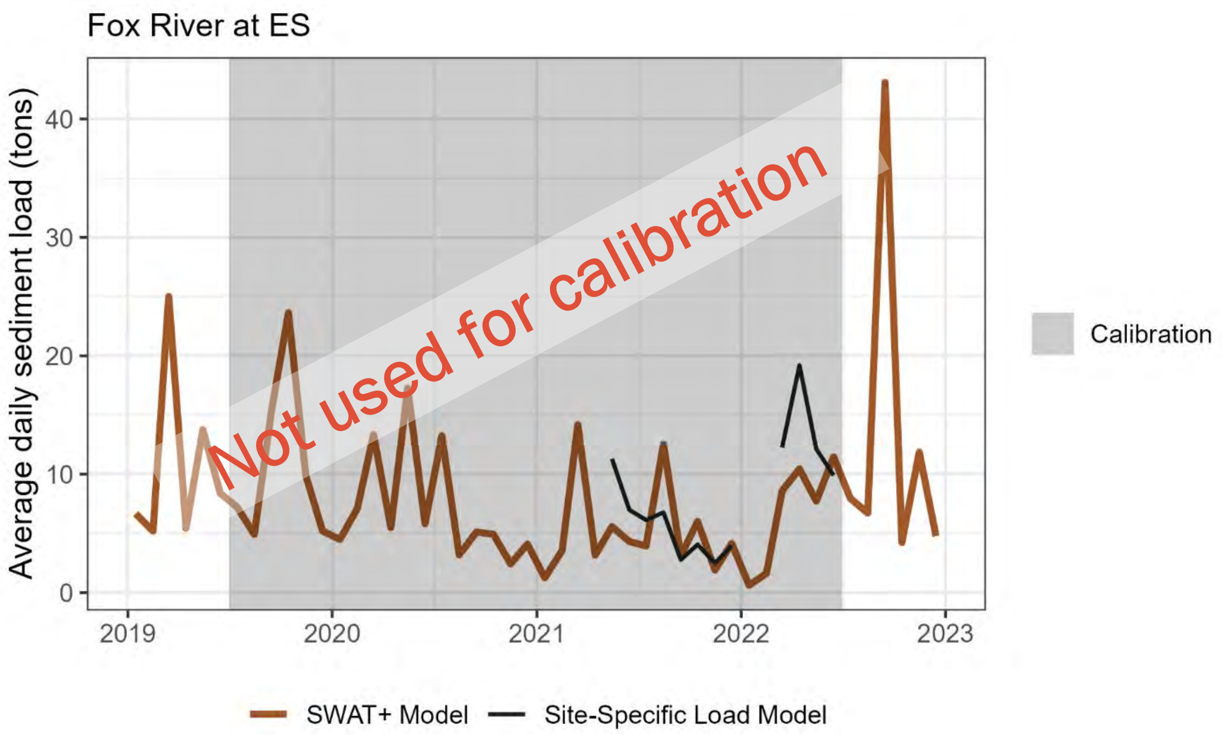

Fox River near New Munster
Average daily flow (cfs)
3000
2000
1000
0
2012
2014
2016
2018
2020
2022
Calibration
Validation
SWAT+ Model
USGS Measured Flows


Des Plaines River at Russell, IL
Average daily flow (cfs)
0
200
400
600
2012
2014
2016
2018
2020
2022
Calibration
Validation
SWAT+ Model
USGS Measured Flows

