Northeast Lakeshore TMDL: SWAT Model Setup, Calibration, and Validation

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1 Overview

This document summarizes the setup, calibration, and validation of the Soil and Water Assessment Tool (SWAT) model for the Northeast Lakeshore (NEL) Total Maximum Daily Load (TMDL) study area. The NEL SWAT model was configured using the ArcSWAT2012 interface in ArcGIS 10.7 (ArcSWAT) and run using SWAT 2012 Revision 664 (SWAT). The Cadmus Group (Cadmus) developed the NEL SWAT model to support the Wisconsin Department of Natural Resources (WDNR) with TMDL development.

The NEL study area covers approximately 1,971 square miles and drains to Lake Michigan in northeastern Wisconsin. The area spans eight counties, from Ozaukee County at the southern boundary to Door County at the northern boundary. The NEL study area is comprised of three major basins that drain to Lake Michigan: the Kewaunee Basin, the Manitowoc Basin, and the Sheboygan Basin. Each of these basins include many streams and rivers that drain to the Kewaunee River, Manitowoc River, Sheboygan River, and directly to Lake Michigan. See *Table 1* for a list of major rivers and streams within each drainage basin.

Table 1. Major rivers and streams within each basin.

Basin Name	**River or Stream Name**
Kewaunee Basin	Kewaunee River
	Ahnapee River
	Silver Creek (near Algoma)
	West Twin River
	East Twin River
Manitowoc Basin	Manitowoc River
	Silver Creek (near Manitowoc)
	Pine Creek
	Point Creek
	Sevenmile Creek
Sheboygan Basin	Pigeon River
	Sheboygan River
	Onion River
	Mullet River
	Sucker Creek
	Sauk Creek

The NEL SWAT model uses information on weather, land cover, soils, slope, and land management practices in the watershed to generate estimates of runoff volumes, phosphorus loads, and sediment loads in stream channels. Outputs from the NEL SWAT model will be used by WDNR to calculate phosphorus and sediment TMDLs. The key outputs from SWAT which will be used for TMDL development include:

- Average annual streamflow in stream and river reaches for the period 2008 through 2019;
- Average annual nonpoint source phosphorus and sediment loads for 2008 through 2019; and
- The relative magnitude of phosphorus and sediment loads from different land cover types (agriculture, urban, natural/background, etc.).

2 Model Setup

2.1 ARCSWAT AND SWAT SOFTWARE

This section references both ArcSWAT and SWAT modeling software. Each program is unique and was applied for distinct purposes as part of this project. SWAT software consists of a single executable (.exe) file which performs the model simulation, executes the model equations, and generates output files. SWAT requires as input a collection of a large number of text files (hundreds to thousands) that store model parameters such as watershed characteristics, stream routing information, and weather data. This large network of text files can be prepared through ArcSWAT. ArcSWAT is an extension for ESRI ArcGIS software that offers a user interface for creating SWAT model input files and facilitates model setup by guiding the user through a step-by-step process.

For this project, ArcSWAT was used to create an initial set of input files for the NEL SWAT model. This process included compiling geospatial map layers for watershed boundaries, land cover, topography, soil characteristics, etc. and using the ArcSWAT interface to prepare SWAT input text files from those map layers. Any instances of “ArcSWAT” in this document refer to this step of creating initial input files. Because of the limitations of ArcSWAT, certain parameter values within the initial input files were then adjusted manually via a text editor or through automated R programming scripts. The SWAT executable (.exe) file was then used to verify that the model successfully ran to completion and to review initial model results.

2.2 SUBBASIN AND REACH DELINEATION

The NEL TMDL study area was divided into 321 subbasins. The subbasin delineation process was completed by the Wisconsin Department of Natural Resources (WDNR) using the following datasets and factors as a guide:

- Topography – A 10-meter resolution digital elevation model (DEM) from the U.S. Geological Survey (USGS) 3D Elevation Program. Cotter et al. (2003) report that SWAT results are sensitive to the resolution of the DEM used for model input and that simulation errors below 10% for streamflow, sediment, and phosphorus could be achieved with DEM resolutions of 300 meters or less. The DEM resolution used for the NEL SWAT model (10 meters) is below this threshold.
- Streamflow monitoring – USGS and WDNR continuous streamflow monitoring sites.
- Impaired waters - Stream/river and lake/reservoir segments listed as impaired on the 2018 Wisconsin 303d Impaired Waters List (WDNR 2018) and those proposed for the draft 2020 list. Consideration was also given to streams that were likely to be impaired but where sufficient monitoring data did not exist.
- Wastewater discharges – Points of permit compliance for wastewater dischargers with Wisconsin Pollutant Discharge Elimination System (WPDES) permits.

- Lakes – Lakes subject to WDNR water quality criteria (surface area greater than or equal to 5 acres). Based on language in Wisconsin NR102.06(6)(b) and the WDNR 1:24,000 Scale Value-Added Hydrography Database.
- Applicable water quality criteria for phosphorus defined in Wisconsin NR102.06(3), summarized in *Table 2*.

Table 2. Applicable phosphorus criteria for streams and rivers in the NEL study area.

Basin Name	**Phosphorus Criterion**	**Relevant Segments**
Kewaunee Basin	75 µg/L	All rivers and tributaries subject to statewide phosphorus criteria.
Manitowoc Basin	100 µg/L	Manitowoc River from confluence of North Branch and South Branch Manitowoc rivers to the opening at the end of the piers at Lake Michigan
	75 µg/L	All other rivers and tributaries subject to statewide phosphorus criteria.
Sheboygan Basin	100 µg/L	Sheboygan River from outlet of Sheboygan Marsh to the opening at the end of the piers at Lake Michigan
	75 µg/L	All other rivers and tributaries subject to statewide phosphorus criteria.

Subbasins were assigned to three separate sub-model groups. Each sub-model group represents the area covered by a single SWAT model application with distinct input and output files. The modeling approach used three separate sub-models rather than a single model in order to improve computation efficiency and better represent variability in hydrologic conditions across the NEL study area. The NEL subbasins and sub-model boundaries are displayed in Figure 1.

The extent of each sub-model area follows the three major river drainages within the study area: the Kewaunee Basin, the Manitowoc Basin, and the Sheboygan Basin. The Kewaunee, Manitowoc, and Sheboygan sub-model areas are comprised of 112, 99, and 110 subbasins, respectively. The average subbasin drainage area used in the NEL SWAT model is approximately 1% of each sub-model and below the recommended values from Jha et al. (2004), which report that SWAT streamflow results are relatively insensitive to subbasin size but recommend drainage area thresholds of less than 3% of the total modeled area for simulating sediment loads and less than 5% for simulating phosphorus loads.

Stream reach data input to ArcSWAT were based on the WDNR 1:24,000 Scale Hydrography Database. WDNR hydrography was edited so that each subbasin contained only one main reach segment. This was necessary because the presence of multiple reaches in a subbasin can result in erroneous channel parameter calculations by ArcSWAT.

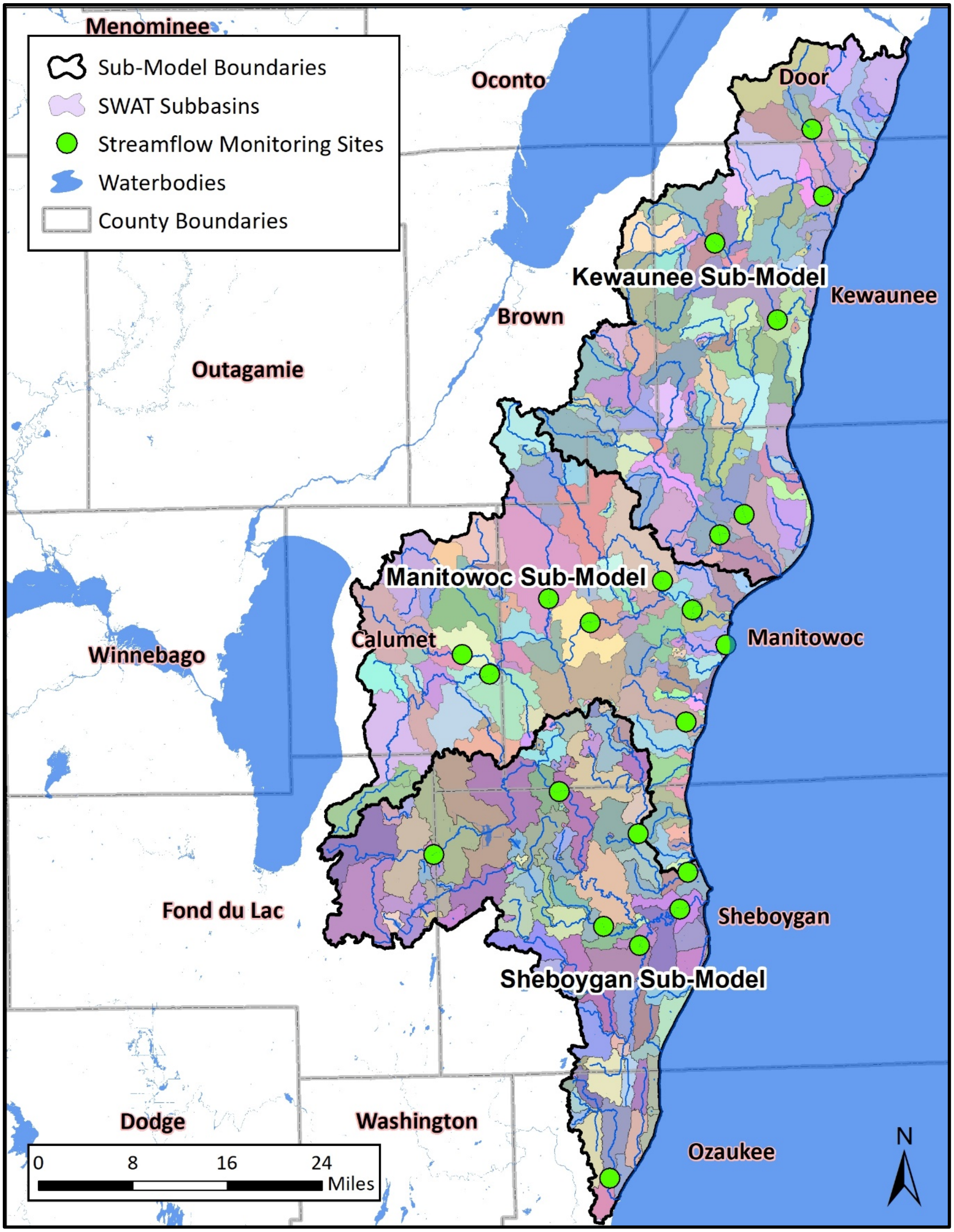

Figure 1. NEL SWAT model subbasins and sub-model boundaries.

2.3 HYDROLOGIC RESPONSE UNITS

Hydrologic Response Units (HRUs) are unique land cover-soil-slope associations within a subbasin and are the fundamental land units used for simulating water balance and water quality processes within SWAT. The HRU is the smallest spatial unit of SWAT and the ArcSWAT interface automatically delineates HRUs within the modeled watershed with user-supplied geospatial datasets on land cover, soil types, and slopes. This section summarizes the input datasets and approach to HRU definition in the NEL SWAT model.

2.3.1 Land Cover

A custom land cover dataset for the NEL SWAT model was developed using a combination of the Wiscland2 land cover dataset (https://dnr.wi.gov/maps/WISCLAND), information on agricultural practices from County Land and Water Conservation Departments (LWCDs) and a review of Nutrient Management Plans, and the boundaries for municipalities with Municipal Separate Storm Sewer System (MS4) permits.

The Wiscland2 land cover dataset was produced by WDNR at four "levels". Each level offers different precision in land cover classification. Level one classifications are the coarsest and describe general land cover categories such as "Agriculture" or "Forest". Level four classifications are the most specific and further classifies the agricultural category into continuous corn; cash grain (alternating corn and soybean plantings); dairy (rotating plantings of corn and alfalfa); continuous hay/pasture; and potato/vegetable. The fourth classification level was used to define agricultural land cover for the NEL SWAT model.

In 2019, WDNR conducted research to refine and expand on the agricultural land cover information in the Wiscland2 dataset. For this research, data was collected using two different methods. First, the eight LWCDs within the NEL study area were administered an agricultural survey with questions related to fertilizer and manure application amounts and timing, planting timing, tillage operations, and crop sequences for different agricultural cover types. A summary of 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).

The second method WDNR used to collect agricultural data involved a review of Nutrient Management Plans for Concentrated Animal Feeding Operations (CAFOs) in the NEL study area. This review provided estimates of manure spreading rates and soil phosphorus concentrations at the subbasin level, which were directly incorporated into the SWAT model. Methods and results of the manure spreading analysis are provided in the Manure spreading analysis report. Methods and results of the soil phosphorus analysis are provided on page 15 of the Agricultural survey summary. Overall, the agricultural land use information gathered from both surveying LWCDs and reviewing CAFO Nutrient Management Plans provided necessary information for SWAT modeling beyond the agricultural land cover classifications offered by Wiscland2.

The Wiscland2 agricultural classes were divided into 16 detailed agriculture classes for SWAT modeling based on results of the WDNR survey of LWCDs and CAFO Nutrient Management Plans. Each agricultural class is associated with a specific set of farming operations (crops planted, tillage, chemical fertilizer application, etc.; see Table 6 of Agricultural survey summary). Note that the 16 detailed agriculture classes do not include potato/vegetable rotations. The potato/vegetable class in Wiscland2 makes up only 2.8% of the NEL study area. County LWCDs confirmed that potatoes and vegetables were not continuously grown in the NEL study area, except in some small direct-to-consumer vegetable operations. Instead, canning vegetables are grown in rotation with other cash grains. Because of this, potato/vegetable rotations were removed during the HRU definition process and reclassified according to the proportion of remaining agricultural cover classes in a subbasin.

Level four classifications were also used to represent the extent of urban land cover in the SWAT model. Level four classifications of urban cover include “Developed, High Intensity” and “Developed, Low Intensity”. The developed land cover classes were further divided into “Permitted MS4” and “Non-permitted” classes to differentiate between developed lands located inside versus outside of areas regulated by MS4 permits. This step used boundaries for municipalities with MS4 permits (Table 5). Map layers of municipal boundaries for all MS4 permitted municipalities in the NEL study areas were acquired from WDNR. Boundaries for towns with MS4 permits were clipped to urban area boundaries in the 2010 Census Urban Area dataset because MS4 permits for towns only apply to the urbanized area within the town (not the entire town boundary).

Wiscland level one classifications were used as SWAT model input for all other land cover types: “Grassland”, “Forest”, “Open Water”, “Wetland”, “Barren”, and “Shrubland”. Two of these classes were aggregated after visual inspection of Wiscland2 pixels and aerial imagery. The “Shrubland” cover class was combined into the “Grassland” class and the “Barren” cover class was combined into the “Developed, Low Intensity” class.

2.3.2 Soils

Soil types were defined using a custom soil dataset that combined two geospatial data products from the USDA Natural Resources Conservation Service: the Digital General Soil Map of the United States (STATSGO2) and the Gridded Soil Survey Geographic Database (SSURGO). The STATSGO2 map layer defines 14 different soil types in the NEL study area. The SSURGO dataset is a higher-resolution soil map, with 647 different soil types in the NEL study area. Each SSURGO and STATSGO2 soil type has a specific set of SWAT soil parameters listed in soil attribute data tables included with ArcSWAT.

The custom soil dataset generated for SWAT modeling was created by dividing STATSGO2 soil units into “low”, “moderately low”, “moderately high”, and “high” runoff potential areas, based on hydrologic soil group classifications in the SSURGO map layer. The custom soil dataset therefore depicts most soil parameters at the scale of STATSGO2 soil types except for hydrologic soil group, which is represented at the more detailed SSURGO scale. Hydrologic soil group describes the runoff potential of a soil type and is a key soil attribute for SWAT modeling.

The following steps were applied to merge the STATSGO2 and SSURGO datasets for the NEL SWAT model:

1. Create a hydrologic soil group map layer from the SSURGO dataset for the NEL study area. Areas with missing hydrological soil group information were filled with the dominant hydrological soil group in the SWAT subbasin.

2. Overlay the hydrologic soil group map layer created in step 1 with the STATSGO2 map layer. This step divided each STATSGO2 soil type into multiple subtypes based on SSURGO hydrologic soil group and resulted in 59 different soil types across all three SWAT sub-models.

3. Create a custom soil attribute table for input to ArcSWAT. Each soil type in the custom soil map created in step 2 was assigned the attributes of the corresponding STATSGO2 soil type and the SSURGO-based hydrologic soil group.

2.3.3 Slope

A gridded slope dataset for the NEL study area was created through ArcSWAT from the USGS 3D Elevation Program 10-meter resolution DEM. A single slope category was used for HRU definition in the NEL SWAT model (i.e., HRUs are not differentiated based on slope alone). The slope dataset was therefore used to calculate the average slope of each HRU and other topographic model parameters.

2.3.4 HRU Definition

HRUs were defined and mapped using the ArcSWAT HRU interface and custom data processing methods. In total, 4,805 HRUs were defined for the NEL SWAT model. HRU counts for each SWAT sub-model are:

- Kewaunee Sub-Model – 1,580 HRUs
- Manitowoc Sub-Model – 1,411 HRUs
- Sheboygan Sub-Model – 1,814 HRUs

The land cover and soil datasets described in Sections 2.2.1 and 2.2.2 were used as the basis of HRU definition. ArcSWAT requires users to specify minimum area thresholds for each land cover category that must be met within a subbasin in order for the category to be defined as a unique HRU. Minimum area thresholds are also specified for soil types. The minimum area thresholds prevent 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, modeling team members from Cadmus, WDNR, and EPA Region 5 weighed implications for model efficiency (fewer HRUs result in shorter runtimes and allow for additional fine-tuning of model parameters during calibration) and the resolution needed for TMDL development. The selected threshold values 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. Further discussion of methods for HRU definition is provided at the end of this section.

For the NEL SWAT model, a minimum area threshold of 20% was defined for soil types and applied through ArcSWAT. Areas containing soil types that did not meet the 20% threshold are redistributed through ArcSWAT to the remaining soil types in a subbasin. Land cover thresholds were defined from the criteria listed below and illustrated in Figure 2 and applied using geospatial analysis tools and a custom automated script written in the Python programming language. This approach allowed for a more detailed and specialized set of criteria for HRU definition. The land cover processing method included the following criteria, results are summarized in Table 3.

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 NEL 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.