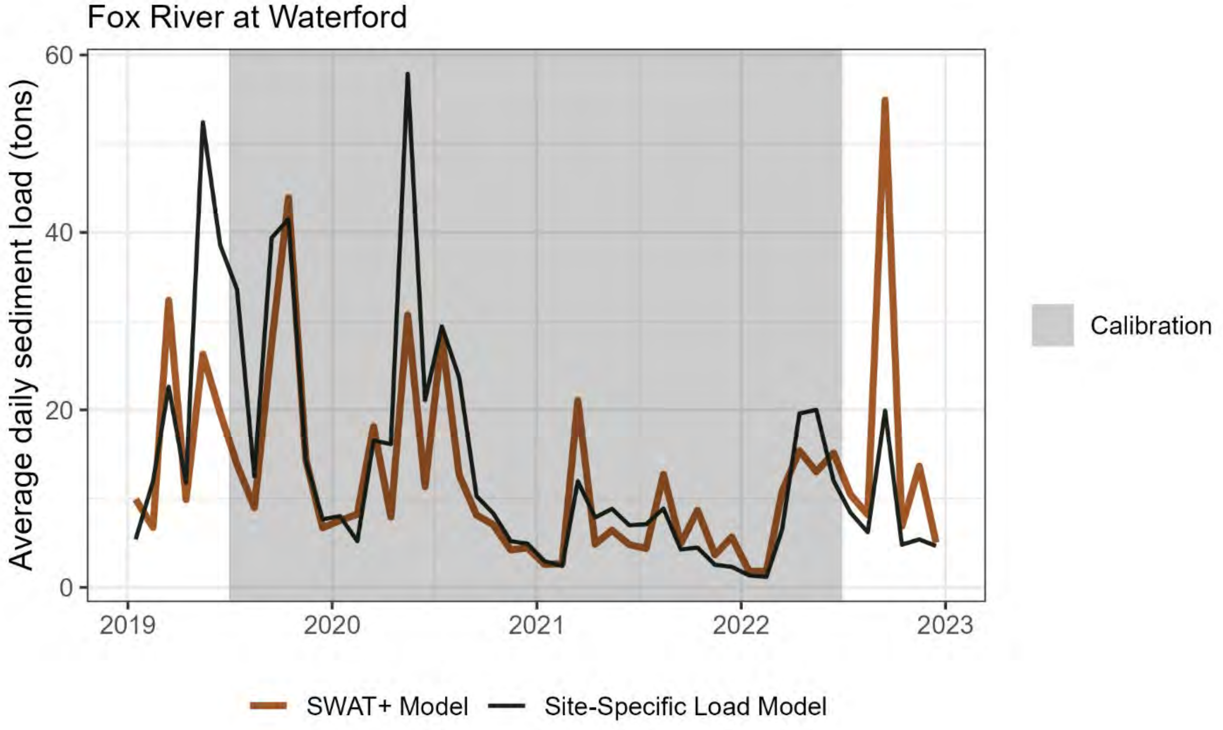
3. SEDIMENT CALIBRATION AND VALIDATION

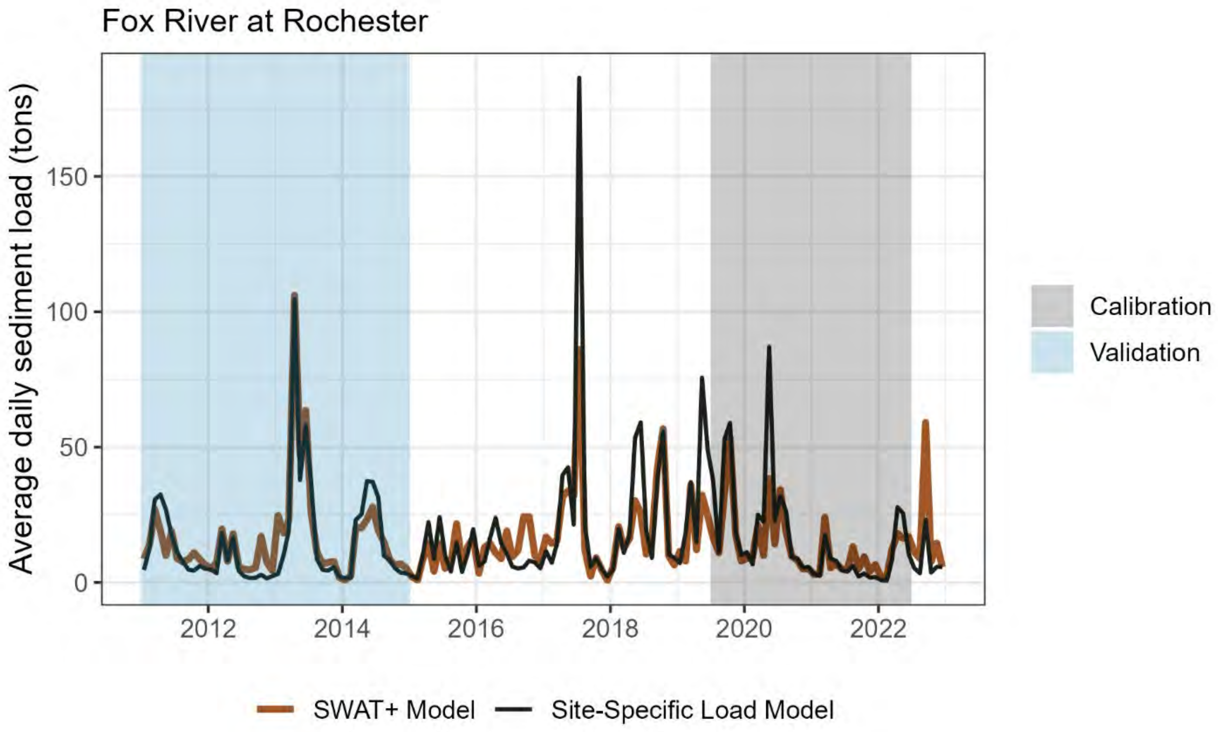

Fox River at Waukesha


Fox River at I

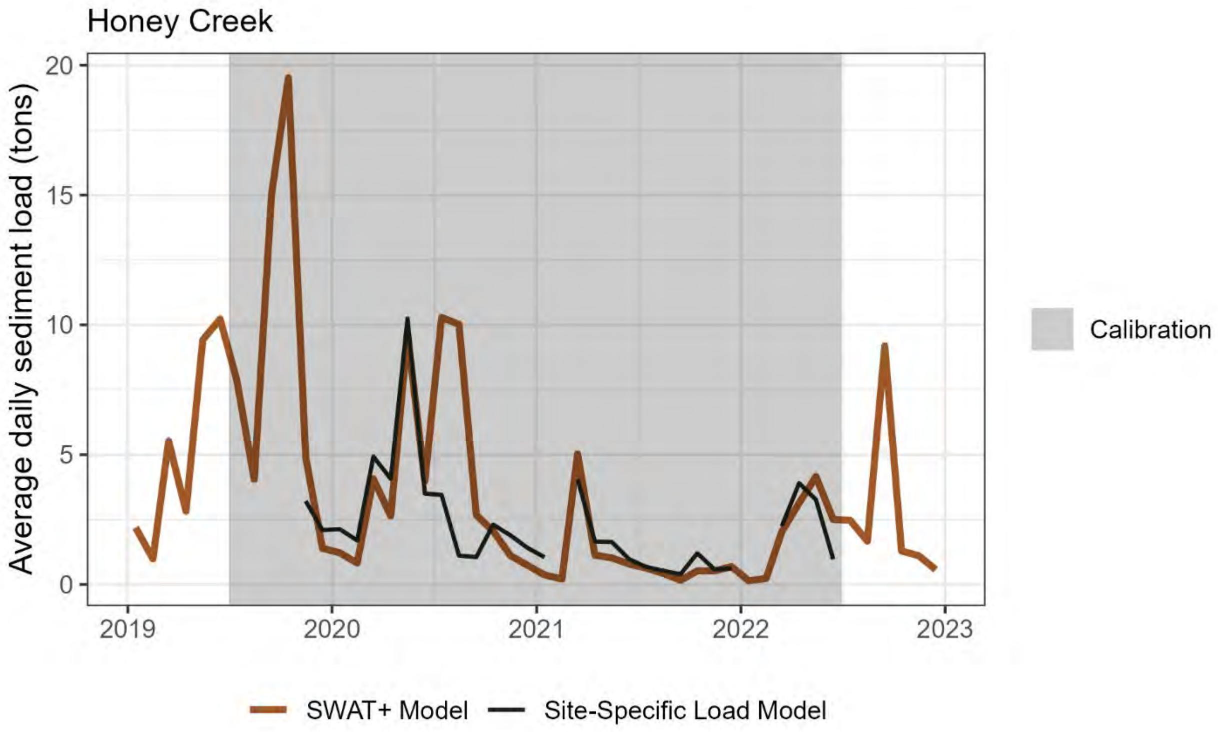

Fox River at ES

z

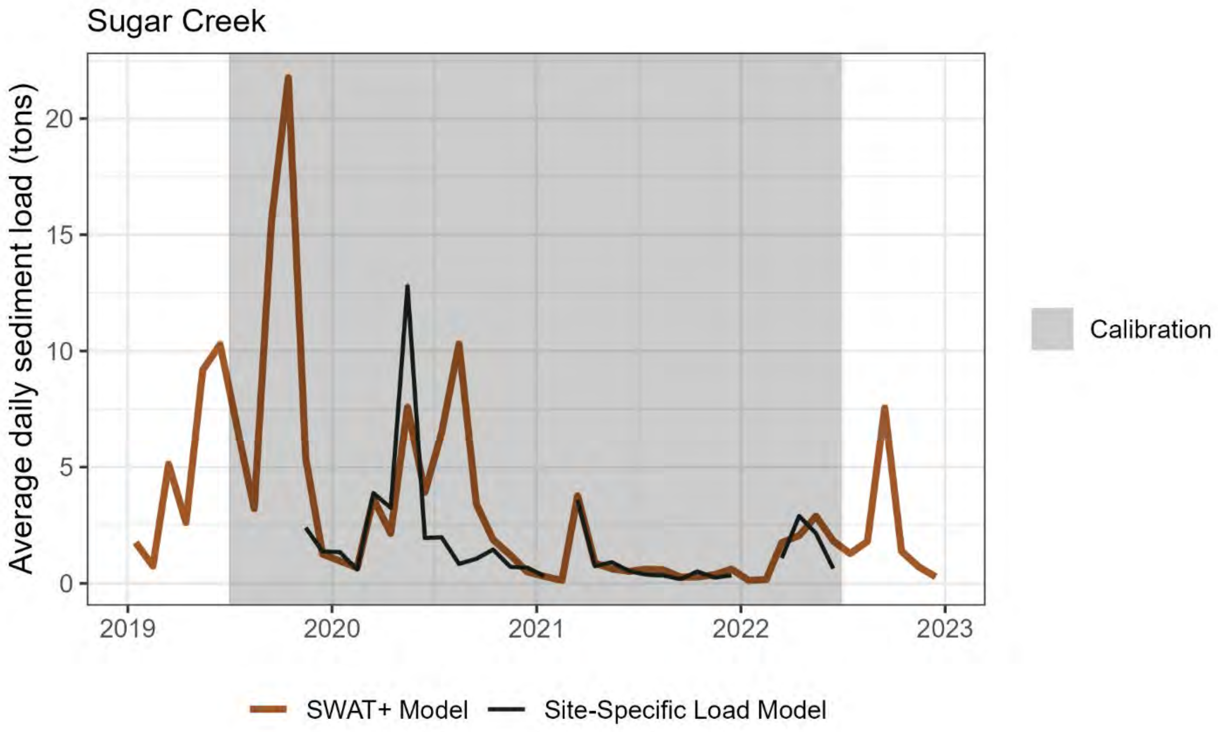

Fox River at Waterford

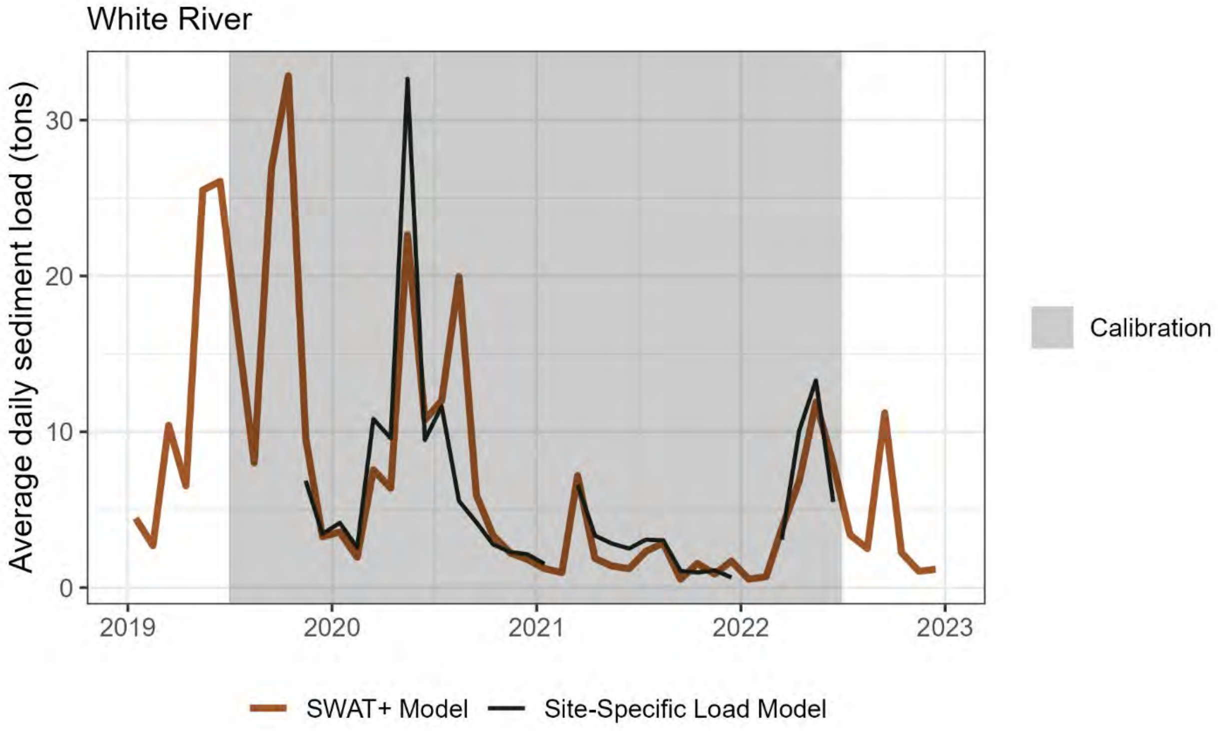


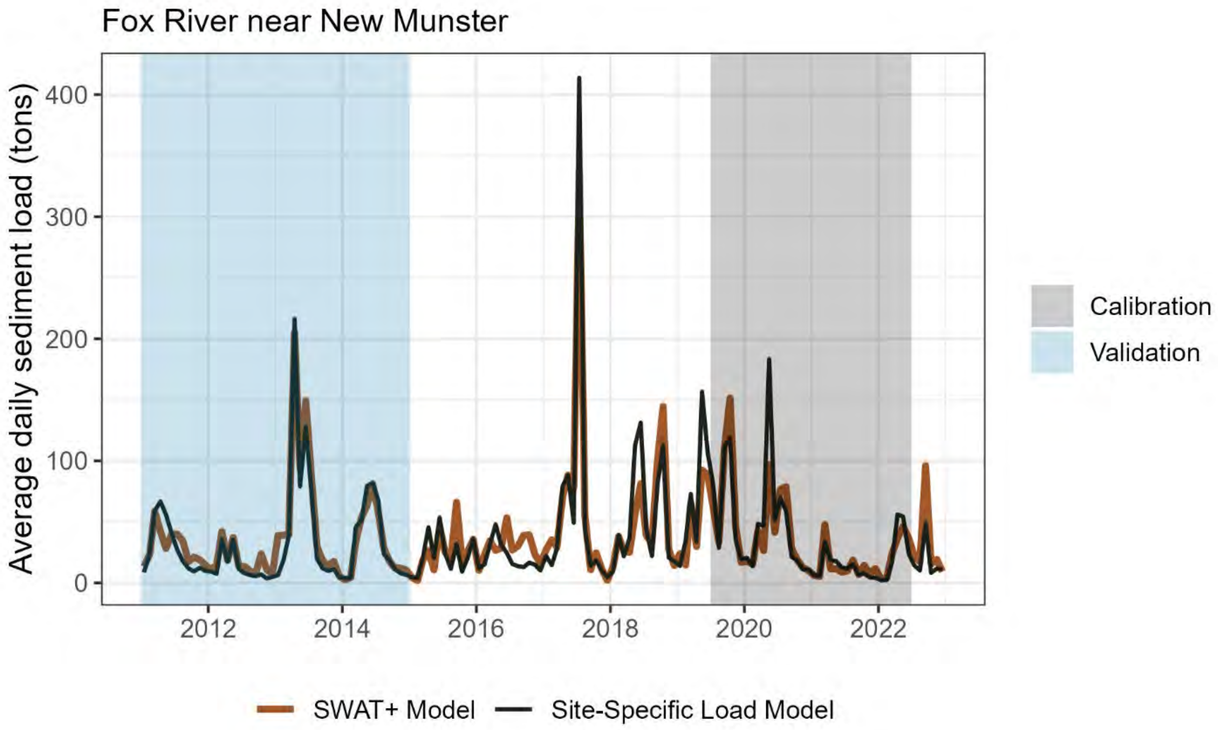
Fox River at Rochester

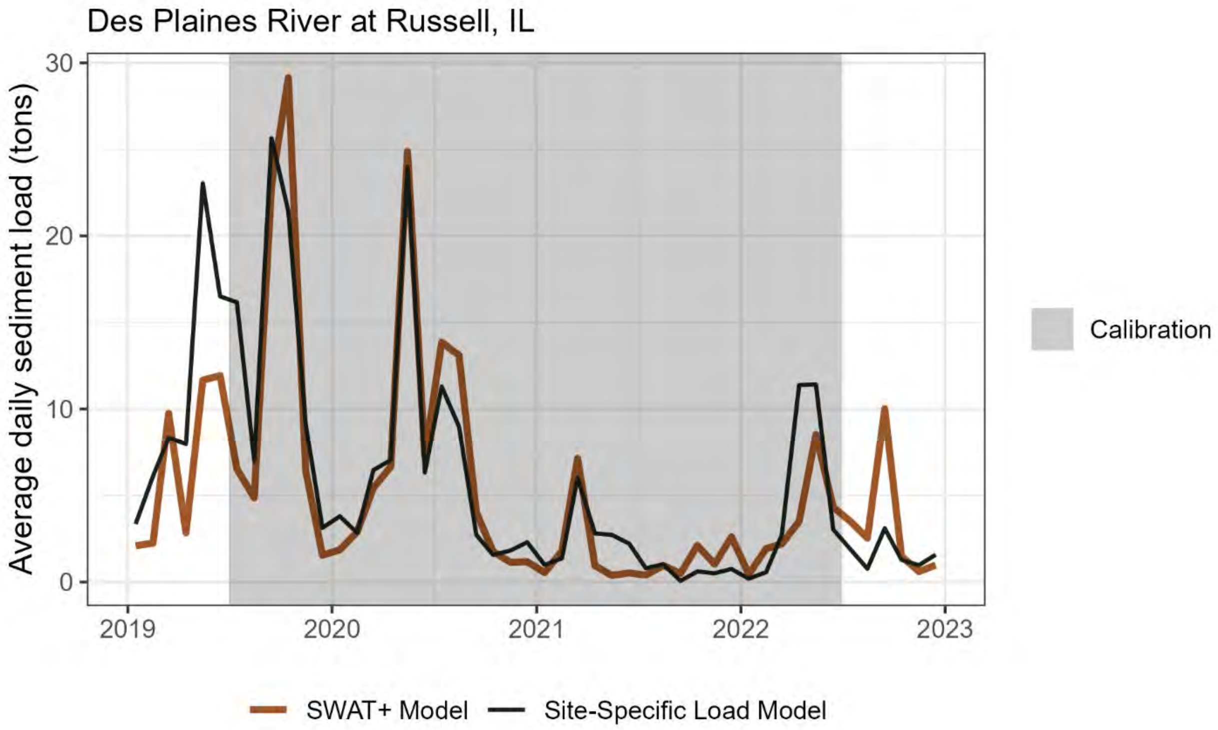


Honey Creek

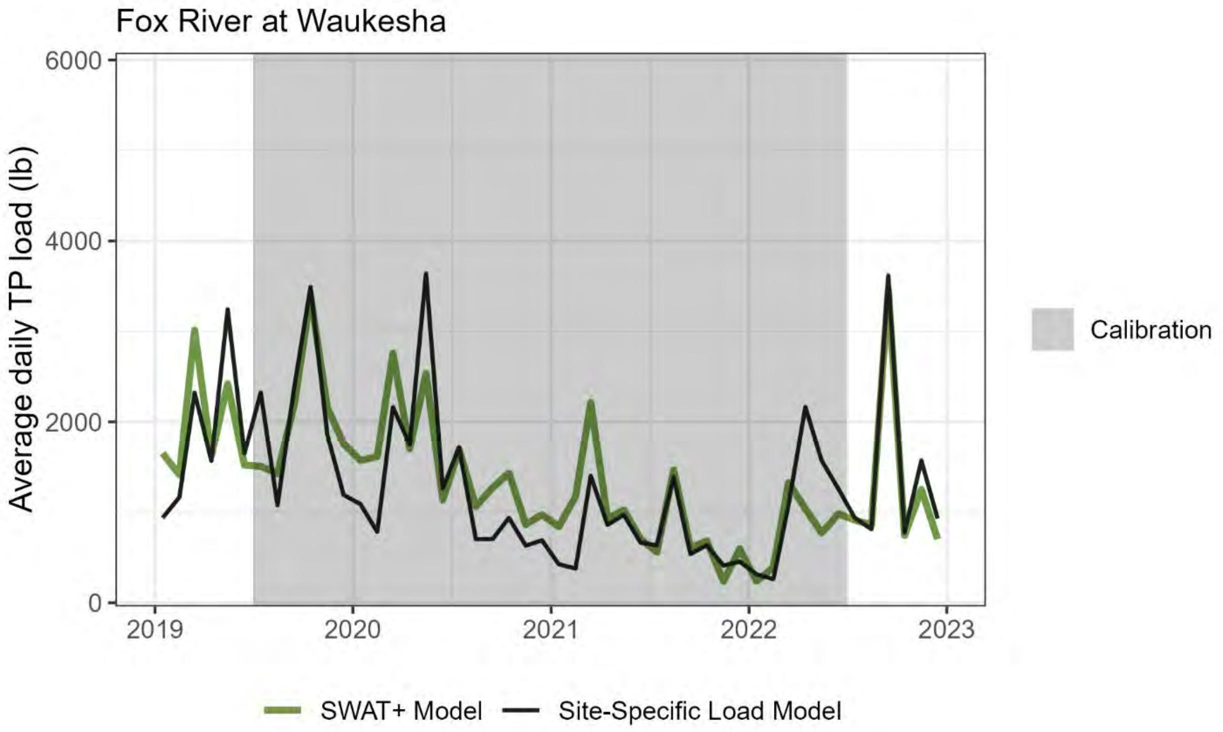

Sugar Creek
Average daily sediment load (tons)
0
5
10
15
20
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Site-Specific Load Model

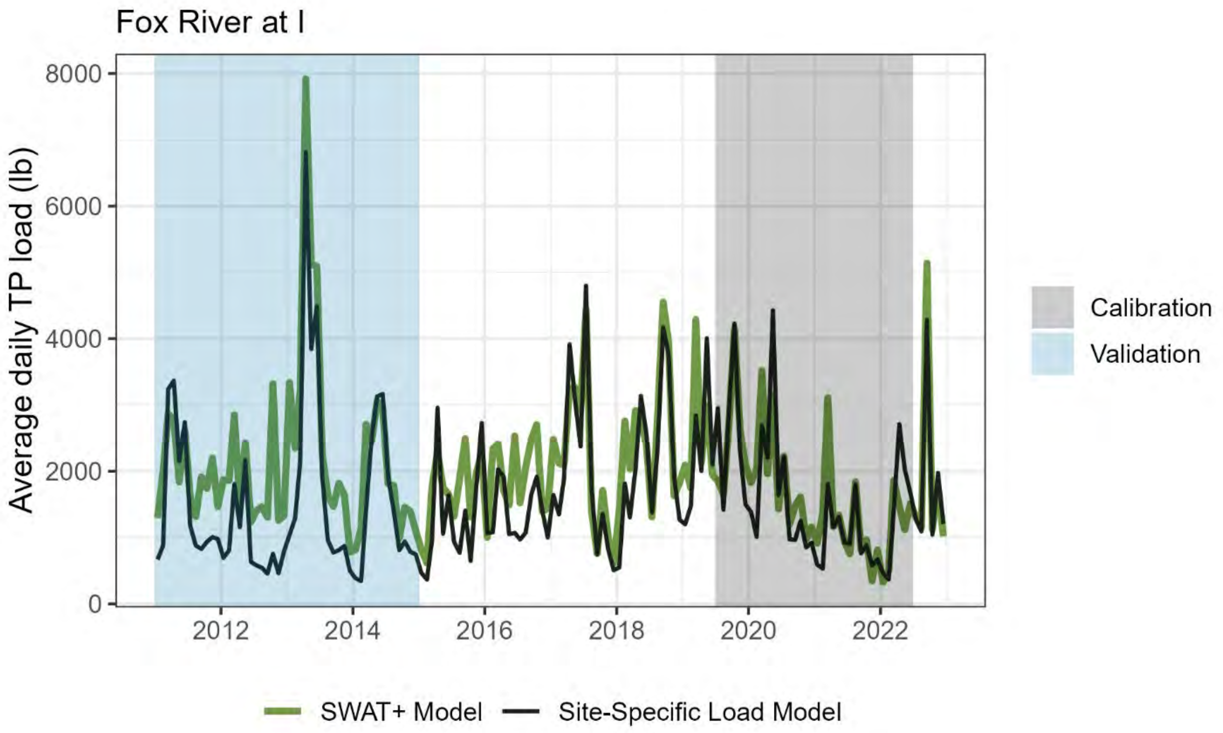

White River
Average daily sediment load (tons)
0
10
20
30
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Site-Specific Load Model