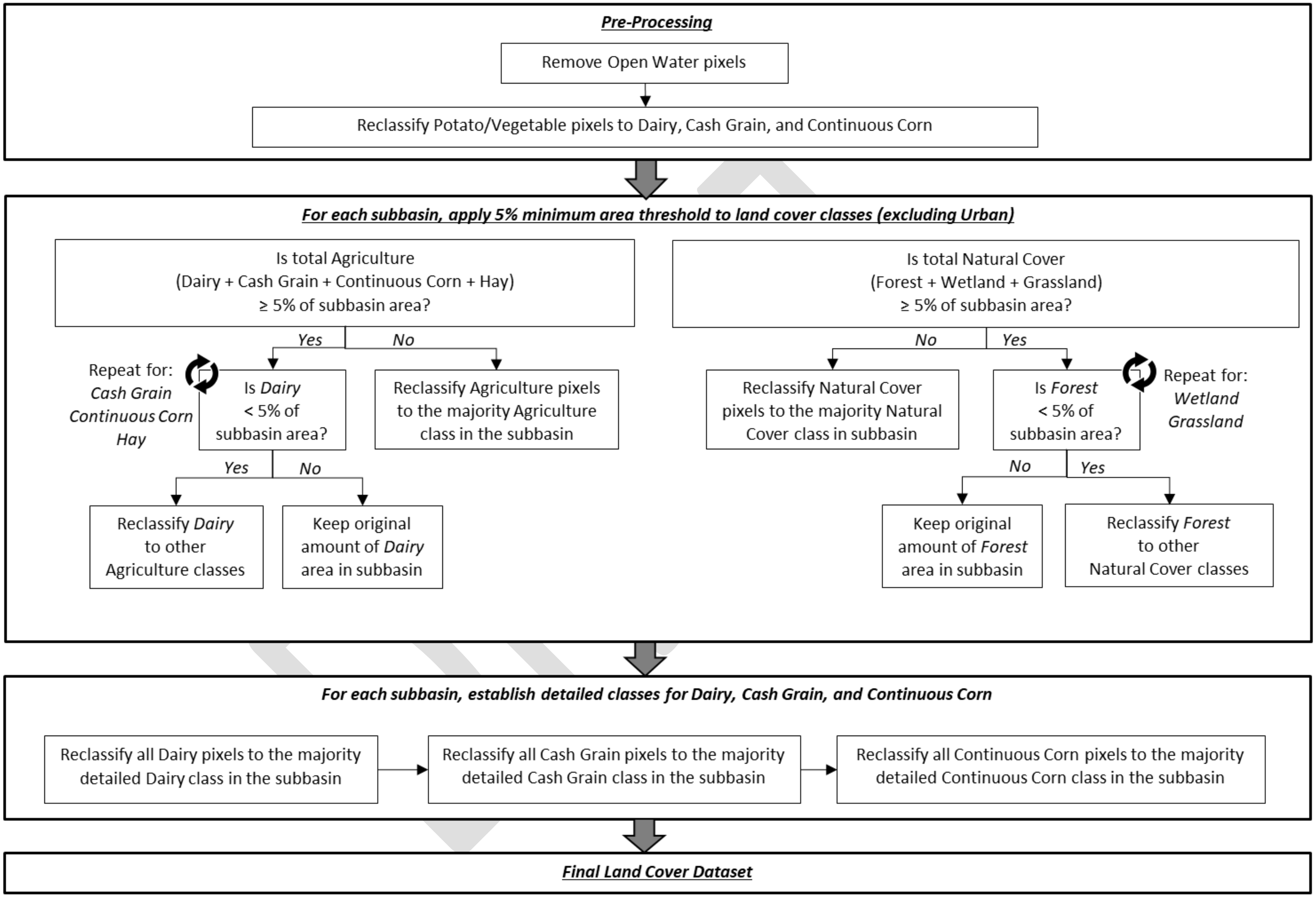

Figure 2. Flow chart describing the steps applied to the land cover map layer for HRU definition.

As noted above, the modeling team considered model efficiency (fewer HRUs result in shorter runtimes and allow for additional fine-tuning of model parameters during calibration) and the resolution needed for TMDL development when developing HRU input data and methods. While the data processing steps described in this section resulted in the removal and reclassification of some land cover and soils types within a subbasin, the final NEL HRUs reflect a high level of detail for SWAT modeling to support TMDL development. As noted above, the methodology resulted in a total of 4,805 HRUs for the NEL SWAT model. This equates to approximately 2.4 HRUs per square mile of study area and is a significantly higher than the number of HRUs in other SWAT models recently developed to support TMDL development in Wisconsin. For example, the SWAT model for the Upper Fox-Wolf Basins included 1.4 HRUs per square mile (8,295 HRUs; 5,842 square mile study area) (The Cadmus Group 2018) while the SWAT model for the Wisconsin River Basin included 0.6 HRUs per square mile (5,351 HRUs ; 9,156 square mile study area) (WDNR 2016).

Table 3. Results of land cover aggregation for HRU definition. The names of agricultural classes correspond to class names in Table 6 of Agricultural survey summary.

Land Cover Class	Percent of Watershed			
	Kewaunee Basin Sub-model	**Manitowoc Basin Sub-model**	**Sheboygan Basin Sub-model**	**Entire NEL Study Area**
Dairy Sequence 1 - Till 1 (Begin Year 1)	16%	18%	3%	13%
Dairy Sequence 2 - Till 1 (Begin Year 1)	2%	0.0%	0.0%	0.6%
Dairy Sequence 3 - Till 1 (Begin Year 1)	1%	0.7%	13%	5%
Dairy Sequence 3 - Till 3 (Begin Year 1)	0.9%	0.0%	0.0%	0.3%
Dairy Sequence 1 - Till 1 (Begin Year 4)	16%	18%	3%	13%
Dairy Sequence 2 - Till 1 (Begin Year 4)	2%	0.0%	0.0%	0.6%
Dairy Sequence 3 - Till 1 (Begin Year 4)	1%	0.7%	13%	5%
Dairy Sequence 3 - Till 3 (Begin Year 4)	0.9%	0.0%	0.0%	0.3%
Cash Grain Sequence - Till 1 (Begin Year 1)	5%	8%	8%	7%
Cash Grain Sequence - Till 2 (Begin Year 1)	0.1%	0.1%	0.4%	0.2%
Cash Grain Sequence - Till 3 (Begin Year 1)	0.6%	1%	0.2%	0.7%
Cash Grain Sequence - Till 4 (Begin Year 1)	0.4%	0.0%	0.0%	0.1%
Cash Grain Sequence - Till 1 (Begin Year 4)	5%	8%	8%	7%
Cash Grain Sequence - Till 2 (Begin Year 4)	0.1%	0.1%	0.4%	0.2%
Cash Grain Sequence - Till 3 (Begin Year 4)	0.6%	1%	0.2%	0.7%
Cash Grain Sequence - Till 4 (Begin Year 4)	0.4%	0.0%	0.0%	0.1%
Continuous Corn - Till 1	1%	0.1%	0.2%	0.5%
Continuous Corn - Till 3	0.1%	0.6%	0.1%	0.3%
Hay	19%	15%	11%	15%
Developed, High Intensity	0.5%	0.7%	1%	0.8%
Developed, High Intensity (MS4)	0.2%	1%	2%	1%
Developed, Low Intensity	3%	3%	3%	3%
Developed, Low Intensity (MS4)	0.2%	1%	2%	0.9%
Grassland	0.0%	1%	6%	2%
Forest	7%	3%	11%	7%
Wetland	15%	19%	12%	16%

2.4 WEATHER

2.4.1 Daymet Weather Data

The Daily Surface Weather and Climatological Summaries (Daymet) dataset was used as the data source for daily precipitation, minimum and maximum temperature, solar radiation, and relative humidity in the NEL SWAT model (https://daymet.ornl.gov/overview). 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 for the years 1998 through 2019. 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. Relative humidity was derived using the method applied for the Wisconsin River SWAT model (WDNR 2016). This estimates saturated vapor pressure using the Antoine equation:

$$\log_{10} p = A - \frac{B}{C + T}$$

where p is saturated vapor pressure, T is average daily temperature from Daymet in degrees Celsius, and *A*, *B*, and *C* are constants associated with water: 8.1, 1731, and 233 respectively. Relative humidity is then calculated as Daymet vapor pressure divided by estimated saturated vapor pressure.

2.4.2 Potential Evapotranspiration

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 (WDNR 2016).

When the Penman-Monteith method is selected to calculate potential evapotranspiration, SWAT requires wind speed data. Wind speed was simulated using wind data from the built-in ArcSWAT weather generator “WGEN_US_FirstOrder”, which is a database of 1,041 first-order U.S climate stations.

2.5 POINT SOURCES

2.5.1 Individual Wastewater Permits

WDNR identified 47 facilities in the NEL study area that were individually permitted to discharge wastewater to surface water through WPDES individual permits that were current during 2008 through 2019, the model simulation period (Table 4).

Discharge volumes, sediment loads, and phosphorus loads were estimated for each facility using monthly and annual discharge monitoring record summaries acquired from WDNR for the period 2008 through 2019. Any missing records for flow volume, total phosphorus (TP), or total suspended solids (TSS) during the model simulation period were populated with:

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

Point source discharge volumes and loads were input to SWAT as monthly values and were assigned to subbasins based on outfall latitude and longitude coordinates. 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 the NEL SWAT model were assumed to take the form of soluble phosphorus. The NEL SWAT model is calibrated to TP rather than individual forms of phosphorus and past SWAT modeling efforts in Wisconsin have shown that the designation of point source loads as soluble phosphorus versus organic phosphorus has a negligible influence on model results since phosphorus is assumed to be conserved in stream channels (i.e., no net gain or loss of TP in the stream network) (Cadmus Group 2018).

Table 4. WPDES individually permitted point source dischargers within the NEL study area that had effluent data incorporated into the SWAT model. Does not include direct discharges to Lake Michigan.

Facility Name	**Permit Number**	**Outfall Number**	**SWAT Sub-Model**	**SWAT Subbasin**
Agropur Inc. Luxemburg	0050237	9	Kewaunee	91
Algoma Wastewater Treatment Facility	0020745	1		44
Belgioioso Cheese Inc. Denmark	0051128	7		63
Casco Wastewater Treatment Facility	0023566	1		96
Denmark Wastewater Treatment Facility	0021741	1		9
Forestville Wastewater Treatment Facility	0028894	1		52
Kewaunee Wastewater Treatment Facility	0020176	1		31
Kossuth Sanitary District No. 2 WWTF	0035874	1		88
Maribel Wastewater Treatment Facility	0061051	2		65
Packerland Whey Products Inc.	0070581	3		98
Packerland Whey Products Inc.	0070581	4		98
Briess Malt & Ingredients Co.	0066257	1	Manitowoc	10
Brillion Wastewater Treatment Facility	0020443	1		51
Chilton Wastewater Treatment Facility	0022799	1		20
Clarks Mills Sanitary District	0036030	1		14
Foremost Farms USA Chilton	0027618	1		48
Hilbert Wastewater Treatment Facility	0021270	1		28
Holy Family Convent Wastewater Treatment Facility	0028142	1		8
Kohler Company Power Systems Americas	0000795	1		79
Lakeside Foods Inc. – Manitowoc Plant	0041475	3		10
Morrison Sanitary District No. 1	0036773	1		47

Facility Name	Permit Number	Outfall Number	SWAT Sub-Model	SWAT Subbasin
New Holstein Wastewater Treatment Facility	0020893	1		88
Newton Meats And Sausage	0042650	1		4
Potter Wastewater Treatment Facility	0029025	1		26
Reedsville Wastewater Treatment Facility	0021342	2		25
Rockland SD1 Wastewater Treatment Facility	0022802	1		25
St Nazianz Wastewater Treatment Facility	0022195	1		23
Valders Wastewater Treatment Facility	0021831	1		15
Whitelaw Wastewater Treatment Facility	0022047	1		66
Baker Cheese Factory Inc.	0050521	3	Sheboygan	98
Belgium Wastewater Treatment Facility	0023353	1		17
Bemis Manufacturing Company Plant D	0027456	1		30
Cedar Grove Wastewater Treatment Facility	0020711	1		9
Cedar Valley Cheese Inc.	0051535	11		20
Gibbsville Sanitary District	0031577	1		22
Howards Grove Wastewater Treatment Facility	0021679	1		41
Johnsonville LLC	0001759	2		44
Johnsonville LLC	0001759	3		44
Kiel Wastewater Treatment Facility	0020141	1		46
Lakeland University	0029335	4		44
Lakeside Foods, Inc. - Belgium Plant	0000817	4		2
Mount Calvary Wastewater Treatment Facility	0035963	1		101
Onion River Wastewater Commission	0036811	1		105
Oostburg Wastewater Treatment Plant	0022233	1		19
Plymouth City Utility Commission WWTF	0030031	1		34
Sartori Company-West Main Building	0041904	1		34
St Cloud Village Utility Commission	0026867	1		48
Waldo Wastewater Utility	0022471	1		95

Facility Name	Permit Number	Outfall Number	SWAT Sub-Model	SWAT Subbasin
Wisconsin Power And Light Edgewater Gen. Station	0001589	14		10

2.5.2 Permitted Municipal Separate Storm Sewer Systems (Permitted MS4s)

The SWAT model was used to calculate phosphorus and sediment loading from urban sources regulated by a WPDES MS4 permit. As part of SWAT model setup, maps of municipal boundaries for cities, villages, and towns with MS4 permits and US Census urbanized areas were overlain with land cover data to define SWAT HRUs with regulated MS4 urban land cover. These HRUs represented areas where runoff and pollutant loading from urban and developed land cover was regulated by a MS4 permit. *Table 5* lists the regulated urban area of permitted MS4s within the NEL study area.

Table 5. Municipalities with Wisconsin Pollutant Discharge Elimination (WPDES) MS4 permits. The regulated area of each municipality was used to define permitted MS4 land cover in the NEL SWAT model.

Municipality	Type	Regulated Area
Taycheedah	Town	Urbanized Area within Municipal Boundary
Sheboygan	Town	Urbanized Area within Municipal Boundary
Wilson	Town	Urbanized Area within Municipal Boundary
Port Washington	City	Entire Municipal Boundary
Howards Grove	Village	Entire Municipal Boundary
Kohler	Village	Entire Municipal Boundary
Sheboygan	City	Entire Municipal Boundary
Sheboygan Falls	City	Entire Municipal Boundary
Manitowoc	City	Entire Municipal Boundary
Two Rivers	City	Entire Municipal Boundary

2.5.3 General Permits

WDNR authorizes certain stormwater and wastewater discharges under a set of general WPDES permits. Unlike individual WPDES permits, the general permits are not written to reflect site-specific conditions of a single discharger but rather are issued to cover multiple dischargers with similar operations and types of discharges. These general permits vary in requirements for chemical monitoring, inspection frequency, and plan development. Examples of discharges that can be covered by WPDES general permits include:

- Stormwater discharge from construction sites;
- Stormwater discharge from industrial sites;
- Discharge of non-contact cooling water from industrial facilities;
- Discharge of construction site pit and trench dewatering wastewater to surface waters or seepage systems;
- Discharge from facilities that wash equipment, vehicles and other objects outside.

Note that individual WPDES permits can be issued for the above examples if they are determined to be a significant source of pollution. A complete list of wastewater general permit categories can be found on the WDNR wastewater website (https://dnr.wi.gov/topic/wastewater/generalpermits.html).

Phosphorus and TSS loads for stormwater general permittees located within an MS4 boundary are implicitly included in the MS4 load. Baseline phosphorus loads for all other stormwater and wastewater general permittees are included in the nonpoint load analysis; however, for the TMDL allocation process, a percentage of the baseline non-regulated urban loads in the subbasin estimated from the SWAT model will be used to explicitly account for general permits located outside of permitted MS4s . The percentage will be based on the number and typical types of facilities present within the watersheds and best professional judgment of the TMDL development team.

Confined Animal Feeding Operations (CAFOs):

A Concentrated Animal Feeding Operation (CAFO) is an agricultural operation that raises 1,000 or more animal units in confined areas. Wastewater that is generated by CAFOs is high in suspended solids and phosphorus from animal sewage and other animal production operations. Because of the potential water quality impacts from CAFOs, animal feeding operations with 1,000 animal units or more are required to have a WPDES CAFO permit. These permits are designed to ensure that operations use proper planning, construction, and manure management to protect water quality from adverse impacts.

WPDES permits for CAFO facilities cover the production area, ancillary storage areas, storage areas and land application areas. Any runoff from CAFO land application activities is considered a nonpoint source and is included implicitly as nonpoint source agricultural loads derived through the SWAT model.

There are 70 CAFOs, summarized in Table 6, whose production areas are located within the NEL study area. An additional 18 CAFOs have productions areas located outside of the NEL study area but have land application fields located inside the NEL study area. Approximately 233,000 acres of land located within the NEL study area are used for land spreading by these 88 CAFOs.

Table 6. List of permitted CAFOs with production areas located in the NEL study area.

Facility Name	**County**	**Permit Number**	**Sub-Model**
Augstian Farms	Kewaunee	0063274	Kewaunee
Cedar Springs Dairy	Manitowoc	0066087	
Da Ran Dairy	Kewaunee	0059579	
Dairy Dreams	Kewaunee	0062057	
Dairyland Farm	Brown	0059552	
Deer Run Dairy	Kewaunee	0063789	
Ebert Dairy Enterprises	Kewaunee	0062235	
El Na Farms	Kewaunee	0063061	
Halls Calf Ranch	Kewaunee	0065013	
Heims Hillcrest Dairy	Kewaunee	0064131	
Kane Family Farm	Brown	0065196	
Kinnard Farms	Kewaunee	0059536	
Legend Farms Dairy	Kewaunee	0066265	
Pagels Ponderosa Dairy	Kewaunee	0059374	
Rolling Hills Dairy Farm	Kewaunee	0062707	

Facility Name	County	Permit Number	Sub-Model
Rustic Wagon Wheel Dairy	Manitowoc	0066354	
S&S Jerseyland Dairy	Door	0062863	
Sandway Farms	Kewaunee	0066346	
Seidls Mountain View Dairy	Kewaunee	0063665	
Stahl Bros	Kewaunee	0061999	
Strutz Farm	Manitowoc	0064017	
The Cattle Corner	Brown	0064157	
United Vision Dairy	Manitowoc	0064319	
Wakker Dairy Farm	Kewaunee	0063673	
Badger Pride Dairy	Manitowoc	0064190	Manitowoc
Blue Royal Farms	Manitowoc	0064637	
Blue Royal Valley Dairy	Manitowoc	0064203	
Calf Source	Brown	0061697	
Clarks Mills Dairy	Manitowoc	0065137	
Collins Dairy	Brown	0065145	
Dallmann East River Dairy	Calumet	0063681	
DenMar Acres	Brown	0065650	
Fitz Pine Dairy Farm	Manitowoc	0065226	
Grotegut Dairy Farm	Manitowoc	0056847	
Hoslum Irish and Holsum Elm	Calumet	0061620	
J & J Pickart Dairy	Fond Du Lac	0066591	
Johnson Hill Farm	Manitowoc	0065111	
Kocourek Bros Partnership	Manitowoc	0065871	
Kostechka Dairy	Manitowoc	0063894	
Lisowe Acres	Fond Du Lac	0064840	
Maple Leaf Dairy	Manitowoc	0058602	
Mueller Dairy Farm	Brown	0062162	
Orthland Dairy Farm	Manitowoc	0065731	
Otto Farms	Manitowoc	0066516	
Rivers Edge Dairy	Calumet	0065960	
Schneider Farms	Calumet	0065978	
Shilo Dairy	Calumet	0062693	
Soaring Eagle Dairy	Manitowoc	0063096	
Sunny Slope Dairy	Manitowoc	0066206	
Twin Cities Vue Dairy	Manitowoc	0066338	
Wayside Dairy	Brown	0061948	
Wenzel Hilltop Dairy	Calumet	0063274	
Wolfgang Dairy	Manitowoc	0061808	
Zirbel Dairy Farms	Brown	0064360	
3D Dairy	Fond Du Lac	0063274	Sheboygan
Anatevka Dairy	Sheboygan	0066125	
Drake Dairy	Sheboygan	0063827	
Goeser Dairy	Sheboygan	0064645	
Hanke Farms	Sheboygan	0063169	
Highland Crossing Dairy	Sheboygan	0063151	

Facility Name	County	Permit Number	Sub-Model
J C Maurer & Sons	Sheboygan	0064726	
Majestic Meadows Dairy	Sheboygan	0064874	
Melichar Road Acres	Ozaukee	0064866	
Mueller Range Line Dairy	Manitowoc	0066095	
Paulus Dairy Main Farm	Ozaukee	0065927	
Quonset Farms	Sheboygan	0063568	
Redtail Ride Dairy	Fond Du Lac	0062979	
Robinway Dairy	Manitowoc	0066231	
Rockland Dairy	Sheboygan	0061786	
Siemers Holstein Farm	Manitowoc	0058572	

2.6 SOIL PHOSPHORUS

SWAT allows users to define estimates of initial soil phosphorus concentrations throughout the modeled area. These initial soil phosphorus concentrations serve as a starting point for simulating soil phosphorus dynamics. Soil phosphorus concentrations are updated in SWAT throughout the simulation period using algorithms that reflect phosphorus inputs, outputs, and transformations.