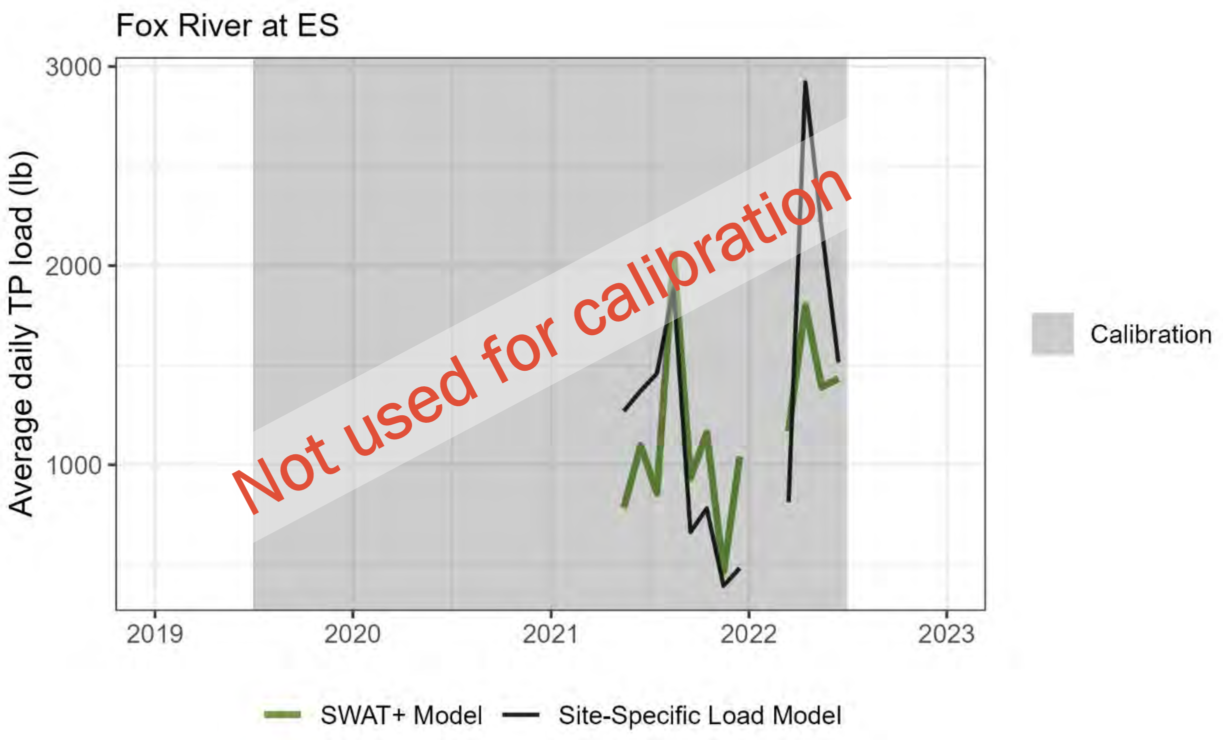

Fox River near New Munster
Average daily sediment load (tons)
0
100
200
300
400
2012
2014
2016
2018
2020
2022
Calibration
Validation
SWAT+ Model
Site-Specific Load Model

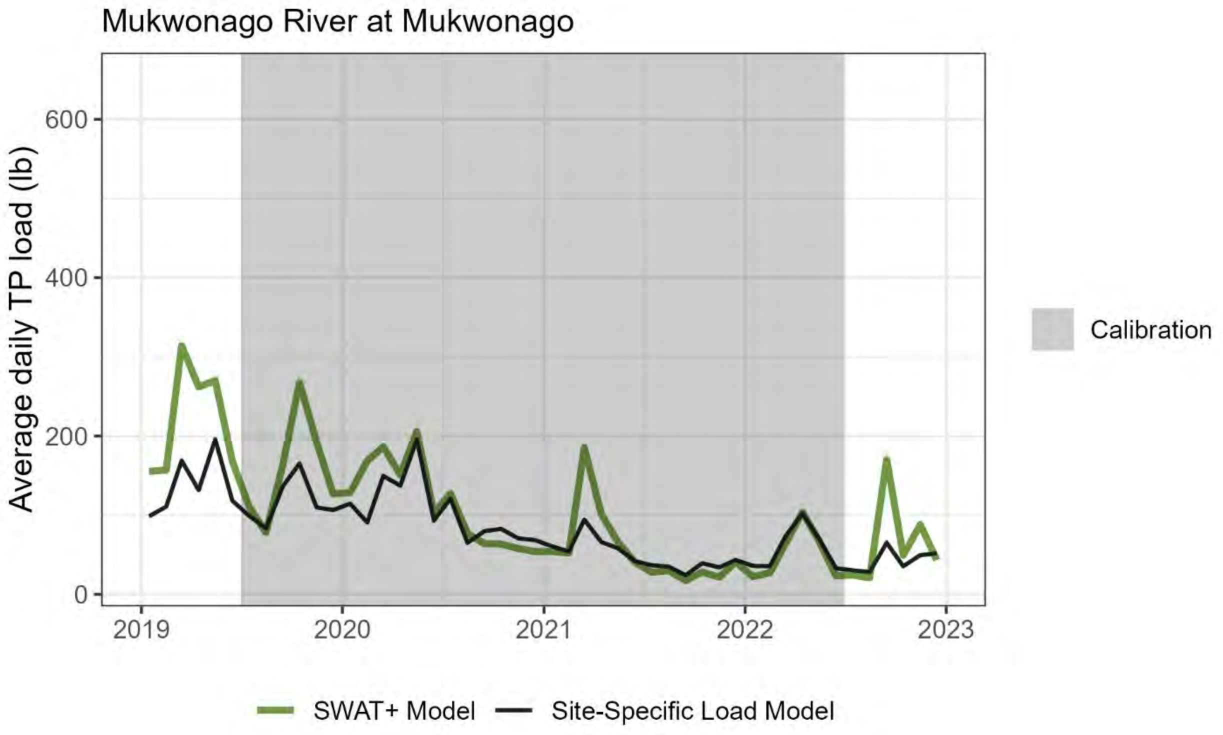

Des Plaines River at Russell, IL
Average daily sediment load (tons)
0
10
20
30
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Site-Specific Load Model

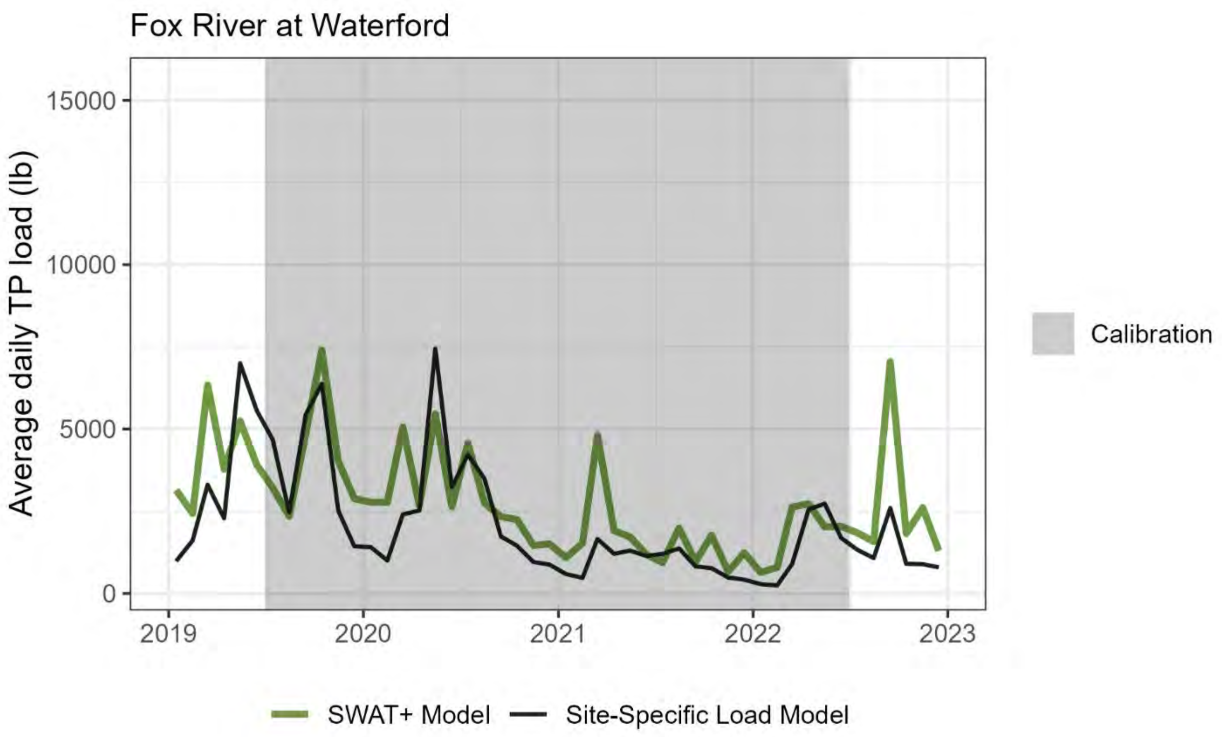
4. PHOSPHORUS CALIBRATION AND VALIDATION

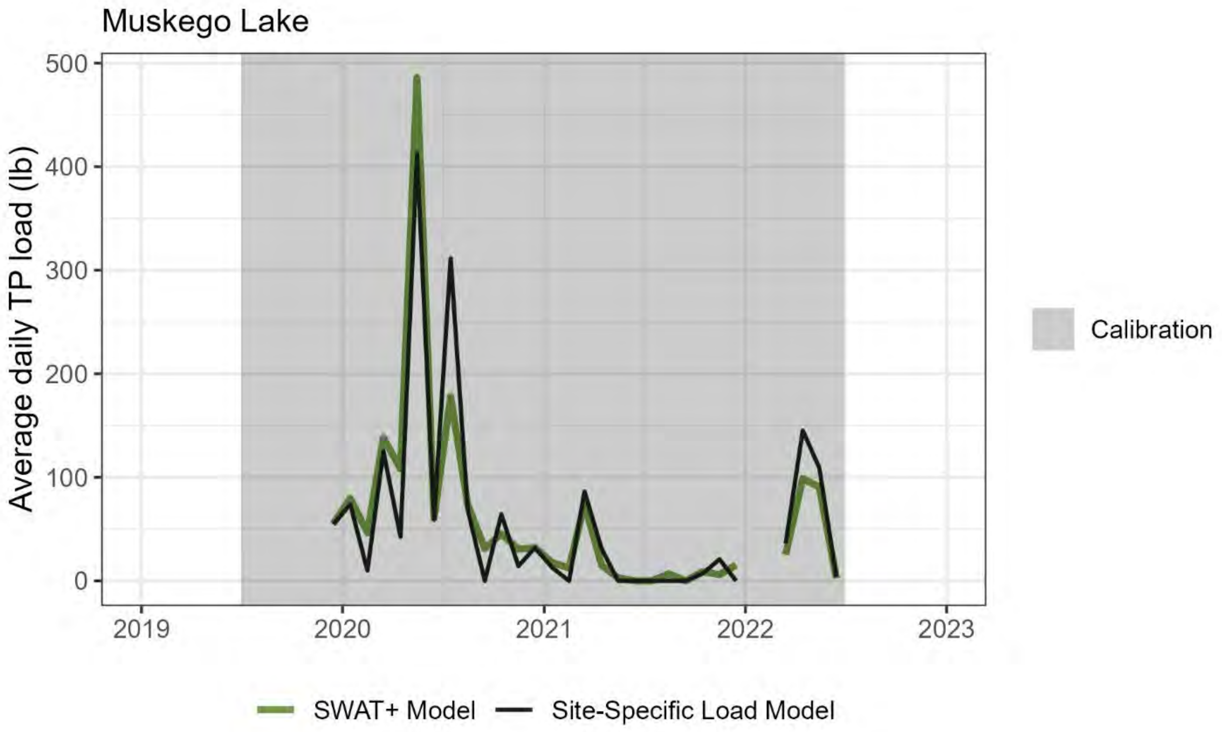

Fox River at Waukesha

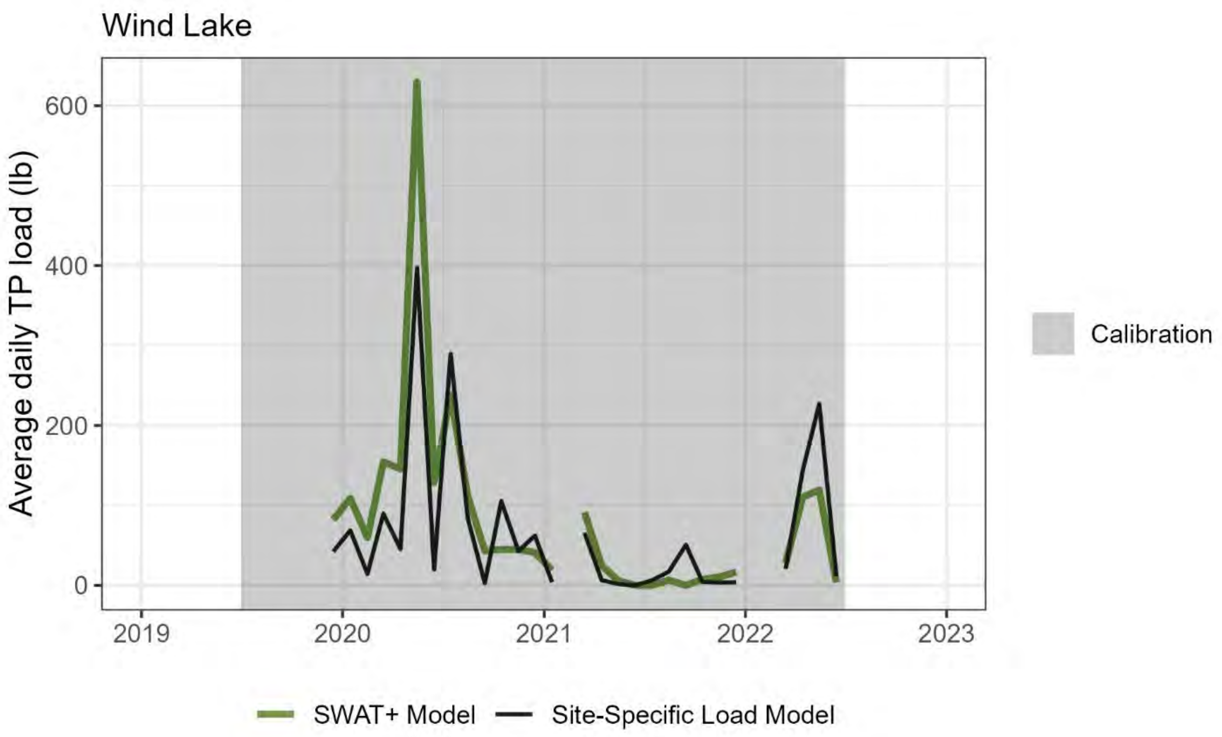

Fox River at I

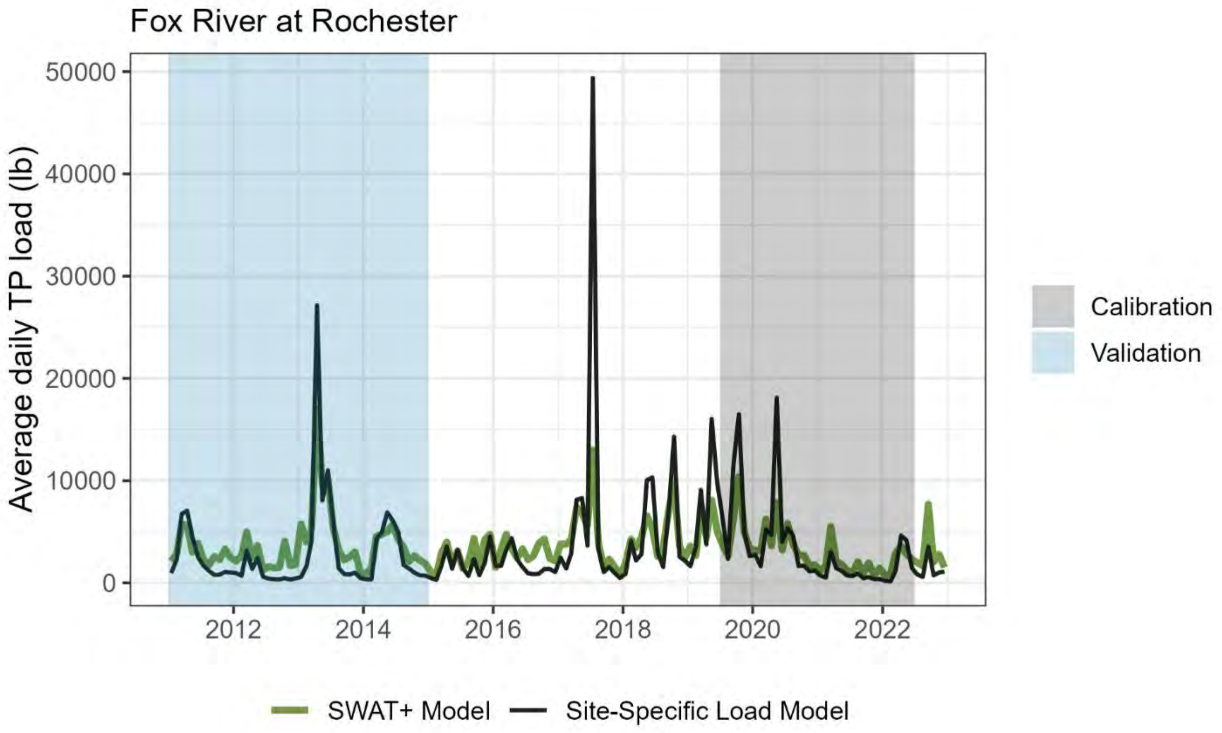

Fox River at ES
Average daily TP load (lb)
3000
2000
1000
2019
2020
2021
2022
2023
Not used for calibration
Calibration
SWAT+ Model
Site-Specific Load Model