To inform SWAT soil phosphorus settings, WDNR reviewed Nutrient Management Plans from 69 CAFOs within the NEL study area. Nutrient Management Plans report the soil phosphorus concentration for each field in the plan, which are based on samples collected from the field. Results of the review were interpolated to create a continuous map layer of soil phosphorus in the NEL study area and estimate the average soil phosphorus concentration within agricultural areas of each SWAT subbasin. Further details of the method for estimating soil phosphorus concentrations is provided in the Agricultural survey summary.

The soil phosphorus concentrations reported in Nutrient Management Plans are generally derived from the Bray-1 testing method and were divided by two for input as initial soil soluble phosphorus concentrations in SWAT, based on recommendations in Vadas and White (2010). The initial soil soluble phosphorus values for agricultural HRUs in each SWAT sub-model are summarized in Table 7. Non-agricultural HRUs were not assigned an initial soil phosphorus concentration; the soil phosphorus concentrations that built up during the model warm-up period were used to provide an estimate for non-agricultural HRUs.

Table 7. Initial soil phosphorus summary statistics for agricultural HRUs, by SWAT sub-model. The reported values are soluble phosphorus concentrations used in the SWAT model.

SWAT Sub-Model	Agricultural Soil Phosphorus (parts per million)			
	Minimum	Maximum	Mean	Standard Deviation
Kewaunee River	8.3	334.6	15.9	4.6
Manitowoc River	8.9	36.2	18.9	5.4
Sheboygan River	5.3	43.5	18.8	6.2

2.7 MANURE APPLICATION

HRUs for dairy land cover classes in the SWAT model receive animal manure applications once in the spring and once in the fall. Each manure application was followed by a tillage operation to simulate the incorporation of manure into the soil profile.

Manure application rates (mass per unit area) were derived from counts of cattle within the NEL study area, an estimated manure production rate per animal, and the total area of dairy classes in each subbasin. Cattle counts were estimated from the 2017 Cattle Census from the National Agricultural Statistics Service as well as cattle head counts in 2018 annual reports prepared by CAFOs within the study area and submitted to WDNR. The calculated manure application rates were validated against rates reported in CAFO Nutrient Management Plans and through review by County LWCDs. Further details of the method for estimating manure application rates is provided in the Manure spreading analysis report.

2.8 BASEFLOW ALPHA FACTOR

The baseflow alpha factor (ALPHA_BF parameter in SWAT) is a relative measure of groundwater discharge in response to groundwater recharge. An average baseflow alpha factor value of 0.0442 was estimated for the NEL study area using long-term daily streamflow records acquired from the USGS National Water Information System for four streams located in the NEL study area and BFLOW baseflow separation software acquired from the SWAT website (http://swat.tamu.edu/software/baseflow-filter-program).

The four monitoring sites were selected because they all had a period of record of approximately 30 years and did not appear to be significantly influenced by regulation from lakes, reservoirs, or point source discharges. Baseflow alpha factor values for the Manitowoc and Kewaunee sub-models were 0.0475 and 0.0470, respectively (Table 8). The value for the Sheboygan sub-model (0.0412) was calculated as the average of the two Sheboygan sub-model sites listed in Table 8.

Table 8. Baseflow alpha factor values for four USGS monitoring sites with continuous streamflow in the NEL study area. Calculated using the BFLOW baseflow separation program (Arnold et. al 1999).

USGS ID	Name	SWAT Sub-model	Start Year	End Year	Alpha Factor
04086000	Sheboygan River at Sheboygan, WI	Sheboygan River	1989	2019	0.0449
040857005	Otter Creek at Willow Road Near Plymouth, WI	Sheboygan River	1990	2018	0.0374
04085427	Manitowoc River at Manitowoc, WI	Manitowoc River	1989	2019	0.0475
04085200	Kewaunee River near Kewaunee, WI	Kewaunee River	1989	2019	0.0470
		Average			0.0442

2.9 INTERNALLY DRAINED AREAS

Internally drained areas occur where runoff flows to a depression on the landscape that has no surface connection to the stream channel network during or after any storm events. Internally drained areas in the NEL were mapped using the WDNR 1:24,000 scale hydrography geodatabase. The WDNR hydrography geodatabase depicts the location of surface water features in Wisconsin and their local drainage areas (i.e., the land area directly draining to a surface water feature). The geodatabase stores descriptive attributes of local drainage areas, including whether they are connected to the surface water network or isolated.

An overlay of isolated areas in the WDNR hydrography geodatabase and SWAT subbasins was created and the total internally drained area per subbasin was calculated. Estimated percentages of internally drained areas ranged from 0% to 34% of the subbasin. SWAT pond files (.PND) were then setup for each subbasin to simulate internal drainage. Pond area and volume parameters were set to very large values so that the pond never overflowed and instead stored water away from the stream network for evaporation or groundwater recharge. Within each pond file, the portion of the subbasin draining to the pond (SWAT parameter PND_FR) was calculated as the internally drained area divided by subbasin area. SWAT model outputs were reviewed to confirm that water entering the internally drained areas (ponds with infinite storage capacity) did not overflow into the stream network.

2.9 MANNINGS N

Manning's roughness coefficient (Manning's *n)* for overland flow was set to ArcSWAT default values for each land cover type. Manning's n for main channels and tributary channels were also set to ArcSWAT default values and reviewed as part of model calibration.

2.10 SUBBASIN SLOPE LENGTH

Average slope length (SWAT parameter SLSUBBSN) is the average distance within a subbasin that sheet flow is the dominant surface runoff flow process. Slope length is automatically in ArcSWAT 2012 but was manually adjusted for subbasins with values exceeding the SWAT manual guideline of 90 meters (Arnold et al. 2012). In this case, a correction was applied based on the equation reported by Baumguart (2005):

$$SLSUBBSN_{ADJ} = 91.4/((HRU\_SLP * 100) + 1)^{0.4}$$

where $SLSUBBSN_{ADJ}$ is the corrected slop length and HRU_SLP is the average slope steepness in the HRU calculated by ArcSWAT.

2.11 SIMULATION PERIOD

The NEL SWAT model was run from January 1, 1998 to December 31, 2019. The first ten years act as a "warm-up" period (January 1, 1998-December 31, 2007), to allow initial conditions to equilibrate within the simulation (e.g., overall water balance, soil phosphorus concentrations, etc.). Model output from the warm-up period was not be evaluated as part of calibration and validation.

2.12 MODEL SETUP DATASET SUMMARY

Table 9 summarizes the name and source of each of the datasets used for SWAT model setup.

Table 9. Summary of datasets used to develop the NEL SWAT model.

Dataset Name	Source	Online Link/Data Source Description	SWAT Model Application
WDNR 1:24,000 Scale Hydrography Geodatabase	WDNR	https://data-wi-dnr.opendata.arcgis.com/datasets/24k-hydro-flowlines-rivers-streams	Model Subbasin Definition Model Hydrography Definition
2020 303(d) Impaired Surface Waters Dataset	WDNR	https://dnr.wisconsin.gov/topic/SurfaceWater/ConditionLists.html	Model Subbasin Definition

1/3 Arc Second National Elevation Dataset (NED)	USGS	https://www.sciencebase.gov/catalog/item/4f70aa9fe4b058caae3f8de5	Slope (HRU Definition)
Wiscland 2	WDNR	https://data-wi-dnr.opendata.arcgis.com/datasets/d7f5d33b182044c187c776e47d72ce84	Land Use (HRU Definition)
WDNR NEL Agricultural Practice Survey Results	WDNR	https://dnr.wisconsin.gov/sites/default/files/topic/TMDLs/NEL_ag_survey_summary.pdf	Land Use (HRU Definition) HRU Management Parameters – Plant/Harvest/Tillage/Fertilization
SSURGO	USDA NRCS	https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627	Soils (HRU Definition)
STATSGO	USDA NRCS	https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053629	Soils (HRU Definition)
Gridded Soil Phosphorus Values from WDNR	WDNR	https://dnr.wisconsin.gov/sites/default/files/topic/TMDLs/Manure_analysis.pdf	Initial Soil Phosphorus Concentration for Agricultural HRUs
2010 Urban Areas Layer	WDNR	https://www.census.gov/cgi-bin/geo/shapefiles/index.php	Land Use (HRU Definition)
2018 US Census County Subdivisions Layer	US Census Bureau	https://www2.census.gov/geo/tiger/TIGER2010/COUSUB/2010/	Land Use (HRU Definition)
WDNR Point Source Dataset for watershed model development	WDNR	Locations: https://dnr.wisconsin.gov/sites/default/files/topic/TMDLs/1_NEL_subbasins_impairments_ptsource.pdf	Locations of Individually permitted surface water outfalls. Effluent monitoring data (Flow, TSS, TP)
Dayment Daily Rainfall, Minimum/Maximum Air Temperature, Solar Radiation, and Water Vapor Pressure	NASA	https://daymet.ornl.gov/single-pixel/	Weather Inputs
WDNR 1:24,000 Scale Hydrography Value Added Geodatabase	WDNR	https://data-wi-dnr.opendata.arcgis.com/datasets/e4694d59b47a4ea88d85c77914727a27	Model Subbasin Definition Internal Drainage Definition

3 Model Calibration and Validation Approach

Model calibration is the process of iteratively adjusting model parameter estimates to improve the fit between model output and real-world observations. Following calibration, model validation is performed by running the model with the calibrated parameter set and comparing outputs to additional observed data (i.e., observed data not used for calibration). Based on the level of agreement between output and these additional observations, the model is either validated for further use or model inputs and parameters are revisited for further calibration.

For the NEL SWAT model, calibration consisted of adjusting parameters related to plant growth, streamflow, total phosphorus loads, and sediment loads. Two general methods of calibration were applied. Manual calibration involved manually adjusting parameter values, running the model, reviewing model results, and repeating these steps until the model outputs of interest sufficiently matched observed data or expected results. Automated calibration was also completed using SWAT-Calibration and Uncertainty Program (SWAT-CUP; Version 2012) software. SWAT-CUP software provides users with the ability to select specific model parameters for auto-calibration within defined boundaries and executes hundreds of SWAT runs to find the optimal set of parameter values that minimize the error between model outputs and observed data (Abbaspour, 2014).

Approximately 75% of subbasins in the NEL SWAT model drain to monitoring sites with observed data for streamflow, sediment, or total phosphorus. Appropriate model parameter adjustments were determined by calibrating to observed data at monitoring sites. For most parameters, adjustments were universally applied to all NEL subbasins. For other parameters, separate adjustments were applied to different groups of subbasins, based on shared subbasin attributes like hydrologic soil group and extent of wetland cover.

The Nash-Sutcliffe Efficiency coefficient (NSE), the coefficient of determination (R^2), and percent bias (PBIAS) were used to evaluate calibration and validation performance of the NEL SWAT model. Thresholds for evaluation of model performance followed guidelines outlined in Moriasi et al. (2007):

- “Very Good” performance
    - Streamflow: NSE ≥ 0.75 and PBIAS ≤ ±10%
    - Sediment: NSE ≥ 0.75 and PBIAS ≤ ±15%
    - Total Phosphorus: NSE ≥ 0.75 and PBIAS ≤ ±25%
- “Good” performance
    - Streamflow: NSE ≥ 0.65 and PBIAS ≤ ±15%
    - Sediment: NSE ≥ 0.65 and PBIAS ≤ ±30%
    - Total Phosphorus: NSE ≥ 0.65 and PBIAS ≤ ±40%
- “Satisfactory” performance
    - Streamflow: NSE ≥ 0.5 and PBIAS ≤ ±25%
    - Sediment: NSE ≥ 0.5 and PBIAS ≤ ±55%
    - Total Phosphorus: NSE ≥ 0.5 and PBIAS ≤ ±70%

4 Calibration and Validation Data

Data used for calibration and validation of the NEL SWAT model included monthly observations of streamflow and stream water quality reported by the USGS and by WDNR (WDNR, in preparation) and county crop yields reported by the USDA. This section describes the datasets used for model calibration and validation.

4.1 Streamflow Data

There are five USGS monitoring sites with monthly streamflow records during the 2008-2019 model simulation period in the NEL model area (Table 10). WDNR collected streamflow data at nineteen additional sites throughout the NEL study area to complement the USGS data and provide a larger diversity of calibration sites (Table 10). The WDNR streamflow data were collected from May 2016 through December 2019. Within that period, the duration of data collection varied by site, from nine months to thirty-five months. Daily streamflow data are incomplete for some months within the sampling period. Incomplete daily streamflow records for a given month were a result of starting or ending sampling mid-month, equipment error, or ice in the stream channel. Only months with daily streamflow records that were at least seventy-five percent complete were used for calibration and validation.

Two WDNR monitoring sites were removed during the streamflow calibration process (Killsnake River at County Road Y, site ID 10042875; Mud Creek at Hilltop Road, site ID 10016717). The Killsnake River at County Road Y (site ID 10042875) site was removed due to a poor stage-discharge rating curve. Figure 3 shows the Killsnake River site during normal flow conditions, while Figure 4 shows the Killsnake River under high flow conditions. These images demonstrate that streamflow becomes largely unchannelized under high water conditions, spilling over the bank into nearby low-lying areas. These are difficult conditions for accurately measuring streamflow because the main channel is indistinguishable. Unchannelized conditions also compromise the accuracy of the stage-discharge relationship used to generate daily streamflow values, as the river stage (depth) shows very little change relative to flow magnitude.

The Mud Creek at Hilltop Road (site ID 10016717) site was removed because there was not a model subbasin outlet at the monitoring site location. A subbasin outlet point is needed to generate model outputs for comparison to monitoring data. The subbasin that originally corresponded to this monitoring location was removed in the early phase of model development because it was located on a stream designated as Limited Aquatic Life (LAL) per s. NR 104.02(3)(b), Wis. Adm. Code. Accounting for the LAL stream reach resulted in the Mud Creek monitoring site being located significantly upstream (about 3.5 miles) of the resulting SWAT subbasin outlet point, creating a large difference between the contributing drainage areas.

Figure 3. The Killsnake River during normal flow conditions.

Figure 4. Killsnake River during high water conditions.

Monthly streamflow records were separated into a calibration dataset and a validation dataset (Table 11). Due to the relatively short record of WDNR monitoring sites, and the importance of streamflow calibration for water quality modeling, all WDNR sites were used for streamflow calibration. The period of record for the five remaining USGS sites was divided evenly in half into calibration and validation periods. Because the WDNR sites offer a robust calibration dataset for the latter part of the modeling period (2016-2019), the calibration period selected the 3 of the 5 USGS sites covered earlier years (2009-2015).

4.2 Water Quality Data

All five USGS monitoring sites in the NEL study area have total phosphorus grab sample concentrations reported within the 2008-2019 simulation period in the USGS National Water Information System. Four of the USGS monitoring sites also have sediment grab sample concentrations reported within the 2008-2019 simulation period.

All WDNR monitoring sites used for streamflow calibration also had accompanying grab sample data for both total phosphorus and sediment concentrations. The period of record and frequency of these samples varies by site. Because observed monthly loads were calculated using the observed streamflow record, only months with daily streamflow records that were at least seventy-five percent complete were used for calibration and validation.

WDNR estimated daily and monthly sediment and total phosphorus loads at USGS and WDNR monitoring sites using the sampled concentrations and daily streamflow records, as outlined in the Streamflow and Load Estimation Methods for Development of the NE Lakeshore TMDL (WDNR, in preparation). The loads estimates were used for model calibration and validation across all sites except for total phosphorus loads at the Fisher Creek site (ID = 040854592) and the Otter Creek site (ID = 040857005). Total phosphorus loads calculated by USGS were used for these two sites instead of WDNR load estimates. Additionally, the Killsnake River at County Road Y site (ID = 10042875) and the Mud Creek at Hilltop Road site (ID = 10016717) were removed from the water quality calibration dataset for the reasons described in Section 4.1.

Water quality records were separated into a calibration dataset and a validation dataset (Table 11). Three USGS sites had water quality data available for the entire model simulation period (Kewaunee River Near Kewaunee, WI; Manitowoc River at Manitowoc, WI; Sheboygan River at Sheboygan, WI). The period of record for these three sites was divided evenly in half into calibration and validation periods. For these three sites, the same calibration and validation time periods selected for streamflow were also applied for water quality calibration and validation. The two remaining USGS sites (Fisher Creek and Otter Creek) were only used for calibration due to their shorter period of record. Among the WDNR sites, 25% were randomly selected for validation and the remaining sites were used for calibration.

4.3 Crop Yield Data

Crop yield data from the USDA National Agricultural Statistics Survey QuickStats 2.0 database were acquired to guide calibration of plant growth parameters. The QuickStats database contains estimates of county-wide crop yields derived from USDA agricultural surveys. Estimates of county-wide crop yields for corn grain, corn silage, soybean, and alfalfa were exported for each county in the NEL study area during the 2008 to 2019 model period. Yields for each crop were then averaged across all NEL counties to create an estimate of the typical observed annual yield for each crop.

Table 10. Monitoring sites with monthly streamflow, sediment load, and total phosphorus (TP) load records during the 2008-2019 model simulation period.