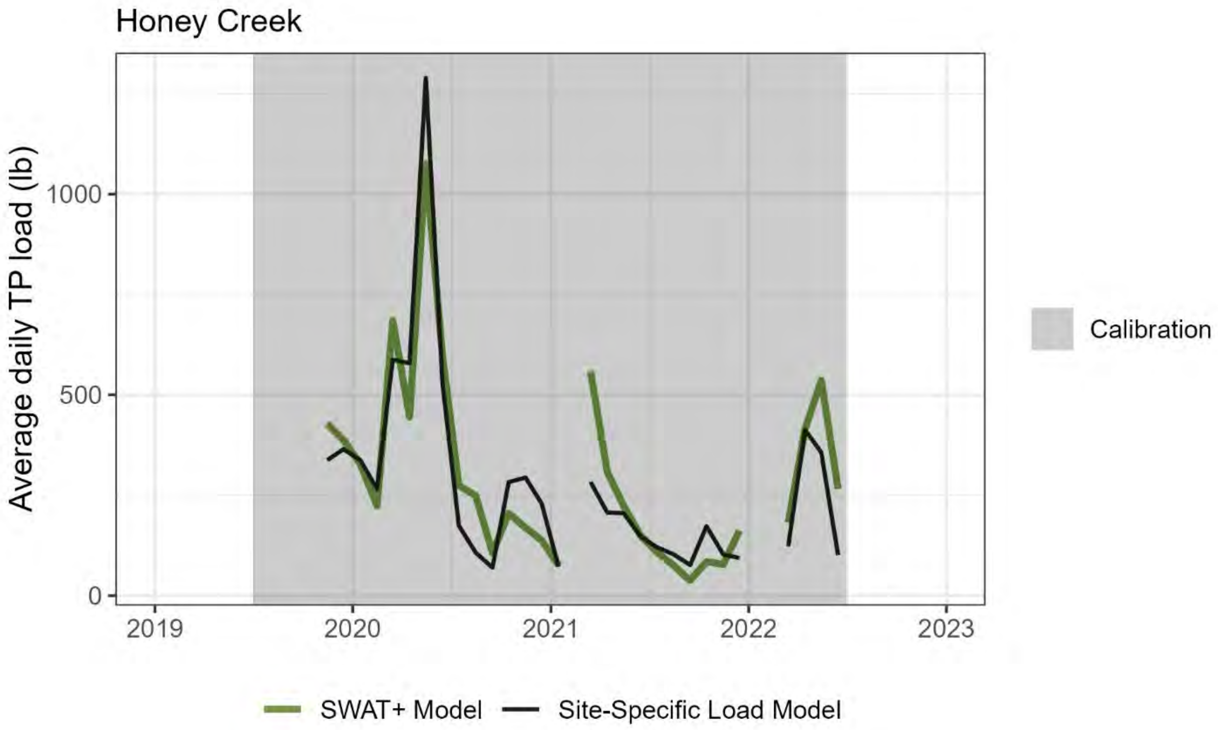

Mukwonago River at Mukwonago
Average daily TP load (lb)
600
400
200
0
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Site-Specific Load Model

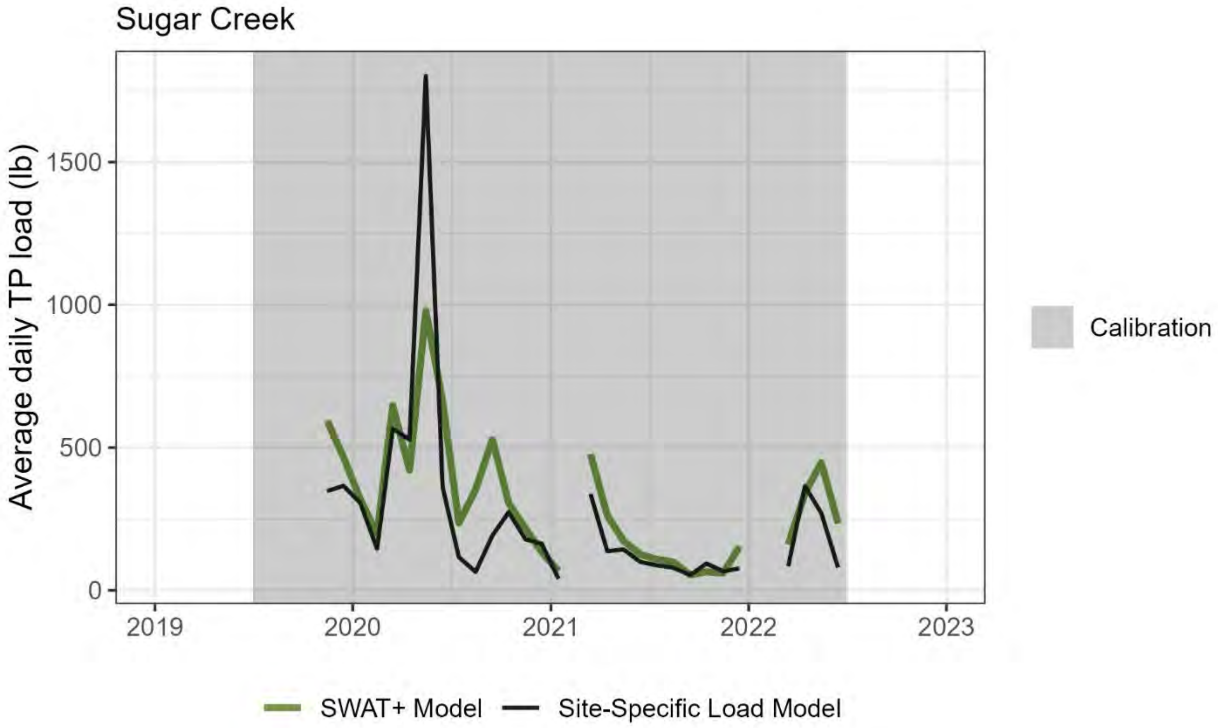

Fox River at Waterford

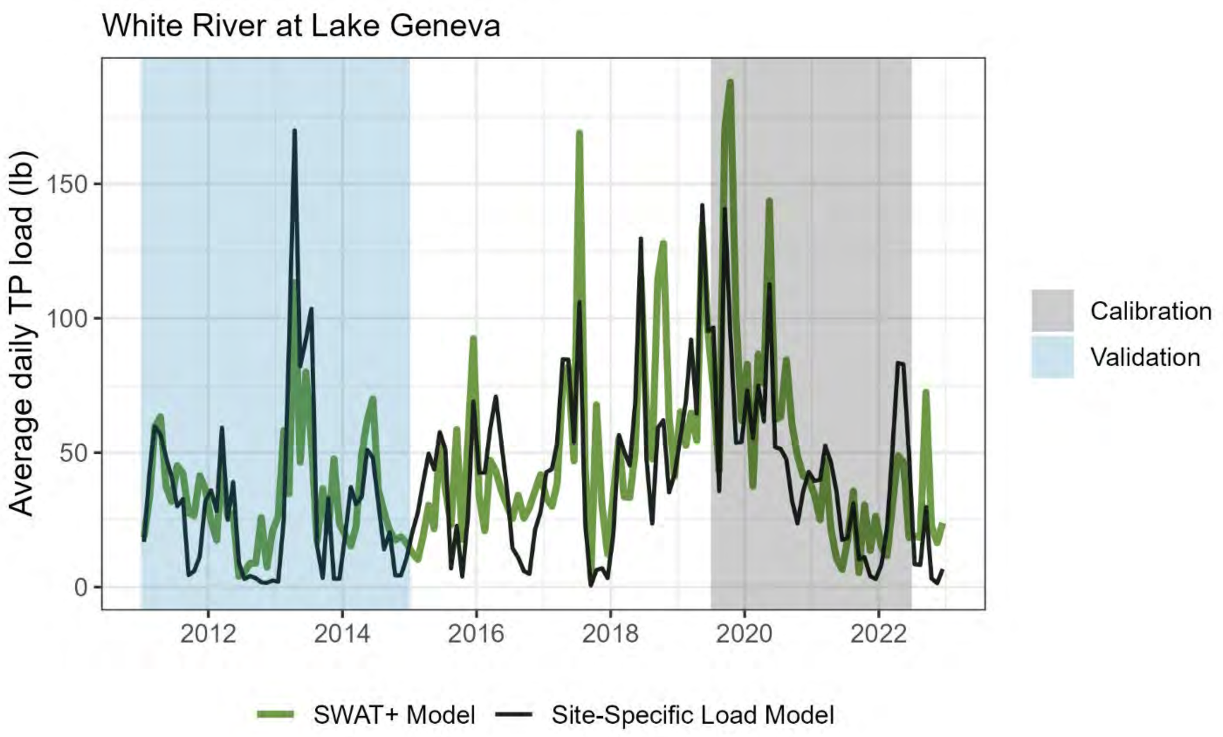

Muskego Lake

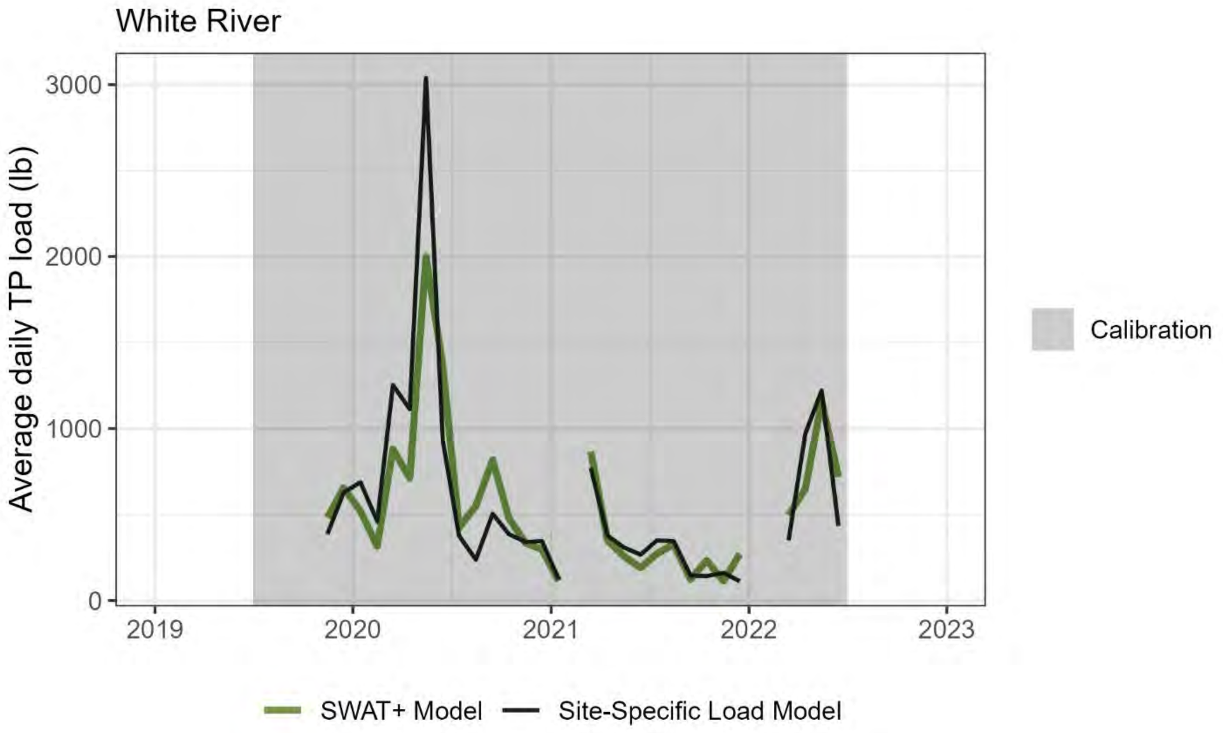

Wind Lake
Average daily TP load (lb)
600
400
200
0
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Site-Specific Load Model

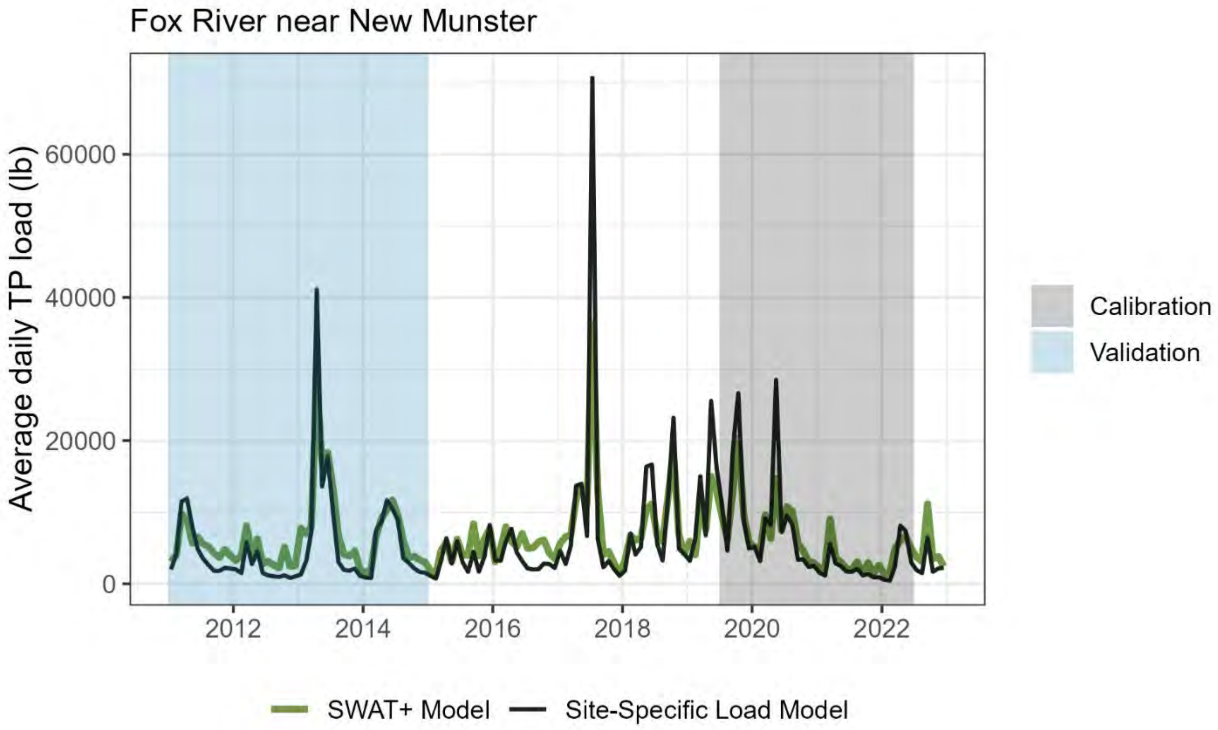

Fox River at Rochester
Average daily TP load (lb)
50000
40000
30000
20000
10000
0
2012
2014
2016
2018
2020
2022
Calibration
Validation
SWAT+ Model
Site-Specific Load Model