Site ID	Source	Site Name	Sub-Model	Streamflow Record	Sediment Load Record	TP Load Record
04085200	USGS	Kewaunee River Near Kewaunee, WI	Kewaunee	1/2008-12/2019	1/2008-12/2019	1/2008-12/2019
04085427	USGS	Manitowoc River at Manitowoc, WI	Manitowoc	1/2008-12/2019	1/2008-12/2019	1/2008-12/2019
04086000	USGS	Sheboygan River at Sheboygan, WI	Sheboygan	1/2008-12/2019	1/2008-12/2019	1/2008-12/2019
040854592	USGS	Fisher Creek at Howards Grove, WI	Sheboygan	6/2011-9/2015; 8/2016-9/2018	-	6/2011-9/2015; 8/2016-9/2018
040857005	USGS	Otter Creek at Willow Road Near Plymouth, WI	Sheboygan	6/2011-9/2018	6/2011-9/2018	6/2011-9/2018
153027	WDNR	Ahnapee River at CTH J	Kewaunee	5/2016-4/2019	5/2016-4/2019	5/2016-4/2019
363313	WDNR	Branch River at Branch River Rd.	Manitowoc	6/2017-11/2019	6/2017-11/2019	6/2017-11/2019
10008207	WDNR	East Twin River at Steiners Corners Rd.	Kewaunee	6/2017-11/2019	6/2017-11/2019	6/2017-11/2019
10029954	WDNR	Kewaunee River at Hillside Rd.	Kewaunee	11/2017-11/2018	11/2017-11/2018	11/2017-11/2018
10042875	WDNR	Killsnake River at County Rd. Y	Manitowoc	7/2017-11/2019	7/2017-11/2019	7/2017-11/2019
10020782	WDNR	Manitowoc River at Leist	Manitowoc	7/2017-11/2019	-	-
363375	WDNR	Manitowoc River South Branch at Lemke Rd.	Manitowoc	6/2017-6/2019	6/2017-6/2019	6/2017-6/2019
10016717	WDNR	Mud Creek - Hilltop Rd.	Manitowoc	6/2017-11/2019	6/2017-11/2019	6/2017-11/2019
10049358	WDNR	Mullet River at Sumac Rd.	Sheboygan	11/2017-11/2019	11/2017-11/2019	11/2017-11/2019
603304	WDNR	Onion River at Ourtown Rd. 5m Bi	Sheboygan	5/2018-11/2019	5/2018-11/2019	5/2018-11/2019
603295	WDNR	Pigeon River at Cth A -And River Rd.	Sheboygan	11/2017-11/2019	11/2017-11/2019	11/2017-11/2019
603051	WDNR	Pigeon River at Mill Rd.	Sheboygan	11/2017-9/2018	11/2017-9/2018	11/2017-9/2018
363368	WDNR	Point Creek at Centerville Rd.	Manitowoc	4/2018-11/2019	4/2018-11/2019	4/2018-11/2019
463070	WDNR	Sauk Creek at Mink Ranch Rd. (Bi)	Sheboygan	11/2017-11/2019	11/2017-11/2019	11/2017-11/2019
10016139	WDNR	Sheboygan R. - Hwy 57 Crossing	Sheboygan	11/2017-12/2019	11/2017-12/2019	11/2017-12/2019
10039440	WDNR	Sheboygan River at Palm Tree Rd.	Sheboygan	3/2019-12/2019	3/2019-12/2019	3/2019-12/2019
10020779	WDNR	Silver Creek (Algoma) at Willow Drive	Kewaunee	5/2016-10/2019	5/2016-10/2019	5/2016-10/2019
363228	WDNR	Silver Creek (Manitowoc) at Cth Ls	Manitowoc	6/2017-11/2019	6/2017-11/2019	6/2017-11/2019
10029482	WDNR	West Twin River at CTH V	Kewaunee	6/2017-11/2019	6/2017-11/2019	6/2017-11/2019

Table 11. Calibration and validation data summary for streamflow, sediment, and total phosphorus. Values in parentheses denote the number of months in the calibration and validation periods.

Site ID	Site Name	Sub-Model	Streamflow		Sediment		TP	
			Calibration	Validation	Calibration	Validation	Calibration	Validation
10029482	West Twin River at CTH V	Kewaunee	7/2017 – 10/2019 (*20*)	-	7/2017 - 10/2019 (*19*)	-	7/2017 - 10/2019 (*19*)	-
10008207	East Twin River at Steiners Corners Rd.	Kewaunee	7/2017 – 10/2019 (*21*)	-	-	7/2017 - 10/2019 (*21*)	7/2017 - 10/2019 (*21*)	-
04085200	Kewaunee River Near Kewaunee, WI	Kewaunee	1/2008 - 12/2013 (*72*)	1/2014 - 12/2019 (*72*)	1/2008 - 11/2013 (*71*)	12/2013 - 10/2019 (*71*)	1/2008 - 11/2013 (*72*)	12/2013 - 10/2019 (*71*)
10029954	Kewaunee River at Hillside Rd.	Kewaunee	4/2018 - 10/2018 (*7*)	-	4/2018 - 10/2018 (*7*)	-	4/2018 - 10/2018 (*7*)	-
10020779	Silver Creek (Algoma) at Willow Drive	Kewaunee	6/2016 - 10/2019 (*30*)	-		6/2016 - 10/2019 (*27*)	-	6/2016 - 10/2019 (*27*)
153027	Ahnapee River at CTH J	Kewaunee	6/2016 - 12/2018 (*24*)	-	6/2016 - 12/2018 (*24*)	-	6/2016 - 12/2018 (*24*)	-
363368	Point Creek at Centerville Rd.	Manitowoc	5/2018 - 10/2019 (*10*)	-	5/2018 - 10/2019 (*10*)	-	5/2018 - 10/2019 (*10*)	-
363228	Silver Creek (Manitowoc) at Cth Ls	Manitowoc	7/2017 - 10/2019 (*22*)	-	7/2017 - 10/2019 (*21*)	-	7/2017 - 10/2019 (*21*)	-
04085427	Manitowoc River at Manitowoc, WI	Manitowoc	1/2014 - 12/2019 (*72*)	1/2008 - 12/2013 (*72*)	12/2013 - 10/2019 (*71*)	1/2008 - 11/2013 (*71*)	12/2013 - 10/2019 (*72*)	1/2008 - 11/2013 (*72*)
363313	Branch River at Branch River Rd.	Manitowoc	7/2017 - 10/2019 (*20*)	-	7/2017 - 10/2019 (*20*)	-	7/2017 - 10/2019 (*20*)	-

Site ID	Site Name	Sub-Model	Streamflow		Sediment		TP	
			Calibration	**Validation**	**Calibration**	**Validation**	**Calibration**	**Validation**
10020782	Manitowoc River at Leist	Manitowoc	8/2017 - 10/2019 (*19*)	-	-	-	-	-
363375	Manitowoc River South Branch at Lemke Rd.	Manitowoc	7/2017 - 5/2019 (*15*)	-	-	7/2017 - 5/2019 (*15*)	-	7/2017 - 5/2019 (*15*)
463070	Sauk Creek at Mink Ranch Rd. (Bi)	Sheboygan	12/2017 - 11/2019 (*19*)	-	-	4/2018 - 10/2019 (*16*)	4/2018 - 10/2019 (*16*)	-
04086000	Sheboygan River at Sheboygan, WI	Sheboygan	1/2014 - 12/2019 (*64*)	1/2008 - 12/2013 (*65*)	9/2013 - 10/2019 (*68*)	1/2008 - 8/2013 (*68*)	9/2013 - 10/2019 (*68*)	1/2008 - 8/2013 (*68*)
603304	Onion River at Ourtown Rd. 5m Bi	Sheboygan	5/2018 - 11/2019 (*16*)	-	5/2018 - 10/2019 (*15*)	-	5/2018 - 10/2019 (*15*)	-
10049358	Mullet River at Sumac Rd.	Sheboygan	4/2018 - 11/2019 (*16*)	-	4/2018 - 10/2019 (*15*)	-	4/2018 - 10/2019 (*15*)	-
603295	Pigeon River at Cth A -And River Rd.	Sheboygan	4/2018 - 11/2019 (*18*)	-	4/2018 - 10/2019 (*17*)	-	4/2018 - 10/2019 (*17*)	-
040854592	Fisher Creek at Howards Grove, WI	Sheboygan	6/2011 - 8/2014 (*39*)	9/2014 - 9/2018 (*39*)	-	-	8/2011 - 9/2015 (*50*)	-
10016139	Sheboygan R. - Hwy 57 Crossing	Sheboygan	4/2018 - 12/2019 (*18*)	-	4/2018 - 11/2019 (*17*)	-	4/2018 - 11/2019 (*17*)	-
10039440	Sheboygan River at Palm Tree Rd.	Sheboygan	4/2019 - 12/2019 (*9*)	-	4/2019 - 11/2019 (*8*)	-		4/2019 - 11/2019 (*8*)
603051	Pigeon River at Mill Rd.	Sheboygan	4/2018 - 8/2018 (*5*)	-	4/2018 - 8/2018 (*5*)	-	4/2018 - 8/2018 (*5*)	-
040857005	Otter Creek at Willow Road Near Plymouth, WI	Sheboygan	6/2011 - 1/2015 (*44*)	2/2015 - 9/2018 (*44*)	7/2011 - 9/2016 (*63*)	-	6/2011 - 9/2016 (*63*)	-

5 Calibration and Validation Results

5.1 Crop Yield/Plant Growth Calibration

Model calibration was initiated by calibrating simulated crop yields to annual yields reported by the USDA National Agricultural Statistics Survey (NASS). Modeled yields were averaged across all years and all HRUs within the NEL study area before comparing to observed yields. Because SWAT reports crop yields in units of kilograms of biomass per hectare, while USDA crop yields are reported in units of bushels per acre for corn and soybean, simulated corn and soybean yields were converted to bushels per acre using conversions listed in Murphy (1993). Additionally, since SWAT's crop yield outputs are dry weights of biomass, and corn silage yields reported by USDA tend to have a high moisture content, corn silage yield results from SWAT were multiplied by a factor of 1.65 for comparison to USDA corn silage yields (Lauer, 2006). Table 13 summarizes crop yield calibration results.

Crop yield calibration focused on adjusting the biomass-energy ratio (BIO_E) in the land cover/plant growth database file (crop.dat) for the major agricultural crops – corn grain, corn silage, soybean, and alfalfa. Soybean yields were still low after adjusting the BIO_E parameter. The maximum potential leaf area index (BLAI) was increased for soybeans to increase soybean yields.

During crop yield calibration, yields from non-agricultural HRUs (forests, wetlands, and urban) were also reviewed to verify that plant growth routines were functioning, and that plant biomass was consistently generated each year. The review of initial SWAT output demonstrated that Bermudagrass was not generating sufficient biomass in urban HRUs in the NEL study area. Bermudagrass is the default cover type for urban HRUs in SWAT, however, Bermudagrass growth parameters in SWAT are most appropriate for lower latitudes of the US. Due to this issue, the plant type for HRUs with urban/ developed land cover was changed from Bermudagrass to Kentucky bluegrass.

Table 12. Comparison of crop yields reported by the USDA National Agricultural Statistics Survey and SWAT simulated yields (all SWAT sub-models).

Crop	**Average USDA NASS Yield (2008-2018)**	**Average SWAT Yield (2008-2019)**
Alfalfa (tons/acre)	2.9	2.4
Corn Grain (bushels/acre)	148.8	151.4
Corn Silage (tons/acre)	17.8	6.7
Soybean (bushels/acre)	45.3	31.4

5.2 Streamflow Calibration and Validation

Streamflow calibration was initiated by reviewing the sensitivity of model streamflow outputs to parameter adjustments. This revealed the following surface runoff and storage parameters as having the highest influence on modeled streamflow: the soil evaporation compensation factor (ESCO), the surface runoff lag coefficient (SURLAG), and parameters controlling snowmelt (SMTMP, SFTMP, SMFMX, SMFMN, TIMP, SNOCOVMX, SNO50COV). Streamflow was also very sensitive to curve number (CN2) and soils properties.

Groundwater parameters with the highest influence on streamflow results were groundwater delay (GW_DELAY), the baseflow recession constant (ALPHA_BF), the threshold depth of water in the shallow aquifer for return flow (GWQMN), the coefficient for determining water movement from the shallow aquifer to the overlying unsaturated zone (GW_REVAP), and the threshold depth for the water movement from the shallow aquifer to the overlying saturated zone to occur (REVAPMN).

After identifying sensitive parameters, BFLOW baseflow separation software was used to separate total observed streamflow into baseflow and surface flow components for all USGS calibration sites listed in Table 10. Manual calibration was then initiated by comparing simulated and observed baseflow hydrographs to ensure that the model adequately simulated baseflow magnitude and patterns. Following manual calibration, SWAT-CUP software was used to further optimize streamflow parameters. SWAT-CUP was configured to maximize values of the NSE statistic. A final round of manual calibration was then completed based on SWAT-CUP results.

Streamflow parameters were adjusted separately for each sub-model to maximize the goodness-of-fit for calibration sites within a sub-model. During this process, it was apparent that the internally drained areas simulated with SWAT pond files (see Section 2.9) had negligible effects on streamflow. It was also determined that the absence of wetland storage was limiting model performance in subbasins with high proportions of wetland cover. SWAT pond files can be used to simulate the effects of water storage and release from a variety of hydrologic features, including wetlands, potholes, and related depressions on the landscape. The SWAT pond files were therefore adjusted to simulate the effects of wetland storage rather than internally drained areas. Internally drained areas were removed from the model and the parameters previously used to simulate those areas were updated to reflect storage and release from wetlands. Specifically, parameters for the fraction of the subbasin draining to wetlands (PND_FR) and the principal area of wetlands in the subbasin (PND_PSA) were changed to reflect the extent of wetland cover in each subbasin. Wetland volume was calculated as the principal area multiplied by a depth of 0.5 meters following the approach used in past Wisconsin SWAT models (WDNR 2016). Calibrated streamflow parameter values are listed in Table 19.

Table 13 lists streamflow calibration performance statistics by site. Model performance for streamflow calibration was good to very good for NSE (≥ 0.65) at 14 of 22 sites and for PBIAS (≤ 15%) at 19 of 22 sites. NSE for the remaining eight sites was satisfactory (≥ 0.5). One site, the Kewaunee River at Hillside Road (10029954), was below satisfactory benchmark for PBIAS (≤ ±25%). The calibration dataset was limited for this site, as it only had nine months of observed streamflow data. This site is discussed further in Section 6 of this report. Streamflow calibration hydrographs are presented in Appendix A.

Table 13. Streamflow calibrations statistics for the NEL SWAT model.

Site ID	Site Name	Sub-Model	R^2	NSE	PBIAS
153027	Ahnapee River at CTH J	Kewaunee	0.61	0.50	12.2%
10008207	East Twin River at Steiners Corners Rd.	Kewaunee	0.79	0.70	-14.2%
10020779	Silver Creek (Algoma) at Willow Drive	Kewaunee	0.70	0.55	-9.4%
10029482	West Twin River at CTH V	Kewaunee	0.70	0.70	-4.9%
10029954	Kewaunee River at Hillside Road	Kewaunee	0.69	0.60	26.5%
04085200	Kewaunee River Near Kewaunee, WI	Kewaunee	0.68	0.67	-10.7%
363228	Silver Creek (Manitowoc) at Cth Ls	Manitowoc	0.72	0.71	3.8%
363313	Branch River at Branch River Rd	Manitowoc	0.75	0.73	12.7%
363368	Point Creek at Centerville Rd.	Manitowoc	0.65	0.59	13.2%
363375	Manitowoc River South Branch at Lemke Road	Manitowoc	0.71	0.63	6.5%
10020782	Manitowoc River at Leist	Manitowoc	0.83	0.74	-9.4%
04085427	Manitowoc River at Manitowoc, WI	Manitowoc	0.81	0.77	-17.1%
463070	Sauk Creek at Mink Ranch Rd (Bi)	Sheboygan	0.90	0.83	-7.7%
603051	Pigeon River at Mill Road	Sheboygan	0.82	0.80	-4.1%
603295	Pigeon River at Cth A -And River Rd	Sheboygan	0.57	0.55	0%
603304	Onion River at Ourtown Rd 5m Bi	Sheboygan	0.88	0.85	-9.9%
10016139	Sheboygan R. - Hwy 57 Crossing	Sheboygan	0.68	0.63	3.2%
10039440	Sheboygan River at Palm Tree Rd	Sheboygan	0.77	0.52	-9.9%
10049358	Mullet River at Sumac Road	Sheboygan	0.81	0.77	8.8%
040854592	Fisher Creek at Howards Grove, WI	Sheboygan	0.86	0.81	18.6%
040857005	Otter Creek at Willow Road Near Plymouth, WI	Sheboygan	0.85	0.75	9.6%
04086000	Sheboygan River at Sheboygan, WI	Sheboygan	0.80	0.76	-13.8%

Table 14 lists streamflow validation performance statistics by site. Two of the five sites show good to very good performance based on NSE (≥ 0.65) and four of five sites show good to very good performance based on PBIAS (≤ 15%). Two sites show satisfactory performance based on NSE (≥ 0.5) and one site shows satisfactory performance for PBIAS (≤ ±25%). See Appendix A for streamflow validation hydrographs.

Table 14. Streamflow validation statistics for the NEL SWAT model.

Site ID	Site Name	Sub-Model	R^2	NSE	PBIAS
04085200	Kewaunee River Near Kewaunee, WI	Kewaunee	0.64	0.63	-0.9%
04085427	Manitowoc River at Manitowoc, WI	Manitowoc	0.82	0.76	-23.7%
040854592	Fisher Creek at Howards Grove, WI	Sheboygan	0.52	0.52	5.6%
040857005	Otter Creek at Willow Road Near Plymouth, WI	Sheboygan	0.61	0.51	6.9%
04086000	Sheboygan River at Sheboygan, WI	Sheboygan	0.83	0.83	-1%

5.3 Sediment Calibration and Validation

Sediment parameters were calibrated following streamflow calibration. Calibration of sediment loading focused on parameters controlling landscape erosion and channel routing. Like streamflow calibration, sediment calibration consisted of an initial manual calibration step to match simulated and observed sediment loads followed by automated calibration with SWAT-CUP software to fine-tune parameter estimates, and further manual calibration based on SWAT-CUP results.

NSE is best suited for evaluating model performance for sites with larger sample sizes, as it is sensitive to outliers, timing of events, and differences in magnitude (McCuen et al. 2006). Due to these factors, NSE was not used to evaluate model performance for sediment at calibration and validation sites with short periods of record (less than 3 years). Monitoring sites with short periods of record include all WDNR monitoring sites. These were optimized for PBIAS only to achieve sediment load estimates that acceptably matched long-term average loads. The USGS monitoring sites, however, were calibrated using both NSE and PBIAS as performance criteria, due to their longer periods of record.

SWAT parameters for the Modified Universal Soil Loss Equation (MUSLE) are the primary determinants of landscape erosion, while tributary and main channel parameters affect sediment deposition and resuspension within stream channels. Sediment loads using initial sediment parameter values were very high (at least one order of magnitude greater than average observed loads at calibration sites). This was attributed to both over-estimated rates of landscape erosion from the MUSLE equation and under-estimated deposition of sediment between edge-of-field sources and subbasin outlets. Two approaches were used to address these issues and reduce simulated sediment loads within the model: (1) use the conservation practice (P) factor parameter to reduce erosion rates simulated by the MUSLE equation; and (2) simulate a vegetated filter strip to increase deposition of eroded sediment before it reached the subbasin outlet.