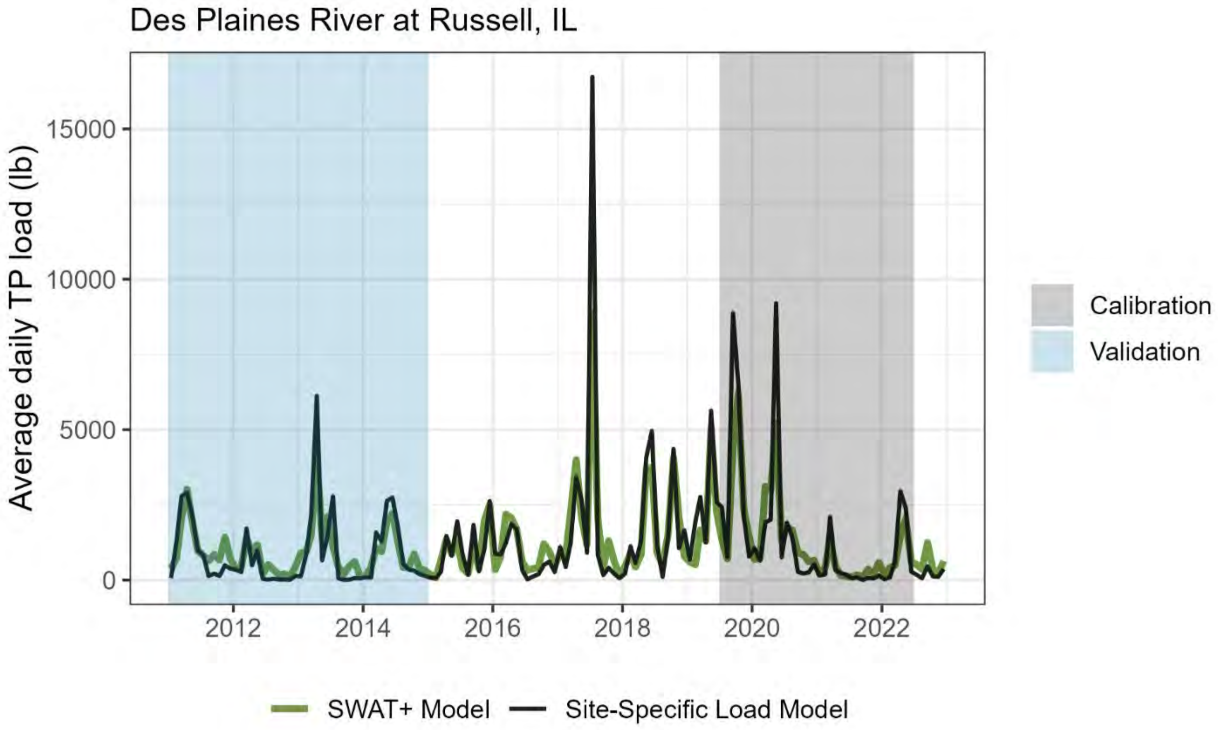

Honey Creek
Average daily TP load (lb)
1000
500
0
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Site-Specific Load Model


Sugar Creek
Average daily TP load (lb)
1500
1000
500
0
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Site-Specific Load Model


White River at Lake Geneva
Average daily TP load (lb)
0
50
100
150
2012
2014
2016
2018
2020
2022
Calibration
Validation
SWAT+ Model
Site-Specific Load Model


White River
Average daily TP load (lb)
0
1000
2000
3000
2019
2020
2021
2022
2023
Calibration
SWAT+ Model
Site-Specific Load Model


Fox River near New Munster
Average daily TP load (lb)
60000
40000
20000
0
2012
2014
2016
2018
2020
2022
Calibration
Validation
SWAT+ Model
Site-Specific Load Model


Des Plaines River at Russell, IL
Average daily TP load (lb)
15000
10000
5000
0
2012
2014
2016
2018
2020
2022
Calibration
Validation
SWAT+ Model
Site-Specific Load Model

5. COMPARISON OF PHOSPHORUS IN RESERVOIRS

			GSM TP Conc (μg/L)			
Lake Name	WBIC	SWAT ID	TP Threshold	Monitored (WATERS)	SWAT Model	% Difference
Pewaukee Lake	772000	res0103	30	17	16.5	-4%
Spring Lake	770600	pnd0500	20	11	11.6	2%
Eagle Spring Lake	768600	res0902	40	17	13.2	-23%
Booth Lake	740400	pnd1000	20	14	17.0	20%
Lake Beulah	766600	res1001	15	15	13.5	-11%
Lower Phantom Lake	765800	res1004	40	16	18.5	15%
Tichigan Lake	763600	pnd1200	30	27	27.6	1%
Little Muskego Lake	762700	pnd1300	30	16	14.4	-10%
Lake Denoon	761300	pnd1600	20	28	19.4	-30%
Waubeesee Lake	760900	res1602	30	19	23.0	19%
Wind Lake	761700	res1604	30	32	26.4	-17%
Eagle Lake	759800	pnd1700	40	134	78.2	-41%
Pleasant Lake	741500	pnd1900	30	13	16.2	29%
Lake Geneva	758300	res2601	15	12	16.4	43%
Bohner Lake	750800	pnd2900	30	20	20.4	1%
Browns Lake	750300	pnd3000	30	20	16.2	-17%
Silver Lake	747900	pnd3202	30	21	24.2	13%
Powers Lake	744200	pnd6100	30	16	22.6	39%
Lake Mary	743000	pnd6105	30	16	17.7	9%
Benet Lake & Lake Shangrila	734800	pnd8000	30	53	43.5	-18%
Paddock Lake	737900	pnd9003	30	17	12.9	-25%
Hooker Lake	738400	pnd9004	30	39	52.5	33%

APPENDIX I

SWAT+ MODEL SUBBASIN LOADING

1. SEDIMENT YIELD BY LAND USE CATEGORIES

FIGURE I.1

Distribution of Average Sediment Yield by Model Watershed

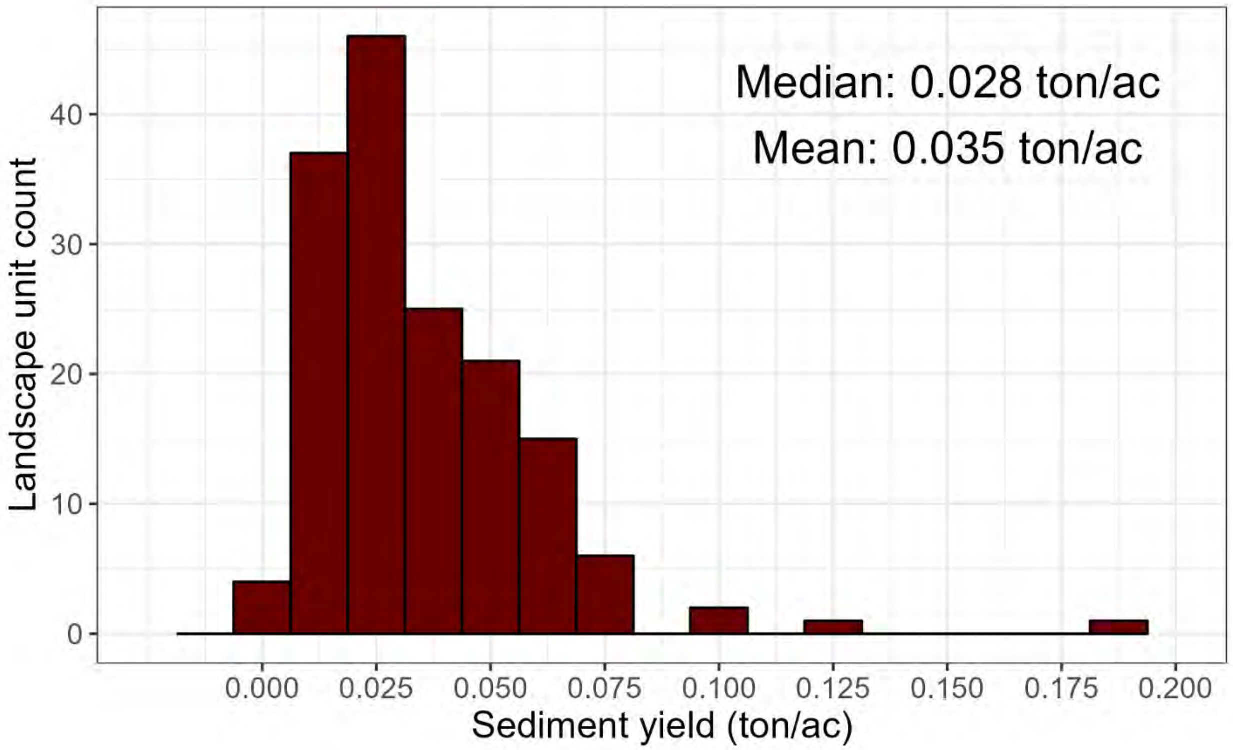


FIGURE I.2

Sediment Yield by Land Use for Model HRUs

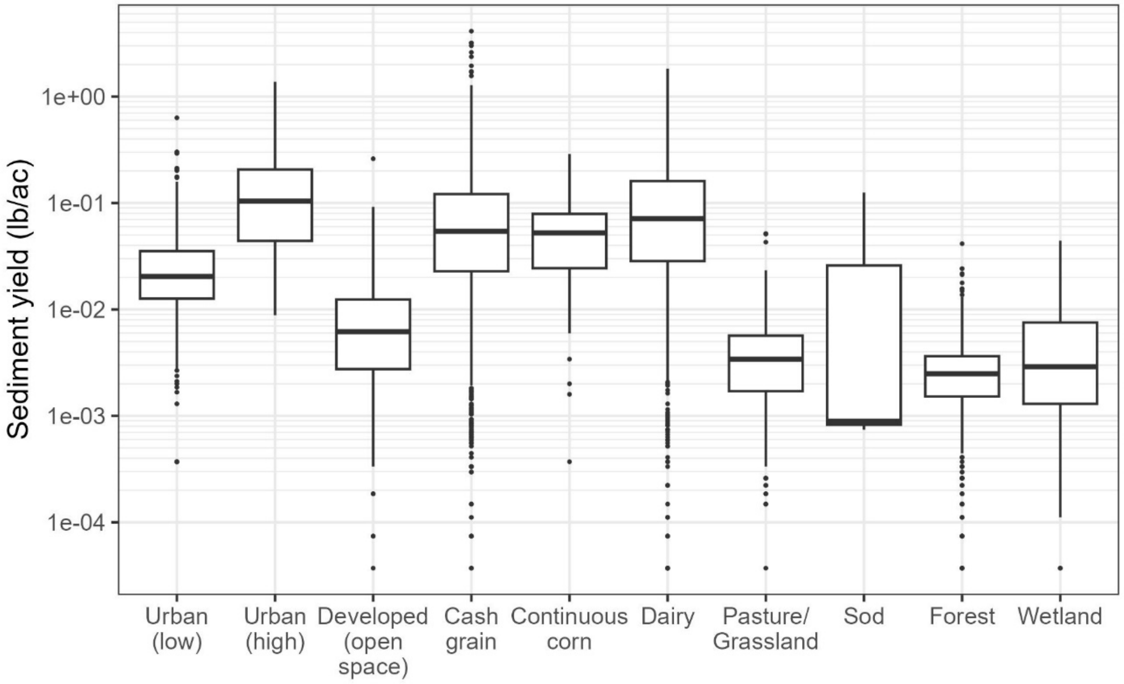


FIGURE I.3

Spatial Distribution of Average Sediment Yield by Model Watershed

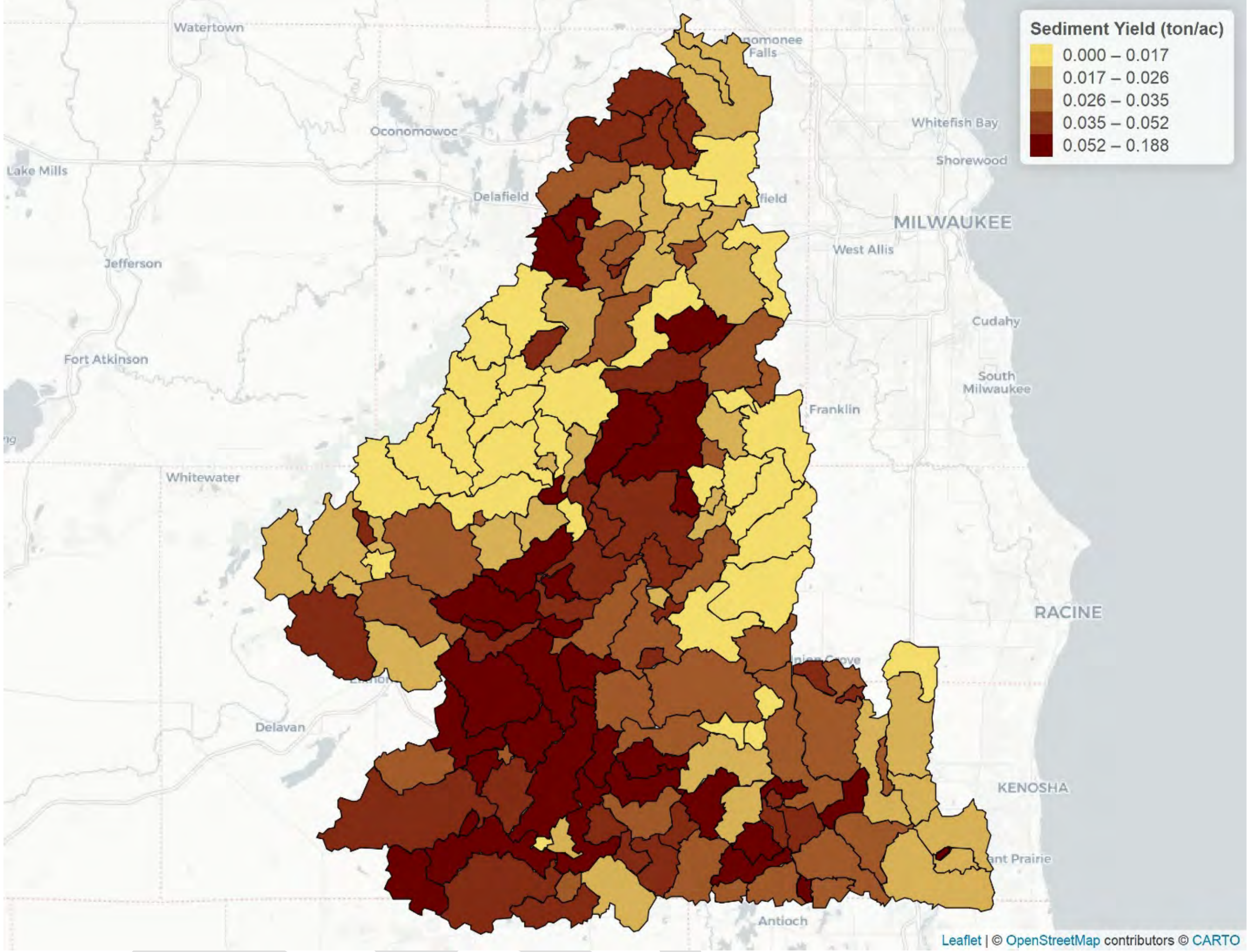


FIGURE I.4

Distribution of Agricultural Sediment Yield by Model Watershed

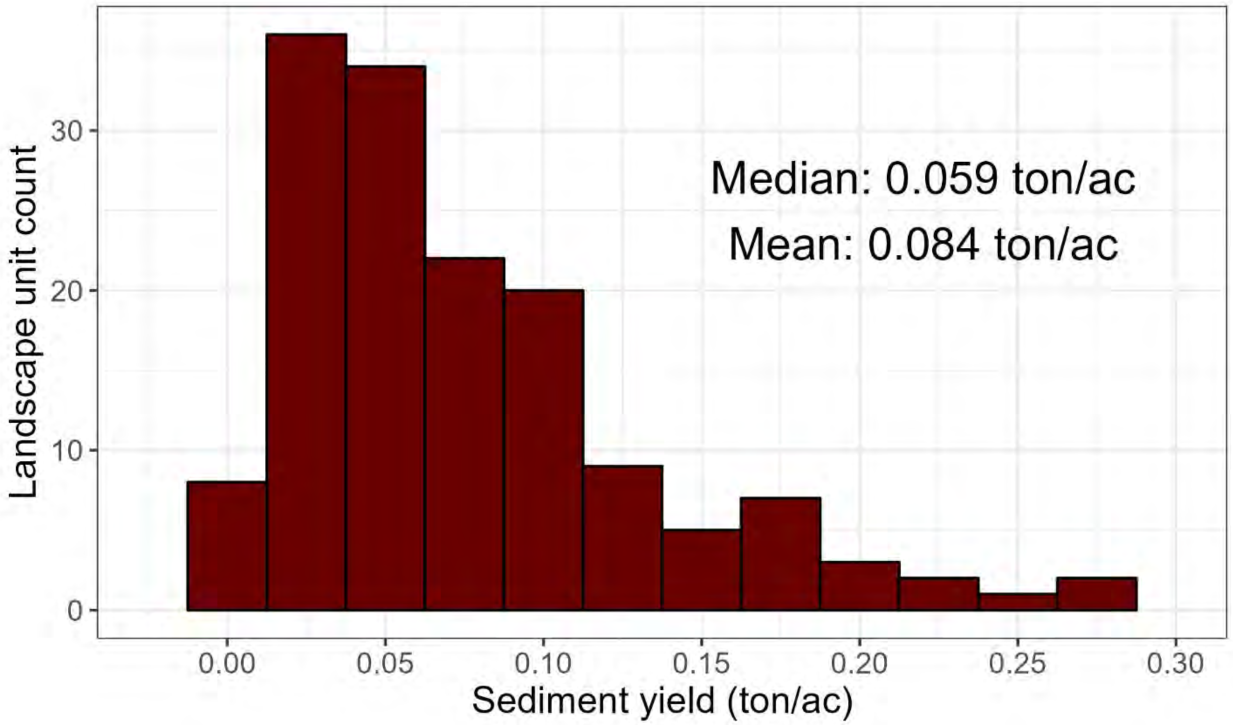