Values of the conservation practice factor (USLE_P) and vegetated filter strip width (FILTERW) were adjusted for each HRU in the model, with values assigned according to the HRU's land cover type and sub-model. For example, all HRUs with Dairy land cover in the Kewaunee sub-model were assigned the same value of USLE_P and FILTERW. These parameter values were first adjusted for agreement between simulated and observed sediment loads at sites located in headwaters and upper watersheds, which were assumed to better reflect landscape erosion than larger, downstream segments where greater channel deposition of sediment occurs.

After HRU sediment loads were optimized using the MUSLE equation parameters, channel routing parameters were adjusted to optimize the agreement between modeled and observed sediment loads across all sites. Parameters that affect tributary and main channel sediment routing include the linear parameter (SPCON) and the exponential parameter (SPEXP) in the equation used by SWAT to calculate sediment deposition and resuspension, the peak rate adjustment factor for sediment routing in the main channel (PRF_BSN) and tributary channels (ADJ_PKR), and Manning's n for the main channel (CH_N2). Of these, only CH_N2 is a subbasin parameter while the rest are basin-wide parameters. Subbasin-specific adjustments to CH_N2 were made according to the percentage of wetlands within the channel corridor of each subbasin (250 meter buffer from the main channel). Calibrated sediment parameter values are listed in Table 19.

Table 15 lists sediment calibration performance statistics by site. Based on PBIAS, model performance for sediment calibration was good to very good (≤ ±30%) for fourteen of sixteen sites. The remaining two calibration sites met the satisfactory benchmark for PBIAS (≤ ±55%).

NSE at long-term sites was good (≥0.65) for two of the four sites and satisfactory for (≥0.5) for one of the four sites. NSE was unsatisfactory (0.42) for one of the long-term sites, Kewaunee River Near Kewaunee, WI (ID = 04085200). However, PBIAS was good (14.4%), suggesting that long-term average loads are accurately represented in the model. Model performance at this site is discussed in more detail in Section 6.

Table 15. Sediment calibration performance statistics for the NEL SWAT model. Asterisk (*) denotes long-term calibration sites.

Site ID	Site Name	Sub-Model	R^2	NSE	PBIAS
153027	Ahnapee River at CTH J	Kewaunee	0.48	0.38	-0.7%
10029954	Kewaunee River at Hillside Road	Kewaunee	0.77	0.50	27.7%
04085200	Kewaunee River Near Kewaunee, WI*	Kewaunee	0.45	0.42	14.4%
10029482	West Twin River at CTH V	Kewaunee	0.48	0.46	6.4%
363313	Branch River at Branch River Rd	Manitowoc	0.44	0.43	12.8%
04085427	Manitowoc River at Manitowoc, WI*	Manitowoc	0.67	0.67	-5.9%
363368	Point Creek at Centerville Rd.	Manitowoc	0.72	0.16	-53.8%
363228	Silver Creek (Manitowoc) at Cth Ls	Manitowoc	0.36	0.34	-12.3%
10049358	Mullet River at Sumac Road	Sheboygan	0.41	0.33	26.2%
603304	Onion River at Ourtown Rd 5m Bi	Sheboygan	0.56	0.34	-31.5%
040857005	Otter Creek at Willow Road Near Plymouth, WI*	Sheboygan	0.66	0.64	29.4%
603295	Pigeon River at Cth A -And River Rd	Sheboygan	0.23	0.14	29.2%
603051	Pigeon River at Mill Road	Sheboygan	0.39	0.33	-14.1%
10016139	Sheboygan R. - Hwy 57 Crossing	Sheboygan	0.29	0.01	18.5%
04086000	Sheboygan River at Sheboygan, WI*	Sheboygan	0.74	0.65	-21.2%
10039440	Sheboygan River at Palm Tree Rd	Sheboygan	0.94	0.91	-11.8%

Table 16 lists sediment validation performance statistics by site. Based on PBIAS, model performance for sediment validation was good to very good (≤ ±30%) for five of the seven sites. The Sauk Creek at Mink Ranch Rd (ID = 463070) site was within the satisfactory range (≤ ±55%) for PBIAS. One site did not meet the satisfactory performance criteria for PBIAS, the Manitowoc River South Branch at Lemke Road (ID = 363375) where PBIAS was 179%. Model performance for this site is discussed in more detail in Section 6.

NSE was good to very good (≥0.65) for two of the three long-term validation sites. NSE was unsatisfactory for the remaining long-term validation site, the Kewaunee River Near Kewaunee, WI (ID = 04085200). The validation dataset demonstrated similar performance as the calibration dataset for this site, where PBIAS was good (18.7%) but NSE fell below the satisfactory performance criteria (0.43). Model performance at this site is discussed in more detail in Section 6. Sediment calibration and validation plots are presented in Appendix B.

Table 16. Sediment validation performance statistics for the NEL SWAT model. Asterisk (*) denotes long-term validation sites.

Site ID	Site Name	Sub-Model	R^2	NSE	PBIAS
10008207	East Twin River at Steiners Corners Rd.	Kewaunee	0.48	0.47	11.3%
04085200	Kewaunee River Near Kewaunee, WI*	Kewaunee	0.44	0.43	18.7%
10020779	Silver Creek (Algoma) at Willow Drive	Kewaunee	0.36	0.30	-13.8%
04085427	Manitowoc River at Manitowoc, WI*	Manitowoc	0.86	0.81	-24.3%
363375	Manitowoc River South Branch at Lemke Road	Manitowoc	0.41	-14.37	178.8%
463070	Sauk Creek at Mink Ranch Rd (Bi)	Sheboygan	0.64	0.35	-34.4%
04086000	Sheboygan River at Sheboygan, WI*	Sheboygan	0.90	0.72	-22.9%

5.4 Total Phosphorus Calibration and Validation

Total phosphorus parameters were calibrated following sediment calibration. Total phosphorus calibration consisted of an initial manual calibration step to match simulated and observed phosphorus loads, followed by automated calibration with SWAT-CUP software to fine-tune parameter estimates, and additional manual calibration based on SWAT-CUP results.

Like sediment calibration, total phosphorus calibration used PBIAS as the primary performance benchmark for evaluating sites with short term records (less than 3 years), which included all WDNR monitoring sites. The USGS sites were calibrated using both NSE and PBIAS as performance statistics due to their longer periods of record.

Total phosphorus calibration focused on the following parameters based on a review of the sensitivity of model outputs to parameter changes: the phosphorus availability index (PSP), the phosphorus soil partitioning coefficient (PHOSKD), and the phosphorus uptake distribution parameter (P_UPDIS). The most recent SWAT soil phosphorus routines were enabled by setting the soil phosphorus routine option (SOL_P_MODEL) to 1. Additionally, the phosphorus enrichment ratio for sediment (ERORGP) was adjusted for HRUs in subbasins dominated by soils with a low infiltration rate (hydrologic soils groups C and D). ERORGP was adjusted to decrease phosphorus loading in these subbasins because the default value resulted in a very high ratio of particulate phosphorus yield to sediment yield. Calibrated total phosphorus parameter values are listed in Table 19.

Table 17 lists total phosphorus calibration performance statistics by site. Based on PBIAS, model performance for total phosphorus calibration was very good (≤ ±25%) for twelve of eighteen sites and good (≤ ±55%) for the remaining six sites. NSE at long-term sites was good to very good (≥0.65) for four of the five sites. NSE was unsatisfactory (0.41) for the Kewaunee River Near Kewaunee, WI site (ID = 04085200). However, PBIAS was very good (2.3%), suggesting that long-term average loads are accurately represented in the model. Model performance at this site is discussed in more detail in Section 6.

Table 17. Total phosphorus calibration statistics for the NEL SWAT model. Asterisk (*) denotes long-term calibration sites.

Site ID	Site Name	Sub-Model	R^2	NSE	PBIAS
153027	Ahnapee River at CTH J	Kewaunee	0.68	0.14	42.8%
10008207	East Twin River at Steiners Corners Rd.	Kewaunee	0.47	0.47	-3%
10029954	Kewaunee River at Hillside Road	Kewaunee	0.44	0.42	-10.6%
04085200	Kewaunee River Near Kewaunee, WI*	Kewaunee	0.43	0.41	2.3%
10029482	West Twin River at CTH V	Kewaunee	0.38	0.38	-0.5%
363313	Branch River at Branch River Rd	Manitowoc	0.42	0.29	28.9%
04085427	Manitowoc River at Manitowoc, WI*	Manitowoc	0.67	0.65	-11%
363368	Point Creek at Centerville Rd.	Manitowoc	0.55	0.31	-35.9%
363228	Silver Creek (Manitowoc) at Cth Ls	Manitowoc	0.26	0.21	-9.6%
10049358	Mullet River at Sumac Road	Sheboygan	0.50	-0.64	51%
603304	Onion River at Ourtown Rd 5m Bi	Sheboygan	0.46	0.38	-22.4%
603051	Pigeon River at Mill Road	Sheboygan	0.11	-0.12	9.5%
463070	Sauk Creek at Mink Ranch Rd (Bi)	Sheboygan	0.59	0.25	-46.6%
10016139	Sheboygan R. - Hwy 57 Crossing	Sheboygan	0.48	0.43	-15.1%
04086000	Sheboygan River at Sheboygan, WI*	Sheboygan	0.73	0.73	0.2%
040854592	Fisher Creek at Howards Grove, WI*	Sheboygan	0.85	0.82	-4.7%
040857005	Otter Creek at Willow Road Near Plymouth, WI*	Sheboygan	0.67	0.66	-1.6%

Table 18 lists total phosphorus validation performance statistics by site. Based on PBIAS, model performance for total phosphorus validation was very good (≤ ±25%) for four sites and good (≤ ±55%) for the remaining three sites.

NSE at long-term sites was very good (≥0.75) for two of the three sites. NSE was unsatisfactory for the remaining long-term site, the Kewaunee River Near Kewaunee, WI site (ID = 04085200). Model performance at this site is discussed in more detail in Section 6. Total phosphorus calibration plots are presented in Appendix C.

Table 18. Total phosphorus validation statistics for the NEL SWAT model. Asterisk (*) denotes long-term validation sites.

Site ID	Site Name	R^2	NSE	PBIAS
04085200	Kewaunee River Near Kewaunee, WI*	0.43	0.41	-7.8%
10020779	Silver Creek (Algoma) at Willow Drive	0.28	0.15	-41.1%
04085427	Manitowoc River at Manitowoc, WI*	0.85	0.85	-10.8%
363375	Manitowoc River South Branch at Lemke Road	0.37	-0.74	33.4%
603295	Pigeon River at Cth A -And River Rd	0.10	0.01	1.7%
04086000	Sheboygan River at Sheboygan, WI*	0.94	0.85	34.2%
10039440	Sheboygan River at Palm Tree Rd	0.44	0.31	-15.2%

Table 19. Calibrated SWAT parameter values.

Parameter	File	Units	Type	Default Value	Calibrated Value		
					Kewaunee	Manitowoc	Sheboygan
SFTMP	.bsn	Degrees C	Basin-wide Streamflow	1	0.86	1.81	1.155
SMTMP	.bsn	Degrees C	Basin-wide Streamflow	0.5	1.2	0.17	1.065
SMFMX	.bsn	Degrees C	Basin-wide Streamflow	4.5	4	3.85	3.36
SMFMN	.bsn	Degrees C	Basin-wide Streamflow	4.5	1.17	1.17	1.551
TIMP	.bsn	-	Basin-wide Streamflow	1	0.266	0.26	0.376
GWQMN	.gw	mm H_2O	Streamflow	1000	1108	1826	399
GW_DELAY	.gw	days	Streamflow	31	300	240	128
SNOCOVMX	.bsn	mm H_2O	Basin-wide Streamflow	1	46.5	48	62.2
SNO50COV	.bsn	mm H_2O	Basin-wide Streamflow	0.5	0.775	0.505	0.485
GW_REVAP	.gw	-	Streamflow	0.02	0.13	0.044	0.085
REVAPMN	.gw	mm H_2O	Streamflow	750	153	152	325
ESCO	.hru	-	Streamflow	1	0.85	0.66	0.98
ALPHA_BF	.gw	-	Streamflow	0.014	0.0965	0.098	0.082
SURLAG	.hru	-	Streamflow	4	0.25	0.2	0.185
OV_N (Wetland HRUs)	.hru	-	Sediment	0.05	0.3	0.3	0.3
USLE_P (Forest/Wetland HRUs)	.mgt	-	Sediment	1	0.5	0.4	0.4
USLE_P (Grassland HRUs)	.mgt	-	Sediment	1	0.5	0.4	0.3
USLE_P (Cash Grain HRUs)	.mgt	-	Sediment	1	0.3	0.3	0.3
USLE_P (Dairy/Hay HRUs)	.mgt	-	Sediment	1	0.3	0.3	0.3
USLE_P (Urban HRUs)	.mgt	-	Sediment	1	0.5	0.5	0.5
FILTERW (Forest/Wetland HRUs)	.mgt	meters	Sediment	0	10	15	15
FILTERW (Grassland HRUs)	.mgt	meters	Sediment	0	12	17	18
FILTERW (Cash Grain HRUs)	.mgt	meters	Sediment	0	10	15	14.5
FILTERW (Dairy/Hay HRUs)	.mgt	meters	Sediment	0	10	15	14.5
FILTERW (Urban HRUs)	.mgt	meters	Sediment	0	5	5	5
BIO_E (Corn)	plant.dat	-	Crop Yield	39	57	50	42
BIO_E (Corn Silage)	plant.dat	-	Crop Yield	39	57	52	42
BIO_E (Soybean)	plant.dat	-	Crop Yield	25	50	47	43
BIO_E (Alfalfa)	plant.dat	-	Crop Yield	20	10	10	8
BLIA (Soybean)	plant.dat	-	Crop Yield	3	6	6	5
ADJ_PKR	.bsn	-	Sediment	1	1.1	1.5	0.9
PRF_BSN	.bsn	-	Sediment	1	1.8	2	1.65
SPCON	.bsn	-	Sediment	0.0001	0.001	0.001	0.001
CH_N2	.rte	-	Sediment	0.014	0.1	0.02	0.02

Parameter	File	Units	Type	Default Value	Calibrated Value		
					Kewaunee	**Manitowoc**	**Sheboygan**
CH_N2 (>50% wetland cover within 0.5 km of main channel)	.rte	-	Sediment	0.014	0.3	0.05	0.24
SPEXP	.bsn	-	Sediment	1	2	2	2
PSP	.bsn	-	Phosphorus	0.4	0.155	0.13	0.1
PHOSKD	.bsn	m^3/Mg	Phosphorus	175	200	40	50
P_UPDIS	.bsn	-	Phosphorus	20	20	20	20
GWSOLP	.gw	-	Phosphorus	0	0.02	0.02	0.02
ERORGP (HRUs in subbasins with hydrologic soil groups C/D dominant soils)	.hru	-	Phosphorus	0	0	0	0.75
PSETLP1	.pnd	m/year	Phosphorus	10	100	10	50
PSETLP2	.pnd	m/year	Phosphorus	10	100	10	50

6 Discussion of Calibration and Validation Results

6.1 Application of Model Results

An evaluation of the performance of the NEL SWAT model should consider the intended application of model results. Key model outputs used to support the development of phosphorus and sediment TMDLs are listed below:

1. SWAT outputs of average annual streamflow in stream and river reaches for 2008-2019 are used in the calculation of allowable phosphorus and sediment loads for stream and river reaches;
2. SWAT outputs of average annual nonpoint source phosphorus and sediment loads for 2008-2019 are used in the calculation of percent reductions from existing sources needed to achieve allowable phosphorus and sediment loads;
3. SWAT outputs of the relative magnitude of phosphorus and sediment loads from major land cover types are used to allocate total allowable phosphorus and sediment loads to nonpoint sources.

6.3 Exceptions to Model Performance Benchmarks

SWAT calibration and validation results show that satisfactory performance guidelines for streamflow, sediment, and phosphorus are met or exceeded at most calibration and validation sites. All exceptions are discussed below.

- Streamflow PBIAS for the Kewaunee River at Hillside Rd. PBIAS fell below the guideline for satisfactory streamflow calibration performance (PBIAS = 26.5%) for this site (ID = 10029954). This site had only nine months of streamflow calibration data and performed poorly during that period. However, the downstream Kewaunee River calibration site (ID = 04085200) had 72 months of streamflow calibration data and fit well (NSE = 0.67; PBIAS = -10.7%), demonstrating that there is not a systematic issue with model over-estimation of streamflow in the Kewaunee River drainage.
- Sediment and phosphorus NSE for calibration and validation sites with short record lengths. The average NSE for water quality calibration sites with less than three years of data was 0.39 for sediment and 0.23 for total phosphorus, which is below the satisfactory performance benchmark (≥ 0.5). For these sites, the average record length for observed water quality data was sixteen months. NSE is highly influenced by individual rainfall/runoff events when the sample size of the observed dataset is small (McCuen et al., 2006). Because the NEL model is intended to estimate long-term average conditions for TMDL development rather than responses to individual storm events, calibration and validation focused on evaluating percent bias (PBIAS) at monitoring sites with short record lengths. Low NSE values for sediment and phosphorus at these sites were therefore considered acceptable.
- Sediment PBIAS for Point Creek at Centerville Rd. The PBIAS for sediment calibration at this site was -53.8%, indicating that the model under-estimated sediment loads relative to observed loads. Although PBIAS fell within the satisfactory performance guideline (≤ ±55%), the difference between simulated and observed sediment loads was notably greater than other sediment calibration sites. Nine sediment samples were collected at this site during the WDNR water quality monitoring effort, whereas the median sample count across all other sediment sites was 51. The small sample size for the Point Creek site likely does not adequately capture the range of sediment levels and flow conditions needed to accurately determine daily sediment loads.

Because the observed dataset for this site is highly uncertain, the elevated PBIAS value does not suggest an issue with sediment simulation in the model.

- <u>Sediment PBIAS for the Manitowoc River South Branch at Lemke Road (PBIAS = 179%).</u> Sediment loads from the SWAT model far exceeded observed loads at the Manitowoc River South Branch at Lemke Road site (ID = 363375). The WDNR estimates of monthly sediment loads used for calibration at this site were generated from sampled sediment concentrations, daily streamflow records, and a statistical model. See Streamflow and Load Estimation Methods for Development of the NE Lakeshore TMDL for detailed methods (WDNR, in preparation). Fit statistics reported by WDNR can be used to evaluate how well the estimated loads from the statistical model match loads calculated directly from sample data (observed sample concentration multiplied by observed streamflow). Fit statistics for the Manitowoc River South Branch at Lemke Road site are poor (R-squared = 0.3, NSE = -0.64, and PBIAS = -1.4%) and the calibration data for this site should therefore be considered highly uncertain.