FIGURE I.5

Distribution of Developed Sediment Yield by Model Watershed

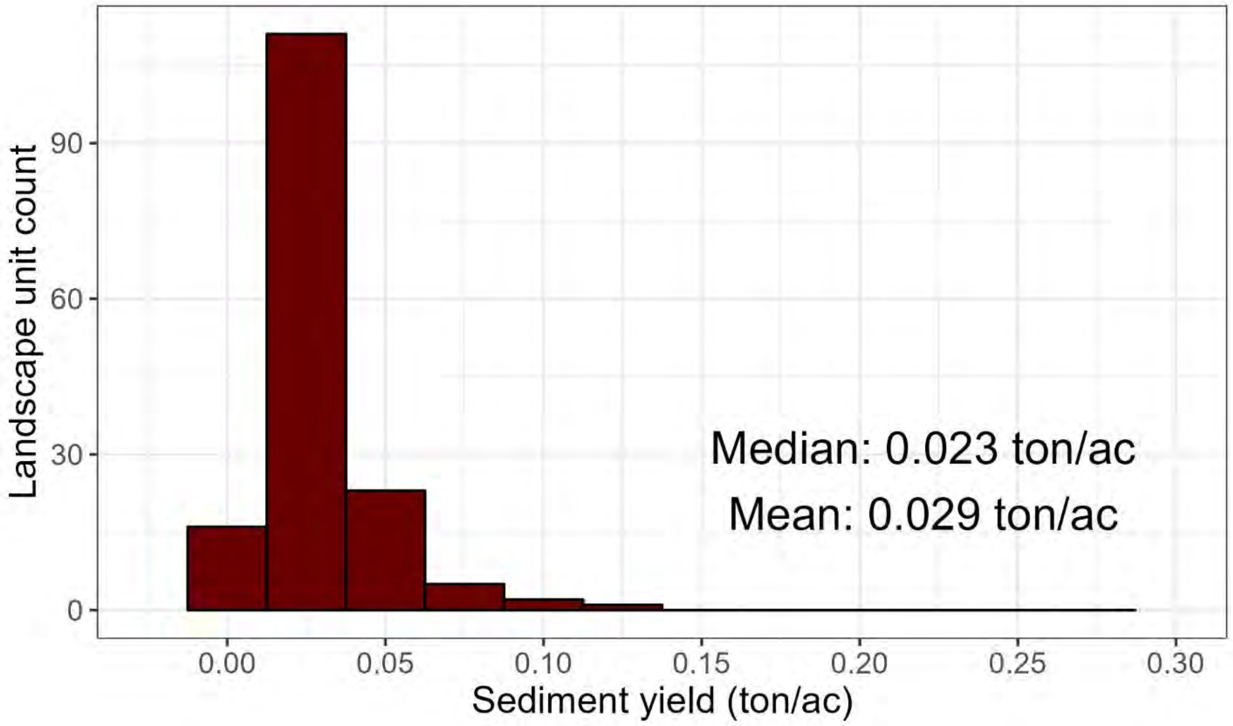


FIGURE I.6

Distribution of Natural Sediment Yield by Model Watershed

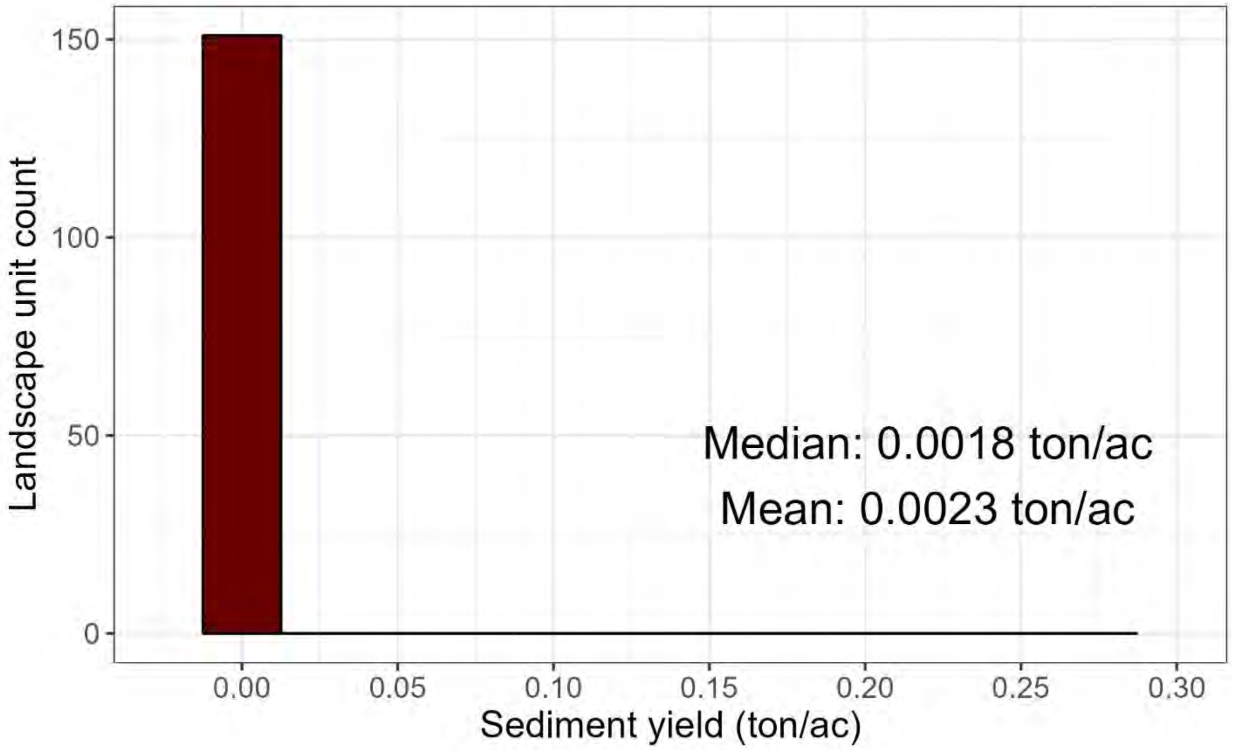


FIGURE I.7

Spatial Distribution of Average Sediment Yield by Land Use Categories

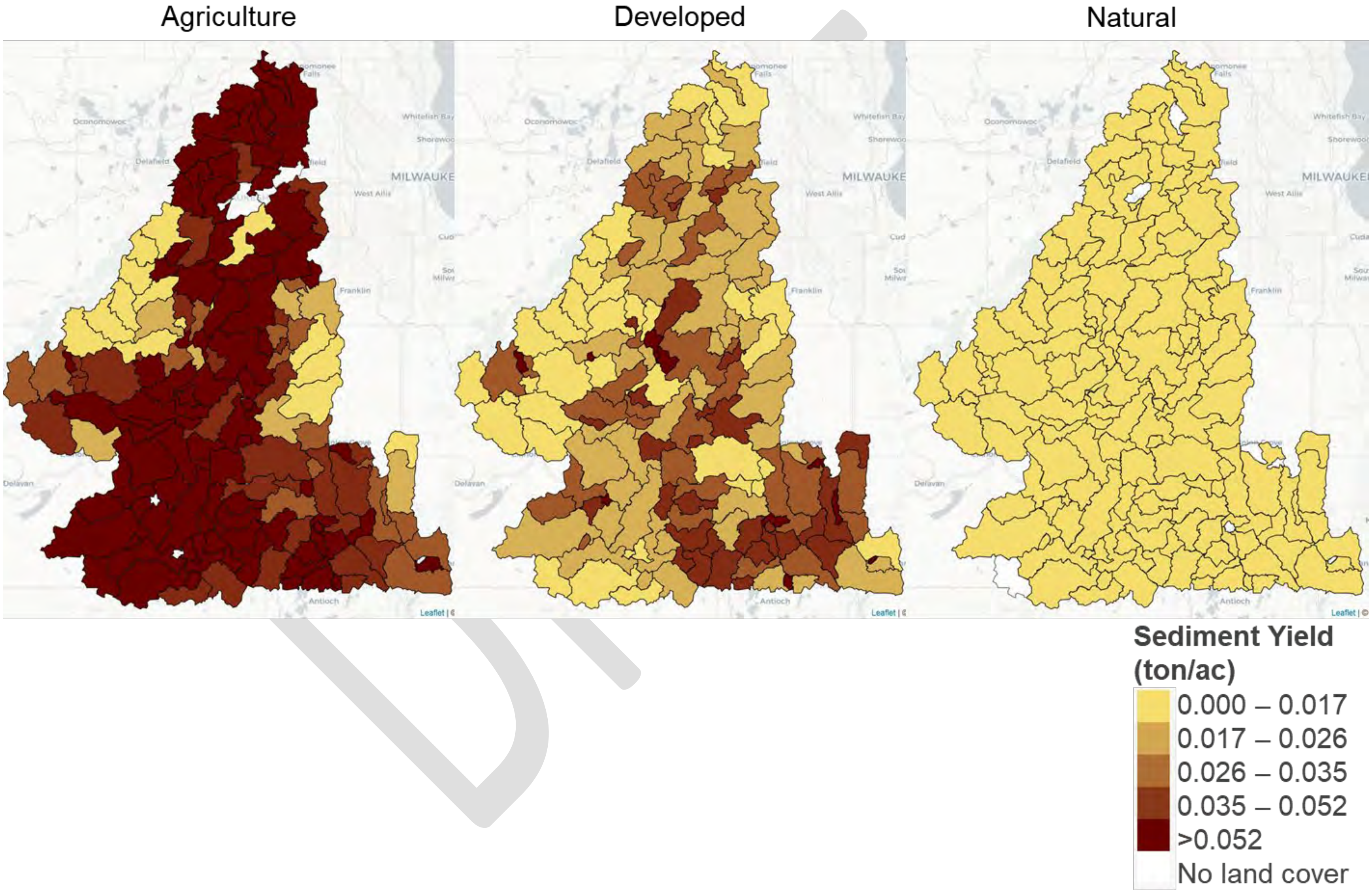


FIGURE I.8

Fraction of Total Watershed Sediment Yield by Land Use Categories

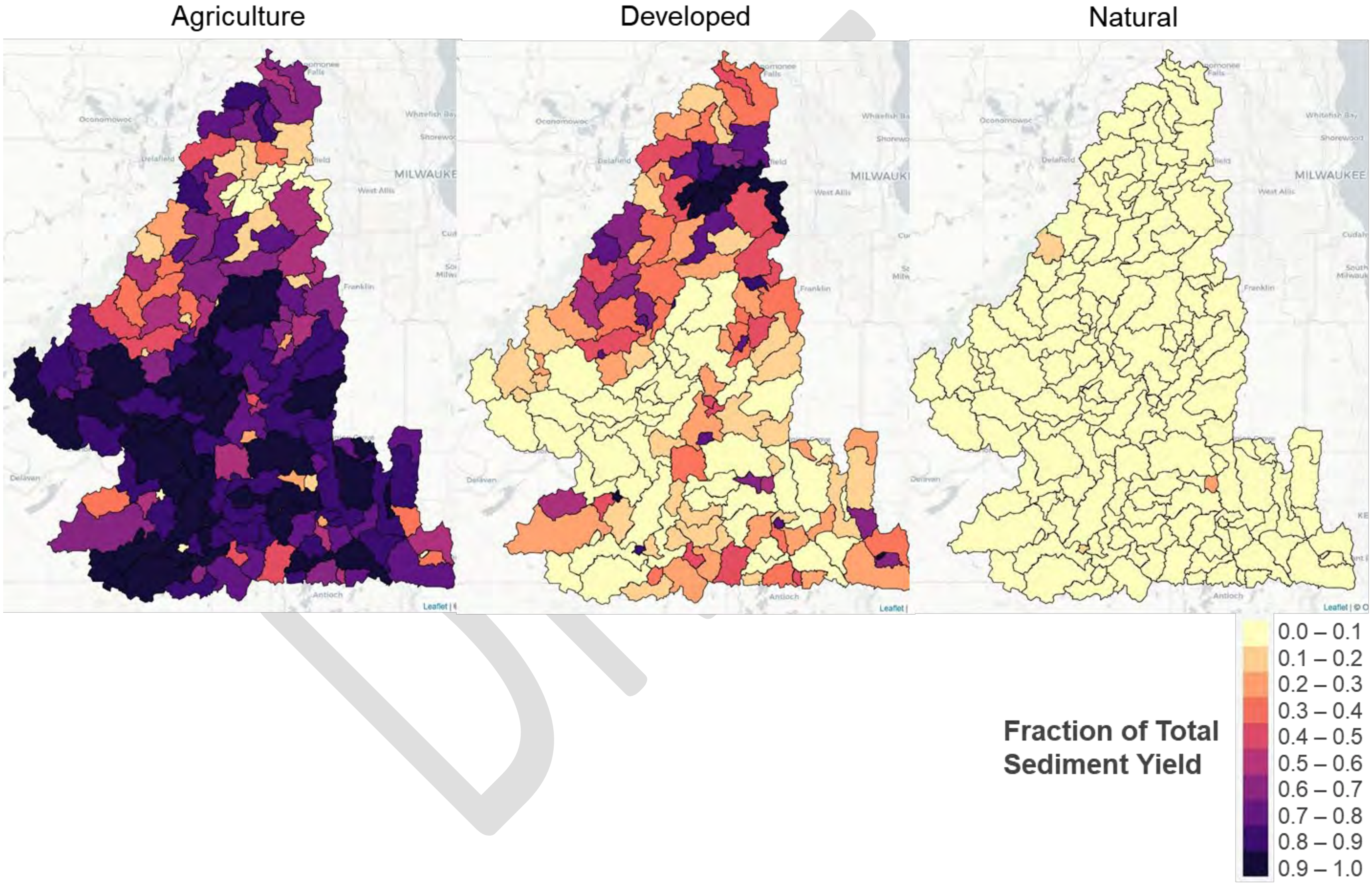
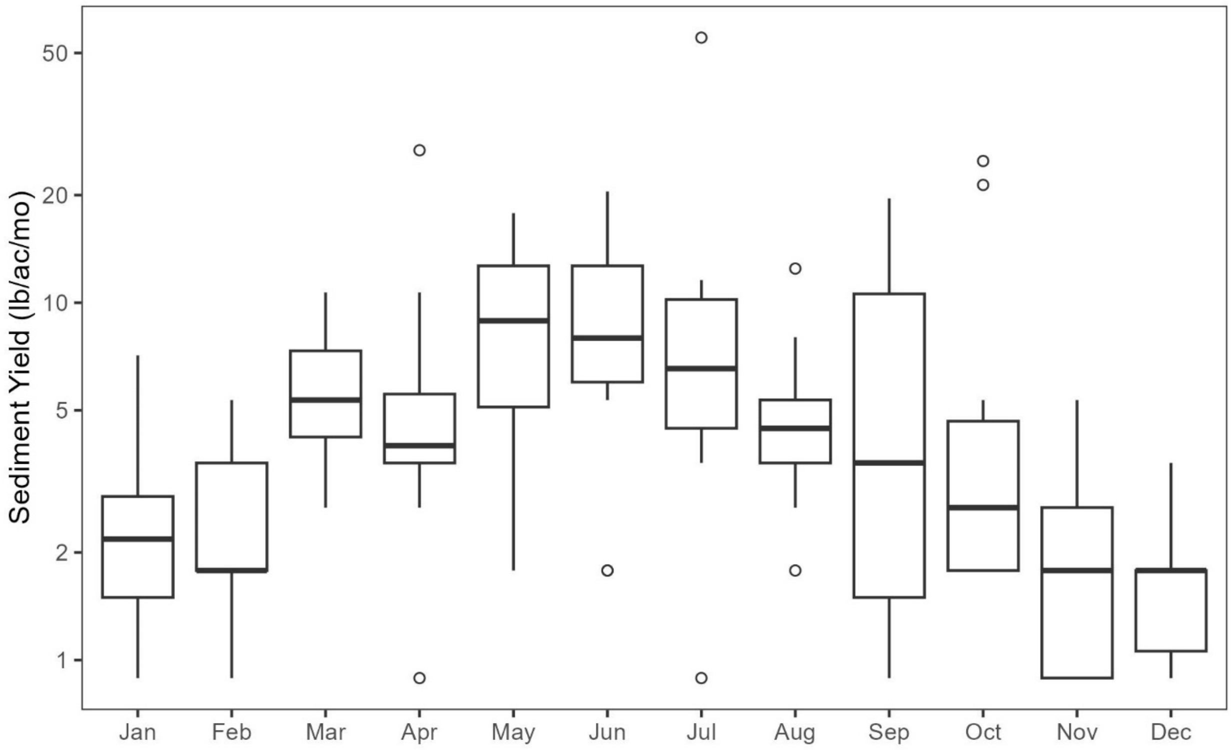