  To assess potential errors or anomalies in the NEL SWAT model that may have resulted in exceptionally high sediment loading at the Manitowoc River South Branch at Lemke Road site, sediment yields from HRUs draining to site were compared to sediment yields from HRUs across all other SWAT subbasins. Median annual sediment yields for the Manitowoc River South Branch at Lemke Road site are similar to mean values (within 0.04 tons per acre per year) for all NEL model HRUs (Table 20).

Table 20. Median annual sediment yields by land use type for HRUs draining to the Manitowoc River South Branch at Lemke Road site (ID = 363375) and for all HRUs in the NEL model.

Land Use Type	**Manitowoc River South Branch at Lemke Road (tons/acre/year)**	**Entire NEL Model (tons/acre/year)**
Cash Grain	0.067	0.100
Dairy	0.016	0.015
Forest & Wetland	0.001	<0.001
Pasture/Grassland	0.005	0.003
Urban High Density	0.070	0.083
Urban Low Density	0.007	0.009

- <u>Sediment and Phosphorus NSE for the Kewaunee River Near Kewaunee.</u> Calibration NSE values for sediment (NSE = 0.43) and phosphorus (NSE = 0.42) at the Kewaunee River Near Kewaunee site were slightly below the satisfactory guideline of 0.5. Calibration time series plots (Appendix B and Appendix C) for this site show isolated months with very large differences between observed and simulated loads. For example, the SWAT model significantly over-estimates phosphorus loads in June of 2008 and under-estimates the phosphorus load in April 2011. Removing these two months from the 72-month record results in a NSE value of 0.62 (above the satisfactory performance benchmark). Such results may be driven by inaccurate weather data during events that are poorly simulated in the NEL SWAT model. Despite the low NSE values, percent bias results demonstrate that the model accurately estimates long-term average loads for both sediment (PBIAS = 18.7%) and phosphorus (PBIAS = 2.3%). Because accurate estimates of long-term average conditions are the primary need for TMDL development, model results were determined to be suitable for the Kewaunee River Near Kewaunee site.

6.4 Phosphorus Loads by Land Use Type

To further evaluate SWAT outputs of phosphorus loading, model results were compared to the recommended range of phosphorus yields for different land use types reported by WDNR in the Wisconsin Lake Modeling Suite (WiLMS) (Wisconsin DNR, 2003). The phosphorus yields reported in WiLMS are not specific to the NEL study area but are derived from two statewide studies of phosphorus yields from watersheds with varied land uses (Corsi et al. 1997; Panuska & Lillie 1995).

Table 21 displays the WiLMS recommended ranges of annual total phosphorus yields and average 2008 to 2019 annual total phosphorus yields from the NEL SWAT model. SWAT yields for most land use types fall within the range of WiLMS recommended values with the exception of grassland cover and high-density urban cover, which fall below the minimum recommended range.

Table 21. Annual total phosphorus yields (in pounds per acre) by land use type from the NEL SWAT model and ranges recommended in the WDNR WiLMS model. SWAT values are the average of 2008-2019 annual yields for all HRUs with the specified land use.

Land Use Type	**NEL SWAT Model**	**WiLMS Recommended Range**		
	Mean	**Minimum**	**Most Likely**	**Maximum**
Forest and Wetland	0.06	0.04	0.08	0.16
Dairy (Mixed Agriculture)	0.67	0.27	0.71	1.25
Corn/Soybean (Row Crop Ag.)	1.04	0.45	0.89	2.68
Pasture/Grassland	0.08	0.17	0.27	0.45
Urban Low Density	0.12	0.04	0.09	0.22
Urban High Density	0.50	0.89	1.34	1.78

6.4 Model Assumptions and Limitations

Key assumptions and limitations of the NEL SWAT model should be considered for other applications of the NEL SWAT model or for future updates. These include:

- As explained in the model setup section (Section 2), the NEL SWAT model uses DayMet weather records as model inputs. DayMet records are interpolated values of weather data. This means that DayMet data in areas without weather stations are a best estimate of conditions based on the nearest observed weather data. If records from additional weather stations became available they could improve the accuracy of model results by providing a more complete representation of spatial variability in precipitation and temperature.
- Performance statistics evaluating the accuracy of observed water quality records were reported by WDNR. These performance statistics were given consideration when calibrating at WDNR sites (i.e., WDNR sites with better fit statistics (R^2/NSE/PBIAS) were evaluated more rigorously than WDNR sites with poorer fit statistics).
- For USGS sites, errors in observed streamflow, sediment, and phosphorus data were not taken into consideration during model calibration and validation.

- Calibration was completed for total phosphorus and sediment loads only. Results for individual forms of phosphorus (i.e., soluble phosphorus) or other water quality constituents should not be used without further calibration.
- Lakes and reservoirs are not simulated in the NEL SWAT model. Output from the NEL SWAT model should not be used to infer conditions within any given NEL lake without coupling to a lake/receiving water model.

7 Summary of Model Results

7.1 Loads by Subbasin

Figure 5 displays average annual sediment and phosphorus yields by subbasin. Sediment and phosphorus loading both share a similar spatial pattern across the NEL study area. Generally, subbasins with the lowest sediment and phosphorus yields are located in:

- nearshore Lake Michigan regions;
- the northern region of the Kewaunee sub-model;
- the western portion of the Manitowoc sub-model;
- the west-central portion of the Sheboygan sub-model.

Subbasins with the highest sediment and phosphorus yields are generally located in:

- far western portions of all sub-models.
- the west-central portion of the Kewaunee sub-model;
- the central portion of the Manitowoc sub-model;
- the east-central portion of the Sheboygan sub-model.

The spatial pattern across subbasins is largely explained by dominant land use type (Figure 6). Specifically, subbasins with higher yields are associated with high density of agricultural areas, whereas subbasins with lower yields are associated with higher density of natural (forest and wetland) areas. Further, the subbasins with the highest yields are those with a larger proportion of cash grain agricultural cover relative to dairy agriculture. These areas are most concentrated in the southern and western portions of the NEL study area where cash grain agriculture makes up a higher proportion of the total agricultural landscape compared to northern and eastern areas that are predominantly comprised of dairy rotations and hay. These results are in large part a reflection of the more intensive tillage and other agricultural operations associated with continuous plantings of corn and soybeans. Although corn is a part of the dairy rotation crop sequence, the presence of multiple years of alfalfa growth in the dairy rotation reduces water quality impacts compared to the cash grain rotation.

The spatial variability of sediment and phosphorus yields is also influenced by slope and hydrologic soil group (Figure 6). Subbasins with very low slopes, such as those in the northern-most regions of the Kewaunee sub-model and those in the west-central region of the Manitowoc sub-model tend to generate the lowest pollutant yields. Conversely, some of the highest yielding HRUs tend to occur in subbasins with steeper slopes. For example, subbasins in the far western portion of the Sheboygan sub-model have a relatively low to moderate proportion of agricultural cover, but steeper slopes result in sediment and phosphorus yields that rank among the highest in the study area.

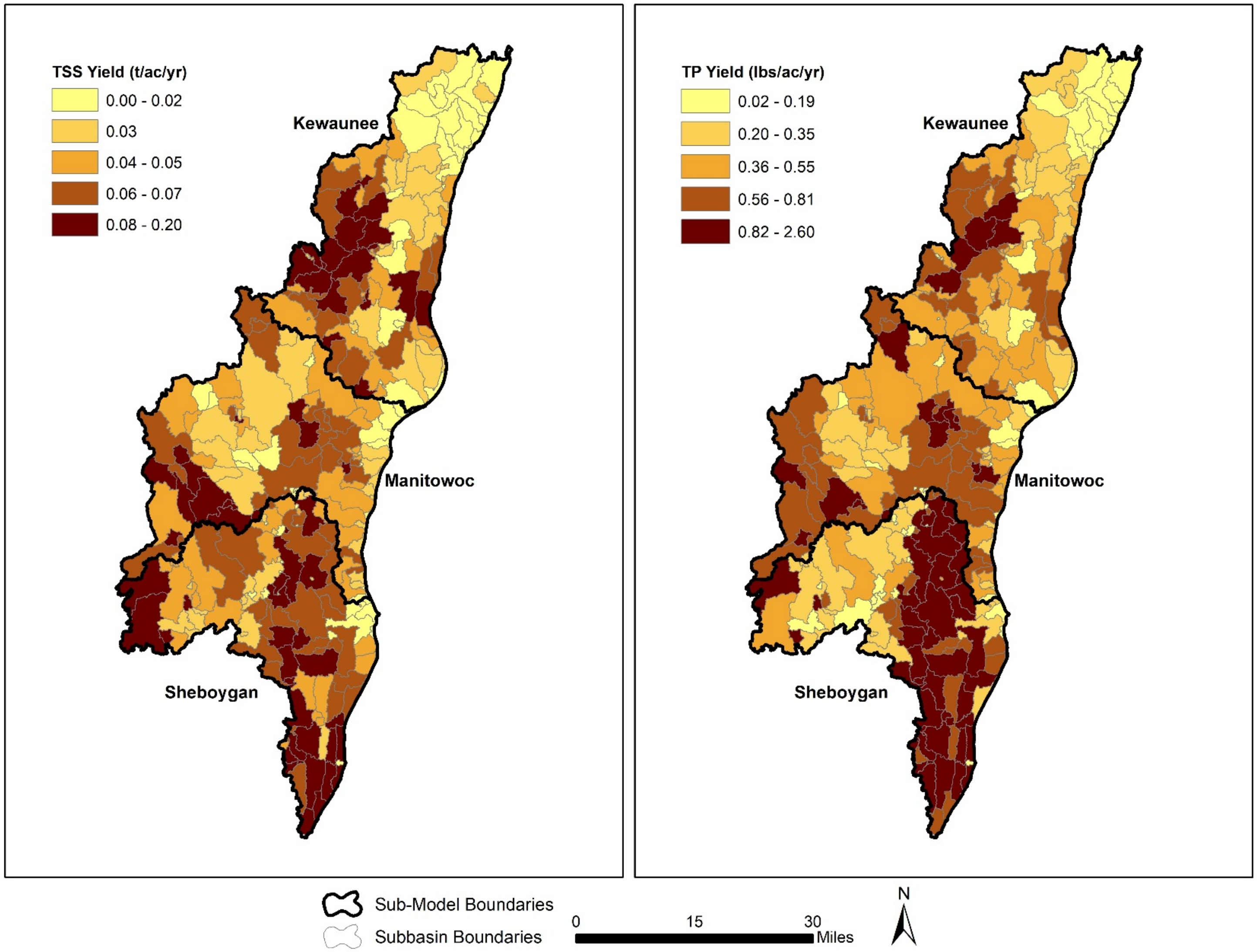

Figure 5. Maps of annual average sediment yield (tons per acre per year) and total phosphorus (TP) yield (pounds per acre per year) for each subbasin in the NEL SWAT model. Color classifications denote quintiles (i.e., 20% of subbasins yield between 0.02 and 0.19 pounds TP per acre per year).

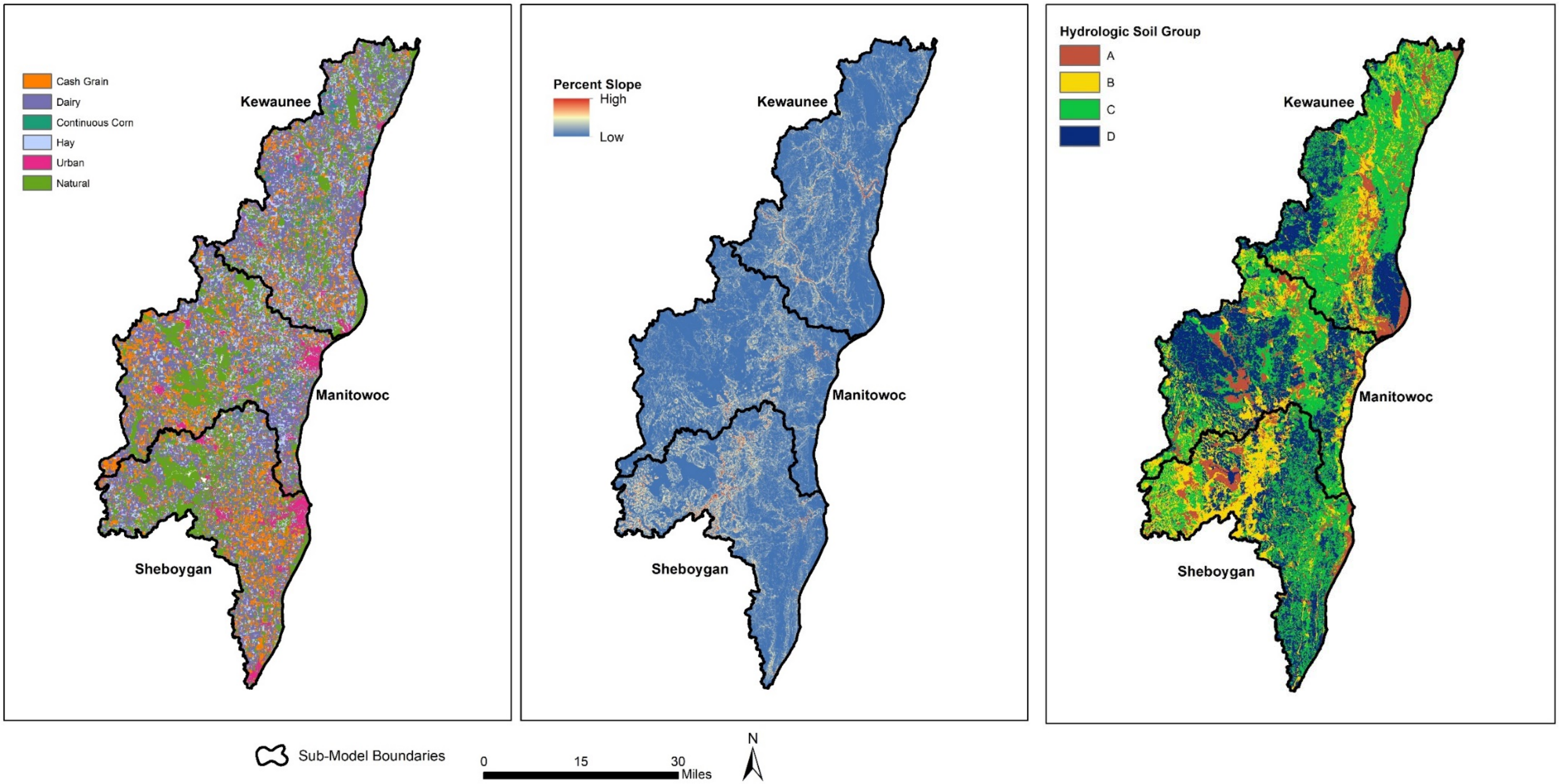

Figure 6. Maps of land use (left) and percent slope (middle) and hydrologic soil group (right) in the NEL SWAT model.

7.2 Loads by Land Use Type

Figure 7 and Figure 8 illustrate average annual yields by land use type for sediment and phosphorus, respectively. Sediment and phosphorus yields are generally highest for agricultural HRUs (cash grain rotations, dairy rotations, and hay) throughout the model area. High phosphorus and sediment yields from agriculture lands are driven by regularly tillage and exposure of bare soils, nutrient applications (chemical fertilizer and animal manure), and high initial soil phosphorus concentrations. Urban HRUs also show elevated sediment and phosphorus yields. However, the spatial extent of urban HRUs in the model is limited relative to agricultural cover, with small clusters of cities, towns, and villages scattered throughout. Natural cover types (forest, wetland, and grassland) are prevalent in the NEL study area but model results show that these areas contribute relatively low yields of sediment and phosphorus.

Flow-weighted concentrations of phosphorus and sediment provide another method for interpreting the relative contributions of different land use types to excess phosphorus and sediment levels. Annual flow-weighted mean concentrations of both total phosphorus and sediment were calculated for each land use type as the HRU pollutant load divided by the flow volume generated in the HRU. The resulting concentrations align with the yields discussed above, with highest total phosphorus and sediment concentrations export from agricultural HRUs, followed by urban HRUs, and natural cover HRUs (Table 22).

Table 22. Average annual flow-weighted mean concentration of total phosphorus (TP) and sediment by land use type in milligrams per liter. Agriculture includes cash grain, dairy, and hay HRUs. Urban includes MS4 and non-MS4 low-density and high-density urban HRUs. Natural includes forest, wetland, and grassland cover HRUs.

Land Use Type	**TP (mg/L)**	**Sediment (mg/L)**
Agriculture	328	561
Urban	56	102
Natural	26	67

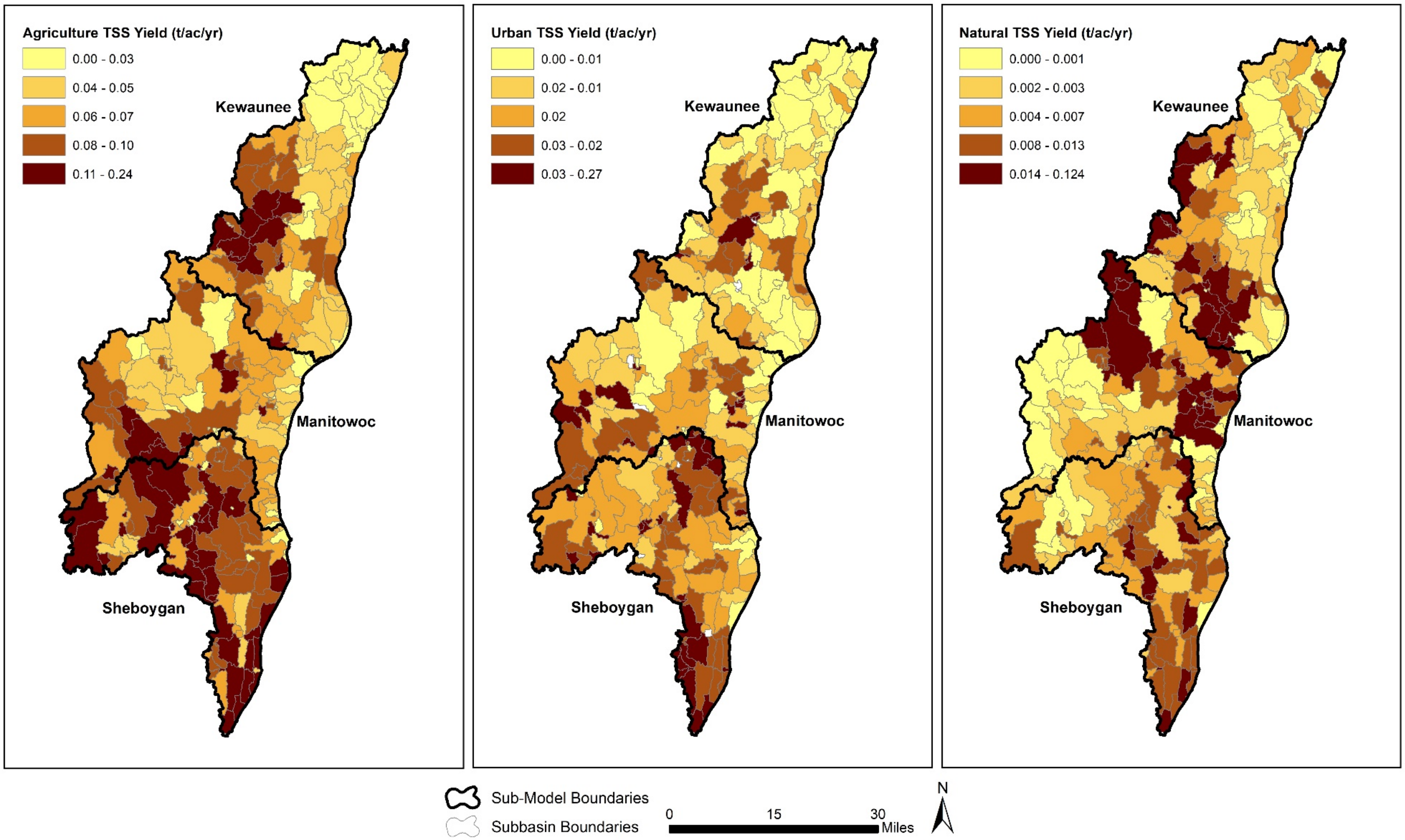

Figure 7. Maps of annual average sediment yield by land use type for each subbasin in the NEL SWAT model. Yields are reported in tons of sediment per acre per year. Color classifications denote quintiles. Agriculture includes cash grain, dairy, and hay HRUs. Urban includes MS4 and non-MS4 low-density and high-density urban HRUs. Natural includes forest, wetland, and grassland HRUs.

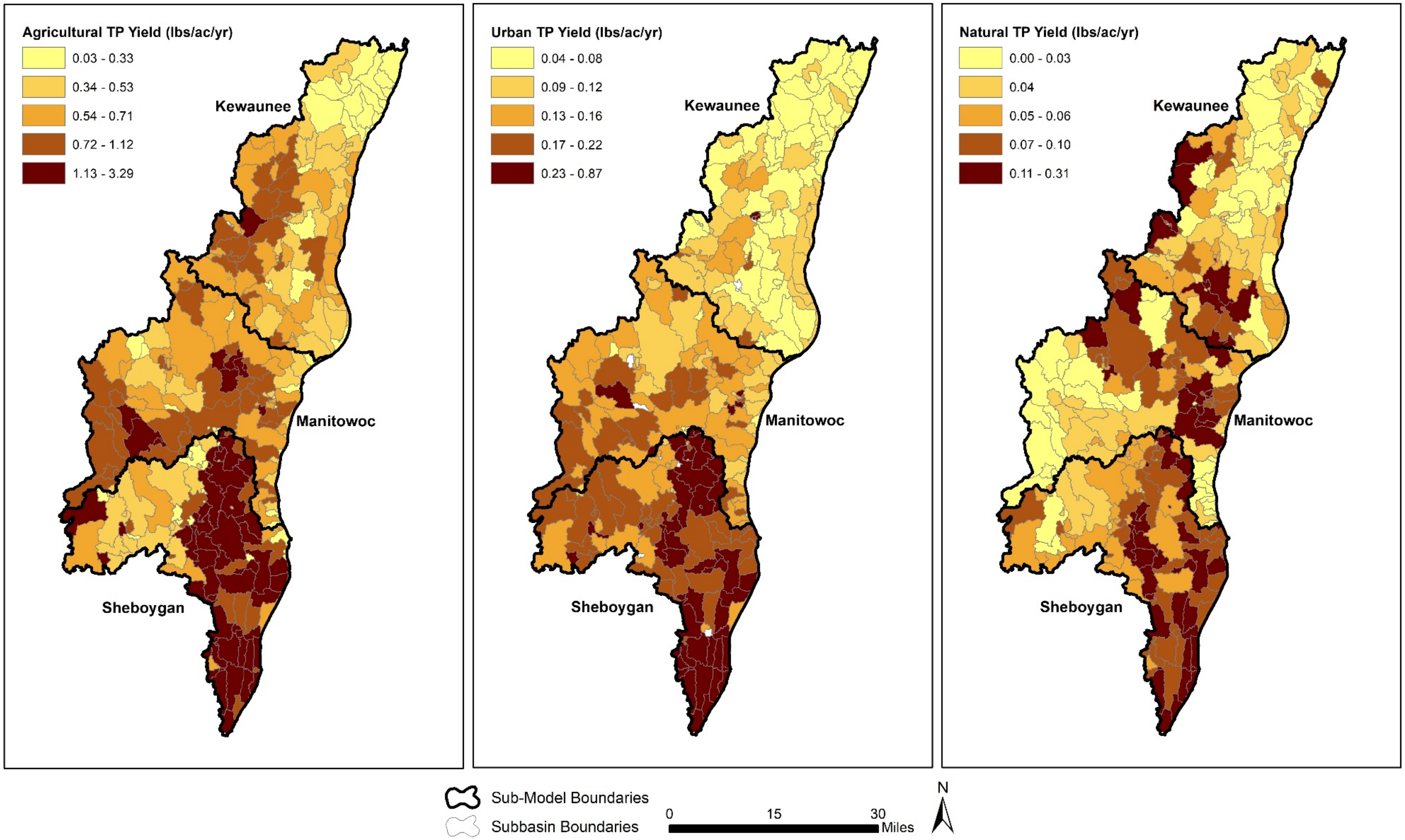

Figure 8. Maps of annual average total phosphorus (TP) yields by land use type for each subbasin in the NEL SWAT model. Yields are reported in pounds of TP per acre per year. Agriculture includes cash grain, dairy, and hay HRUs. Urban includes MS4 and non-MS4 low-density and high-density urban HRUs. Natural includes forest, wetland, and grassland HRUs.

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Appendix A. Streamflow Calibration and Validation Time Series Plots

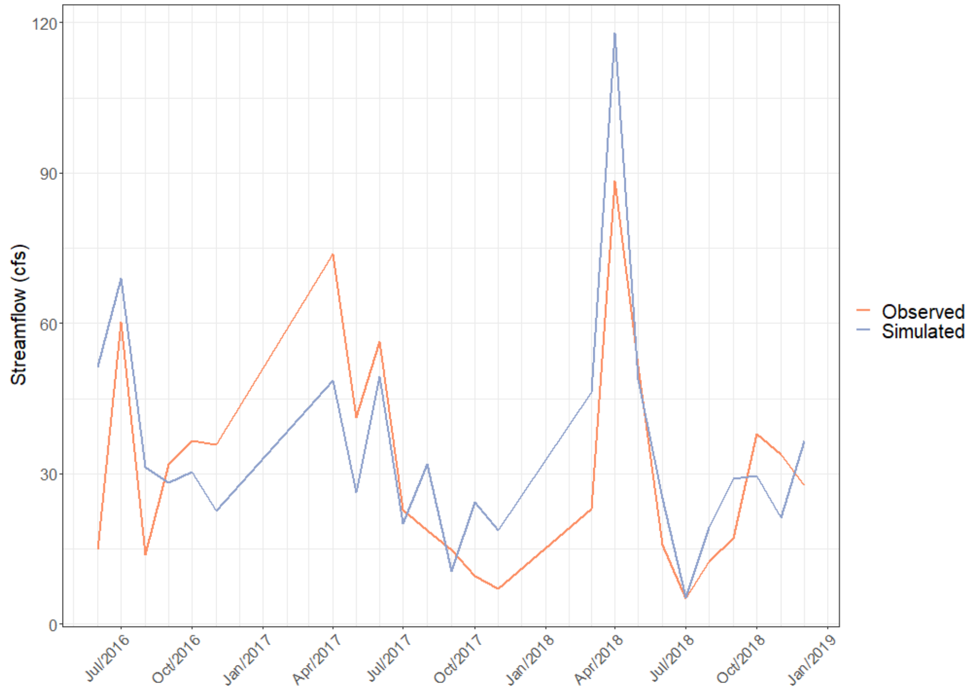

Figure A-1. Monthly streamflow calibration plot for WDNR site ID 153027 (Ahnapee River at CTH J).

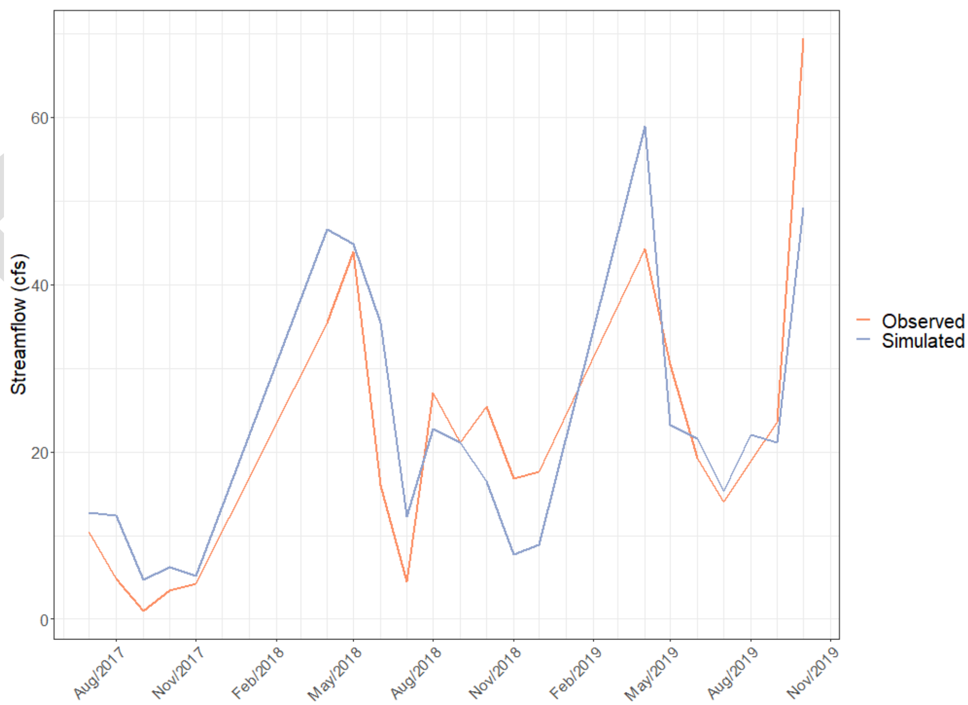

Figure A-2. Monthly streamflow calibration plot for WDNR site ID 363228 (Silver Creek (Manitowoc) at Cth Ls).

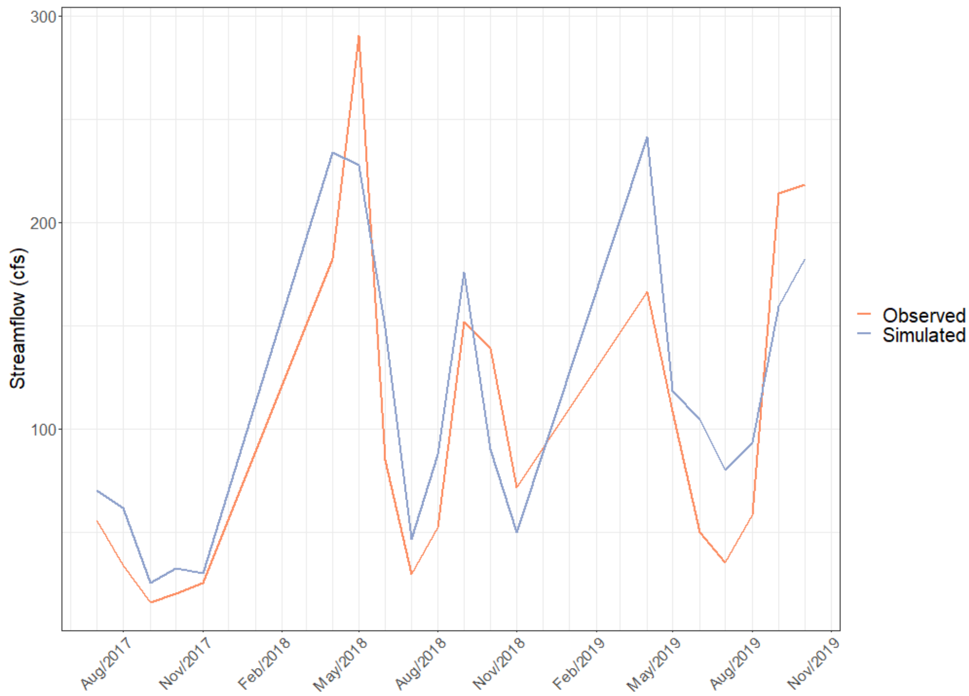

Figure A-3. Monthly streamflow calibration plot for WDNR site ID 363313 (Branch River at Branch River Rd.).

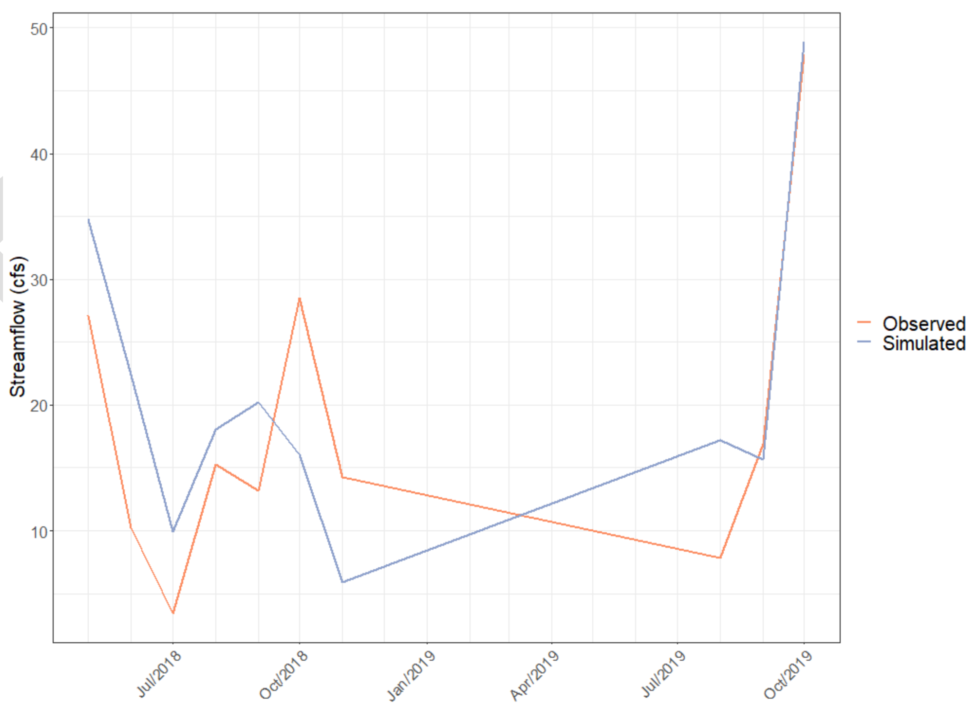

Figure A-4. Monthly streamflow calibration plot for WDNR site ID 363368 (Point Creek at Centerville Rd.).

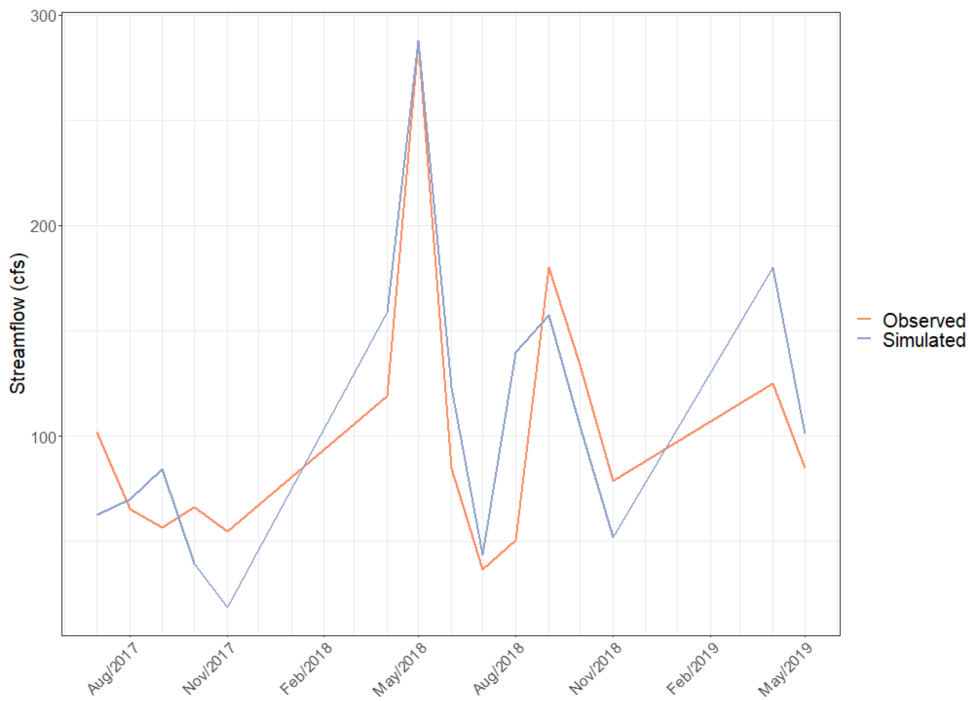

Figure A-5. Monthly streamflow calibration plot for WDNR site ID 363375 (Manitowoc River South Branch at Lemke Rd.).

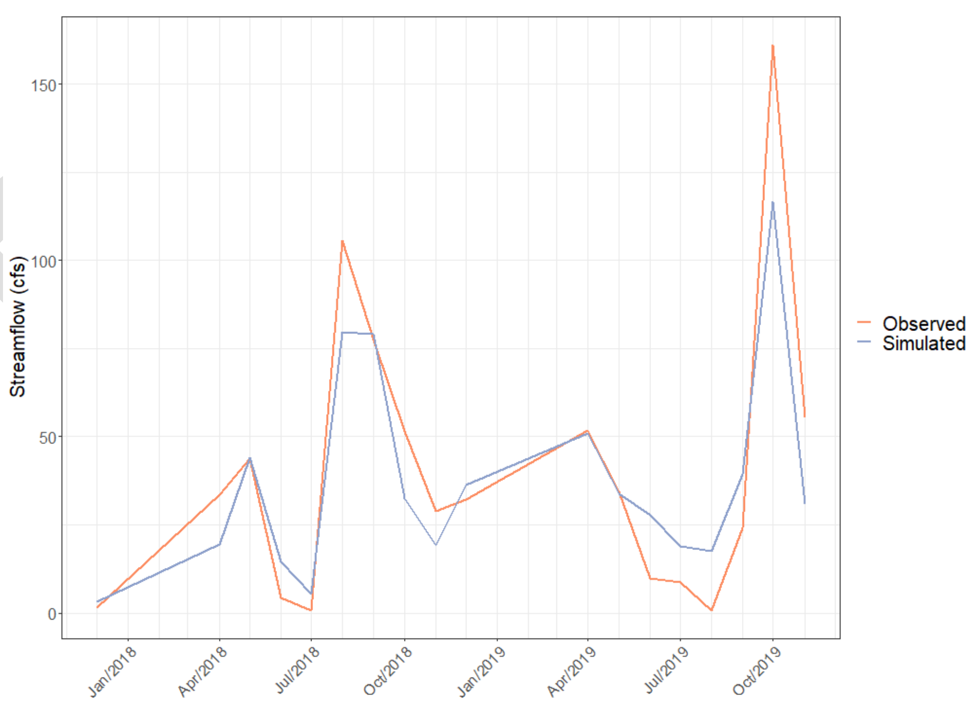

Figure A-6. Monthly streamflow calibration plot for WDNR site ID 463070 (Sauk Creek at Mink Ranch Rd. (Bi)).