FIGURE I.9

Average Monthly Sediment Yield for Entire Study Area



2. PHOSPHORUS YIELD BY LAND USE CATEGORY

FIGURE I.10

Distribution of Average Phosphorus Yield by Model Watershed

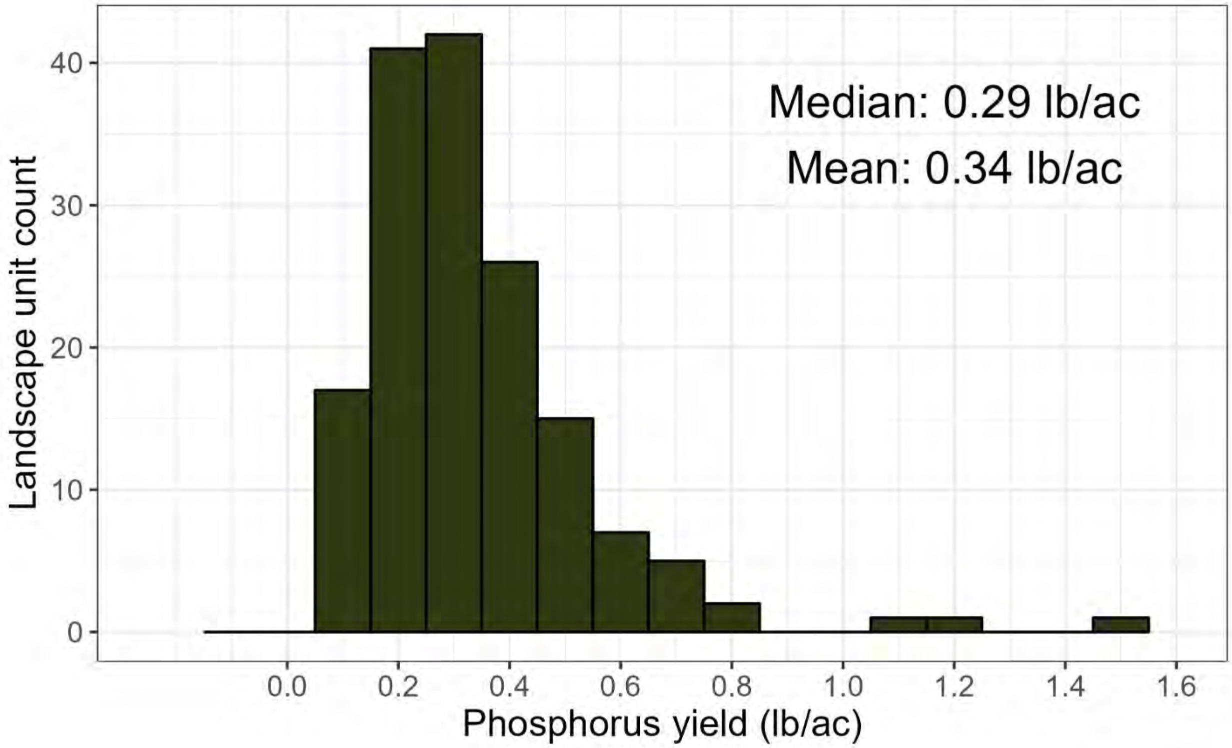


FIGURE I.11

Phosphorus Yield by Land Use for Model HRUs

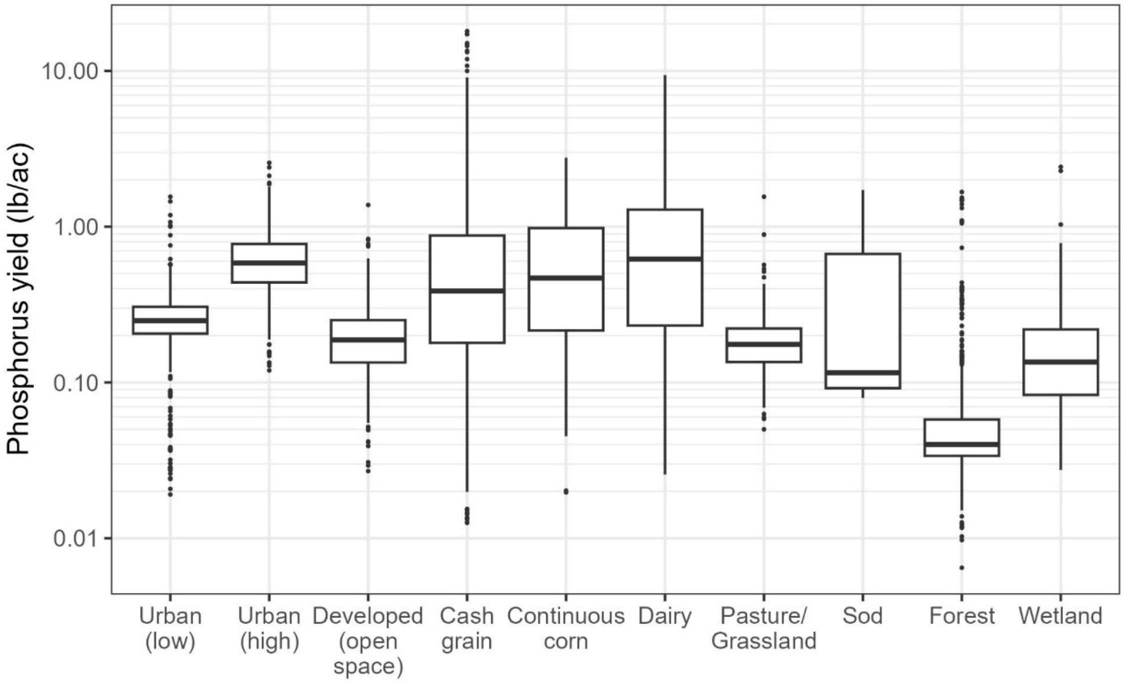


FIGURE I.12

Spatial Distribution of Average Phosphorus Yield by Model Watershed

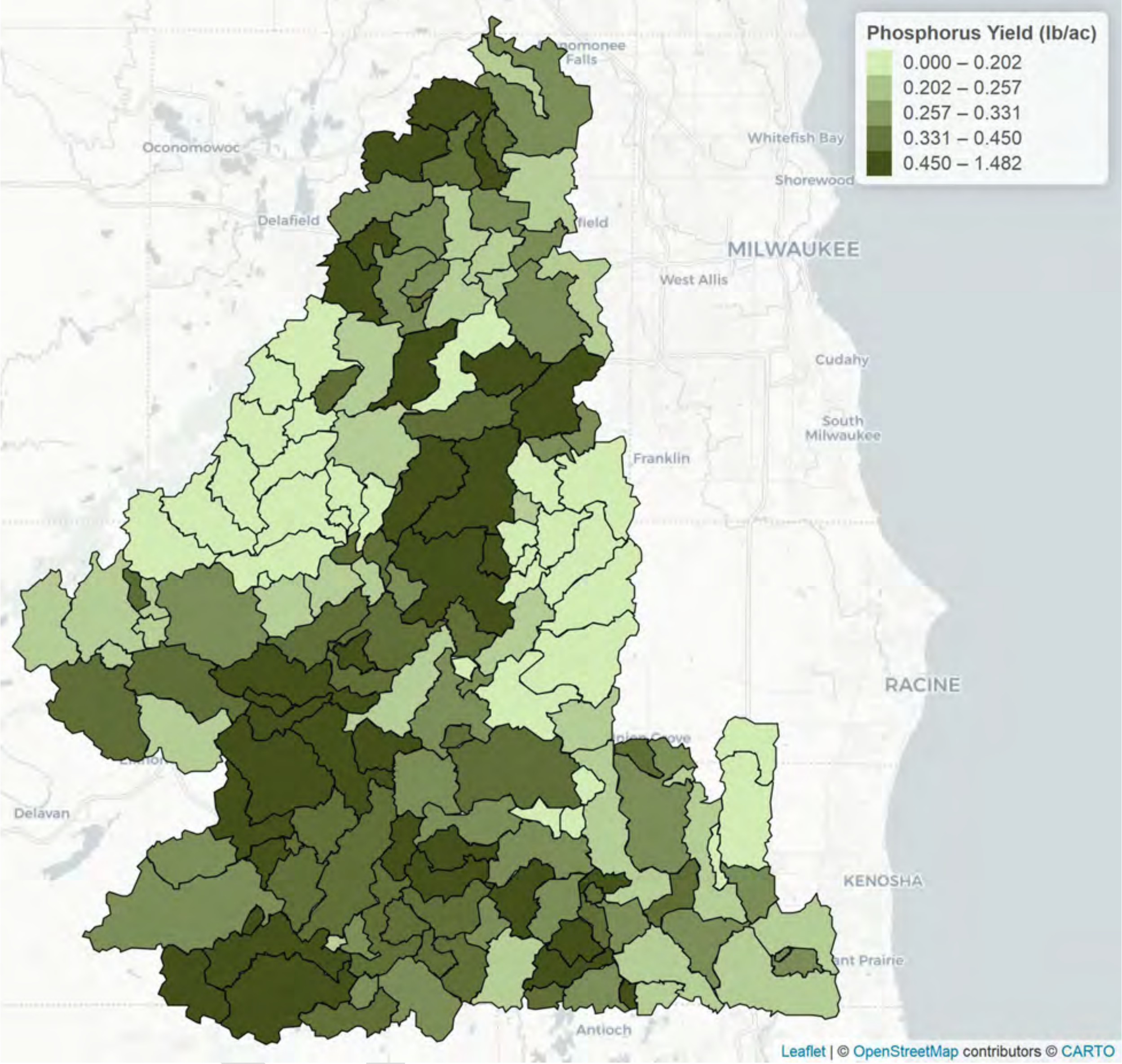


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FIGURE I.13

Distribution of Agricultural Phosphorus Yield by Model Watershed

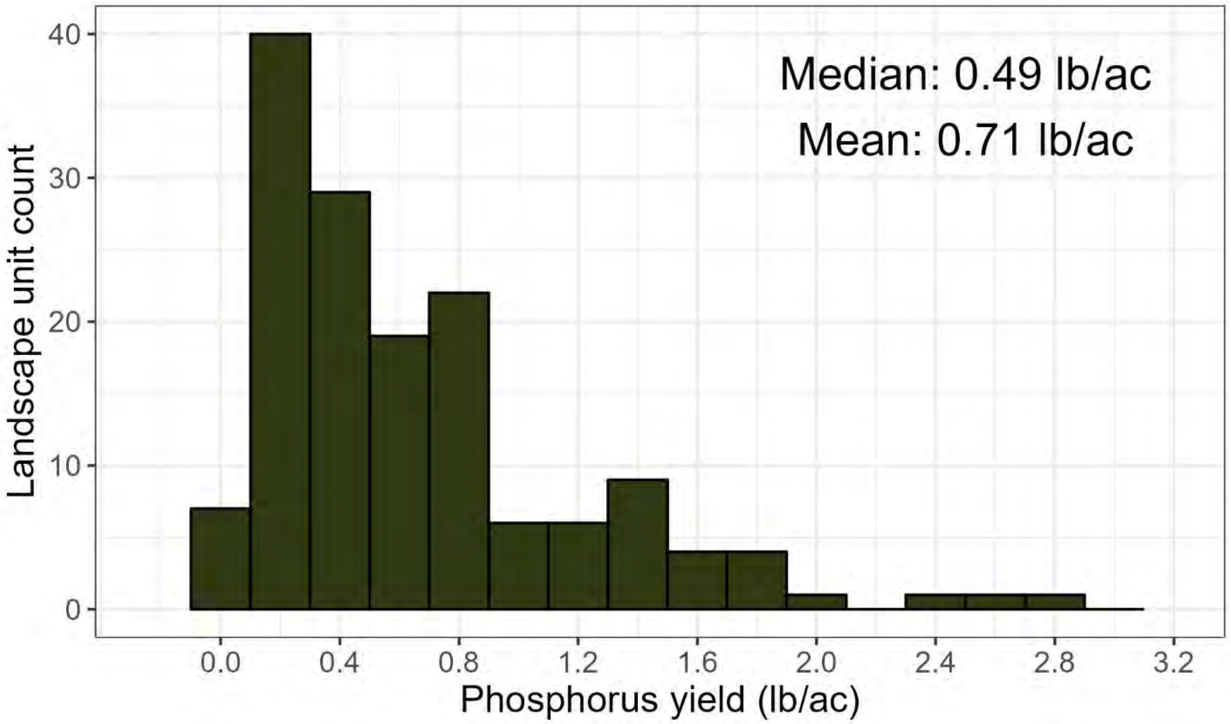

FIGURE I.14

Distribution of Developed Phosphorus Yield by Model Watershed

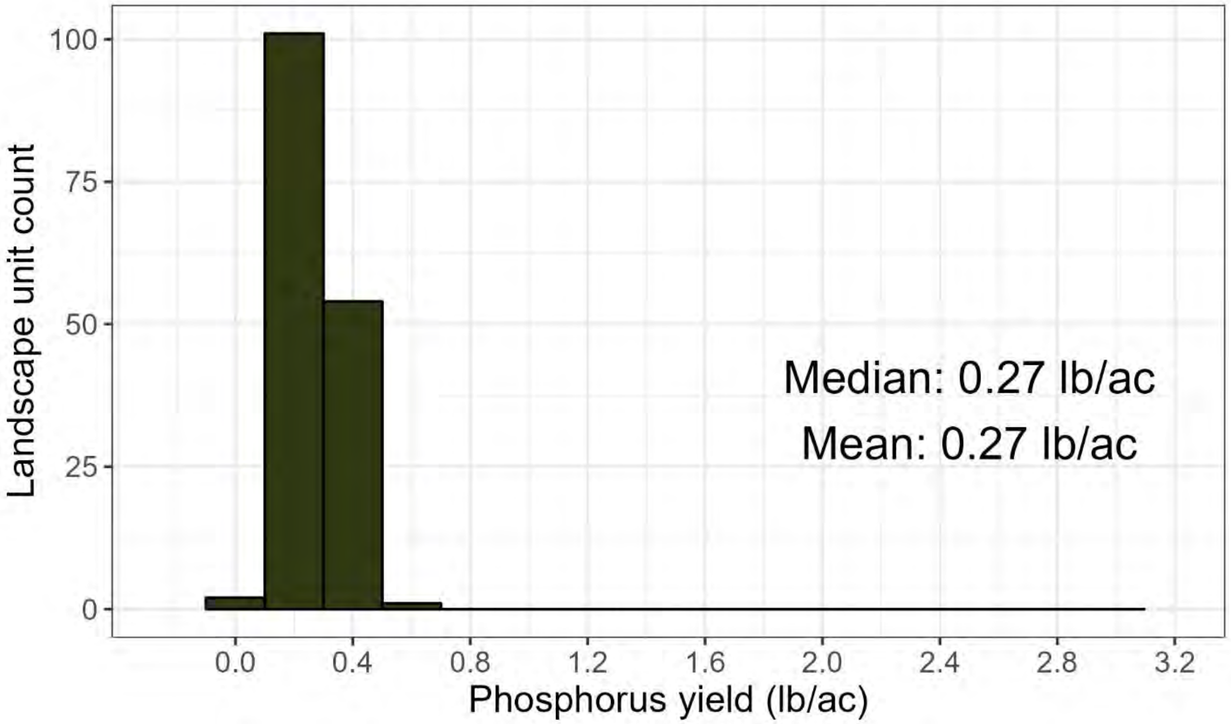

FIGURE I.15

Distribution of Natural Phosphorus Yield by Model Watershed

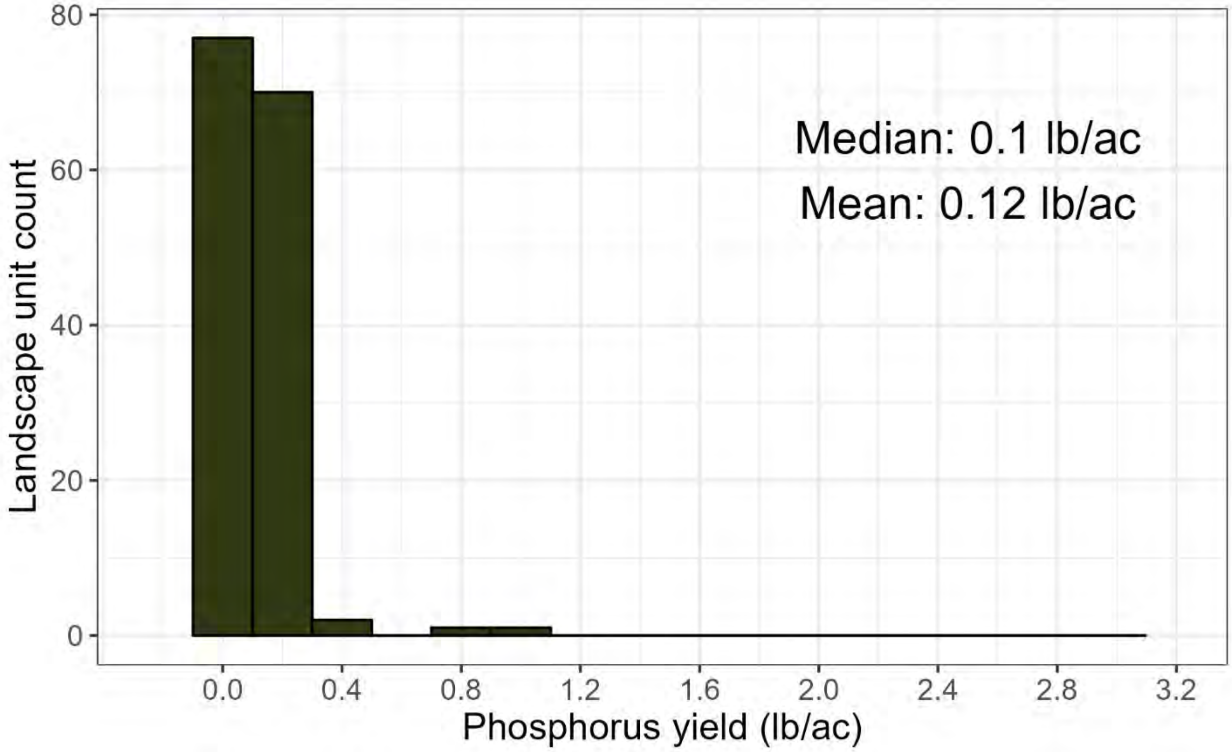

FIGURE I.16

Spatial Distribution of Average Phosphorus Yield by Land Use Categories

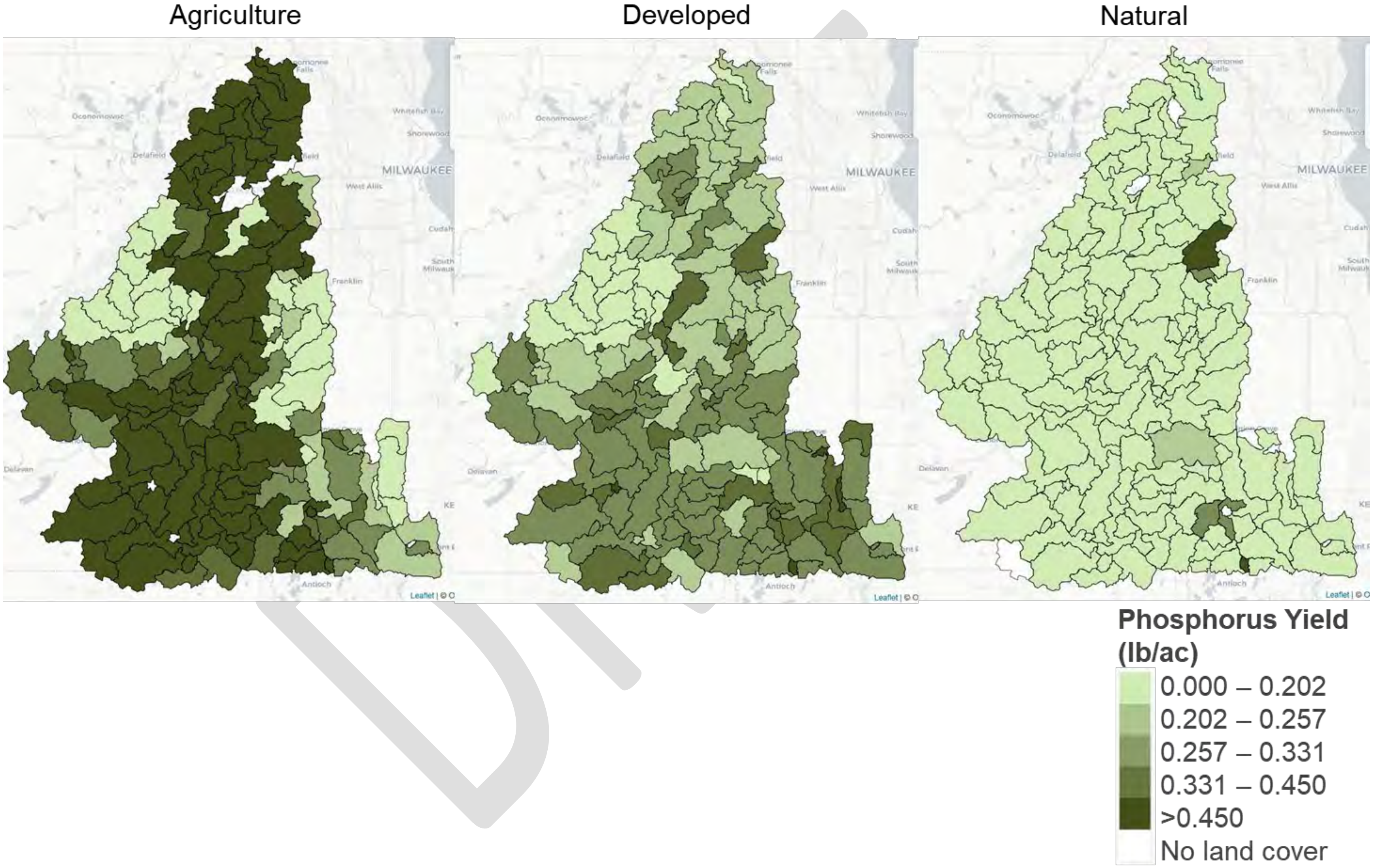

FIGURE I.17

Fraction of Total Watershed Phosphorus Yield by Land Use Categories

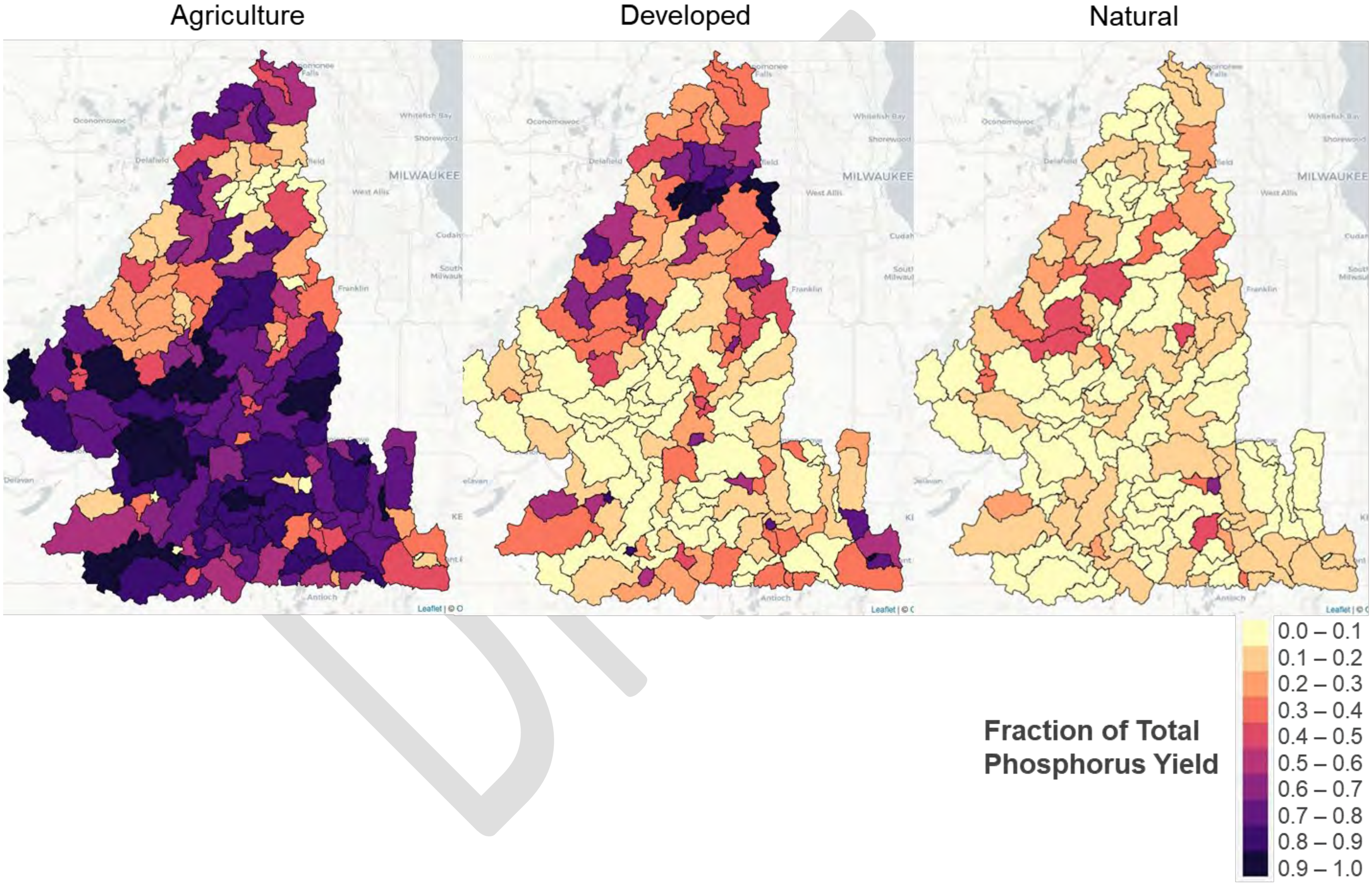

FIGURE I.18

Average Monthly Phosphorus Yield for Entire Study Area