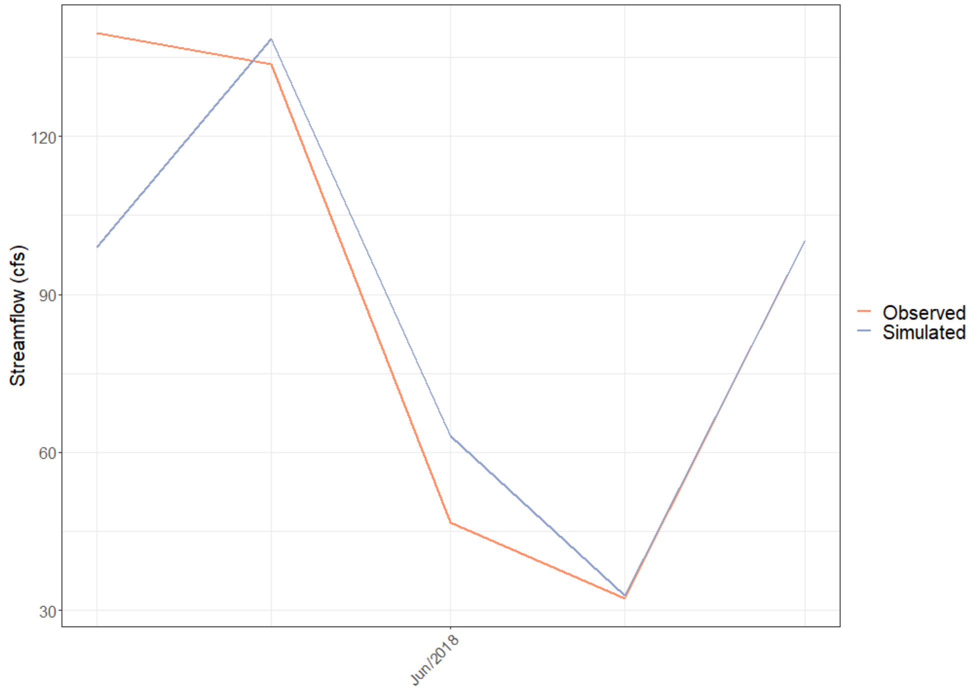

Figure A-7. Monthly streamflow calibration plot for WDNR site ID 603051 (Pigeon River at Mill Rd.).

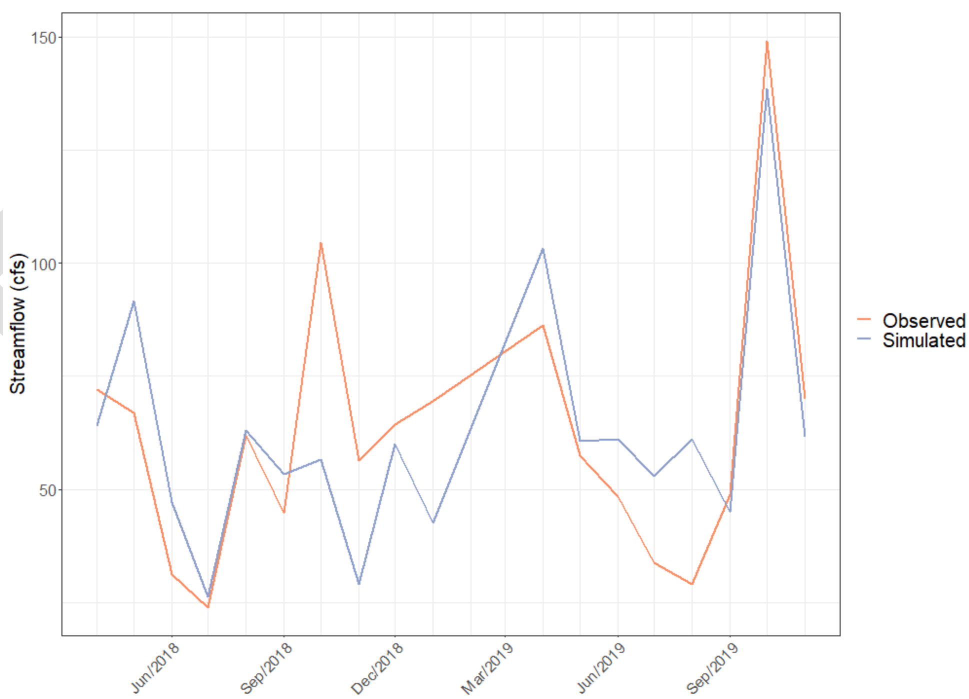

Figure A-8. Monthly streamflow calibration plot for WDNR site ID 603295 (Pigeon River at Cth A -And River Rd.).

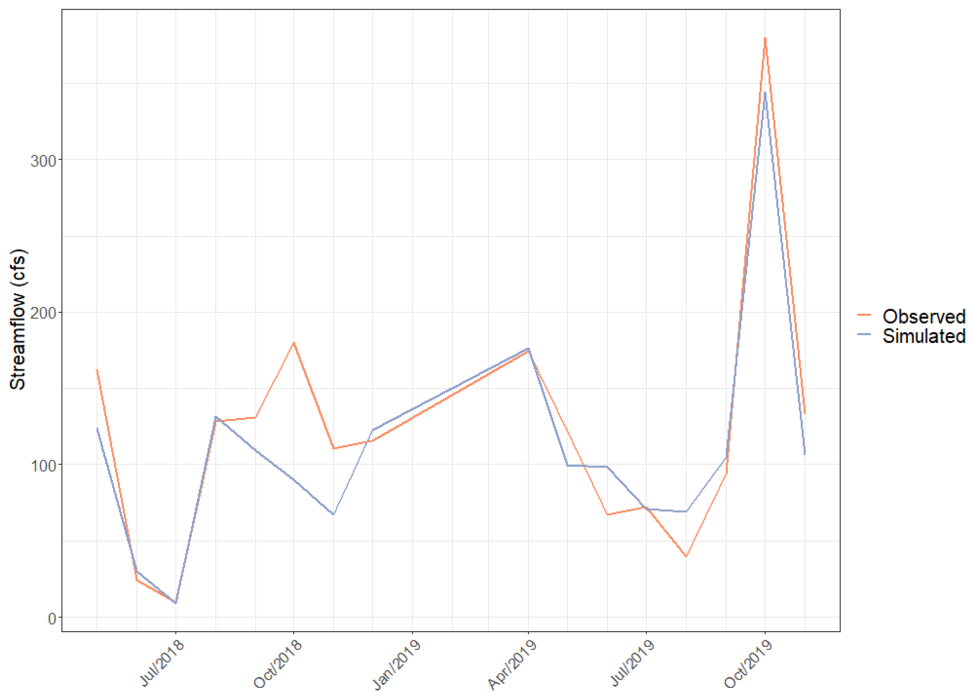

Figure A-9. Monthly streamflow calibration plot for WDNR site ID 603304 (Onion River at Ourtown Rd. 5m Bi).

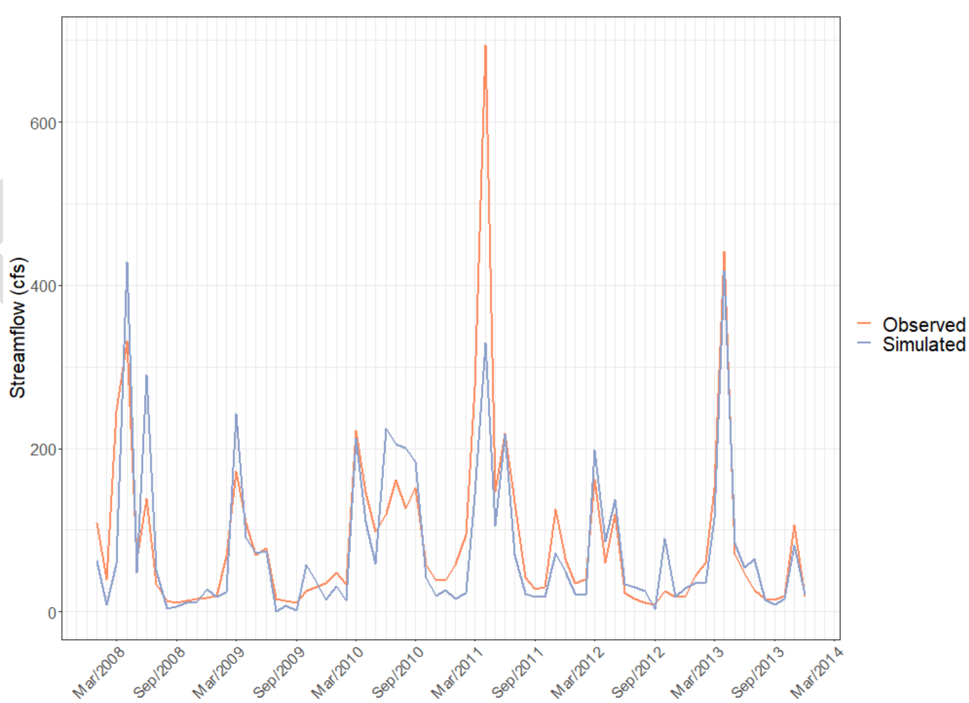

Figure A-109. Monthly streamflow calibration plot for USGS site ID 04085200 (Kewaunee River Near Kewaunee, WI).

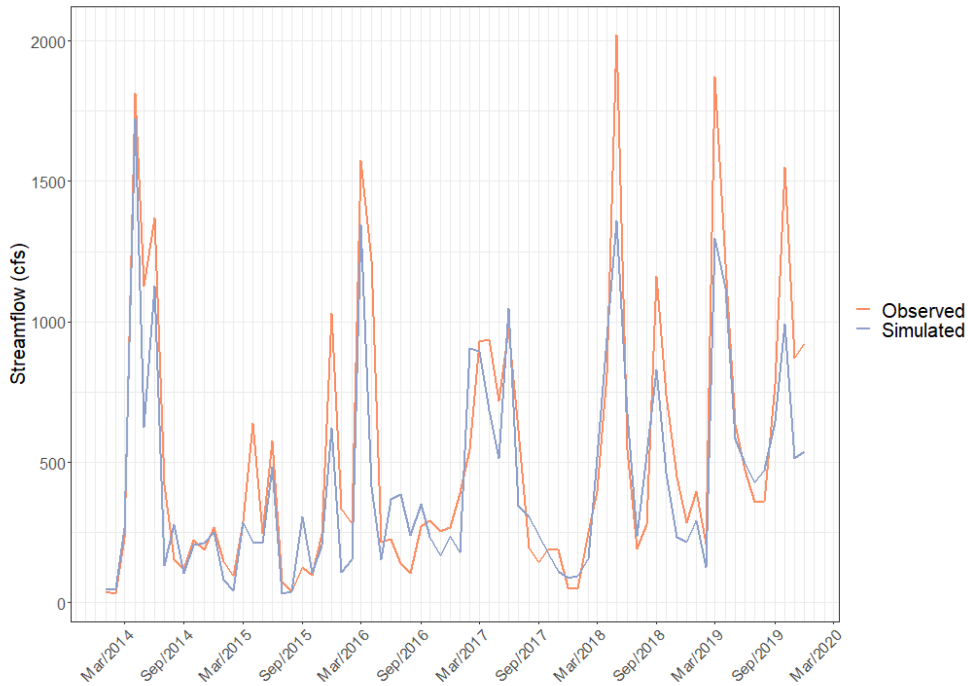

Figure A-11. Monthly streamflow calibration plot for USGS site ID 04085427 (Manitowoc River at Manitowoc, WI).

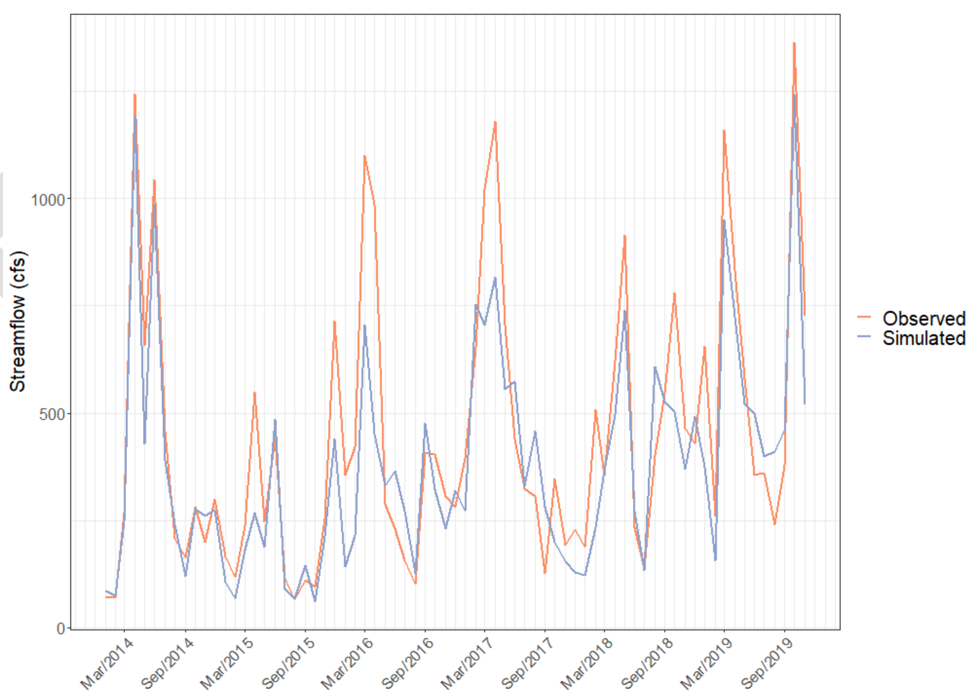

Figure A-12. Monthly streamflow calibration plot for USGS site ID 04086000 (Sheboygan River at Sheboygan, WI).

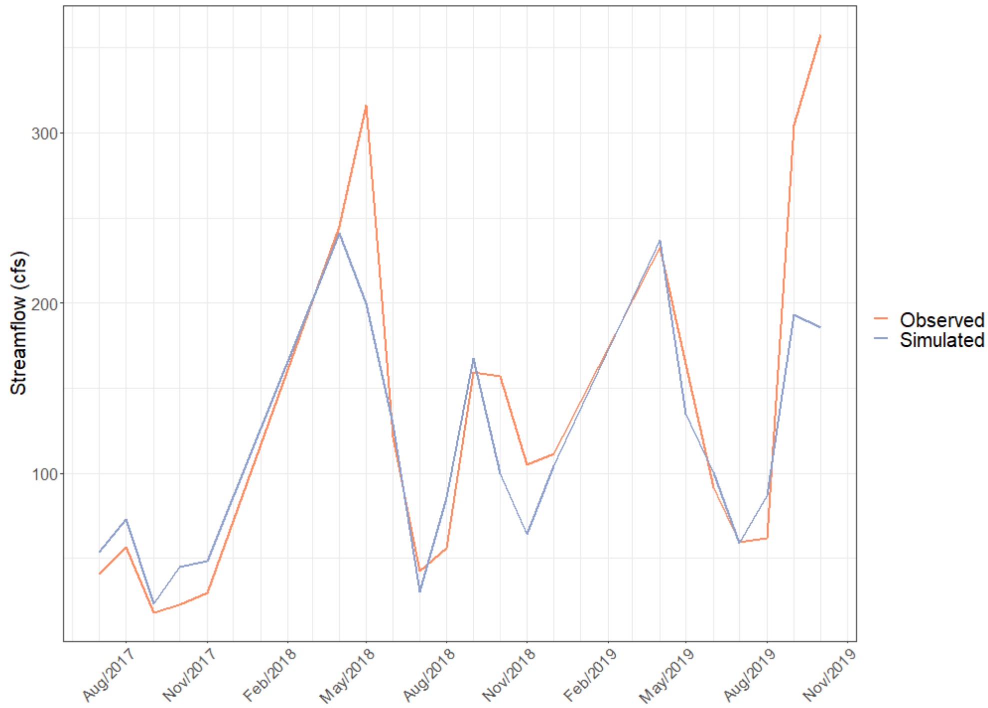

Figure A-13. Monthly streamflow calibration plot for WDNR site ID 10008207 (East Twin River at Steiners Corners Rd.).

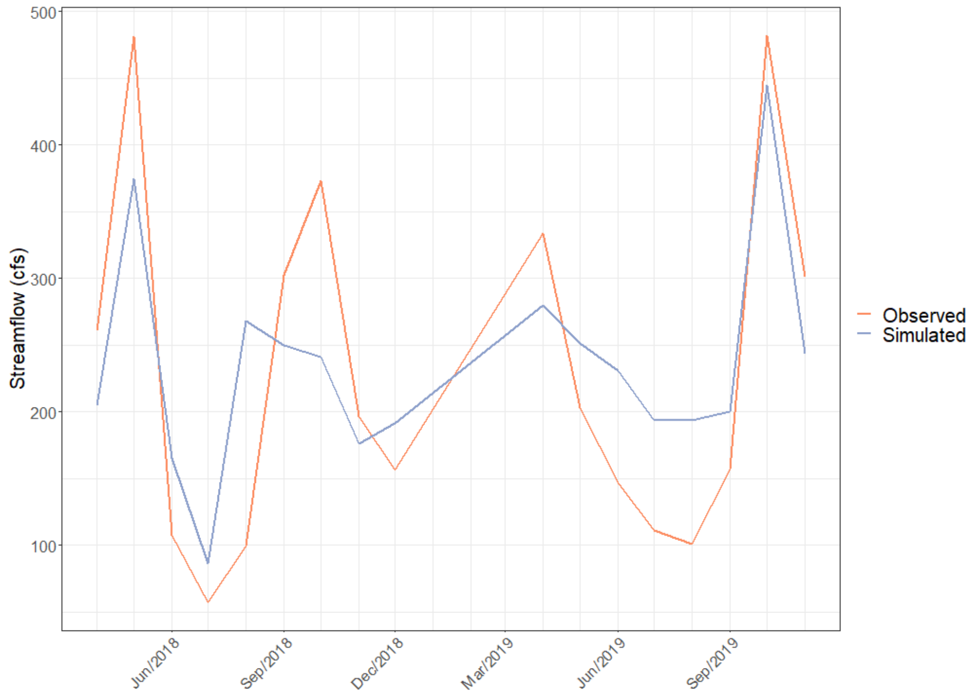

Figure A-14. Monthly streamflow calibration plot for WDNR site ID 10016139 (Sheboygan R. - Hwy 57 Crossing).

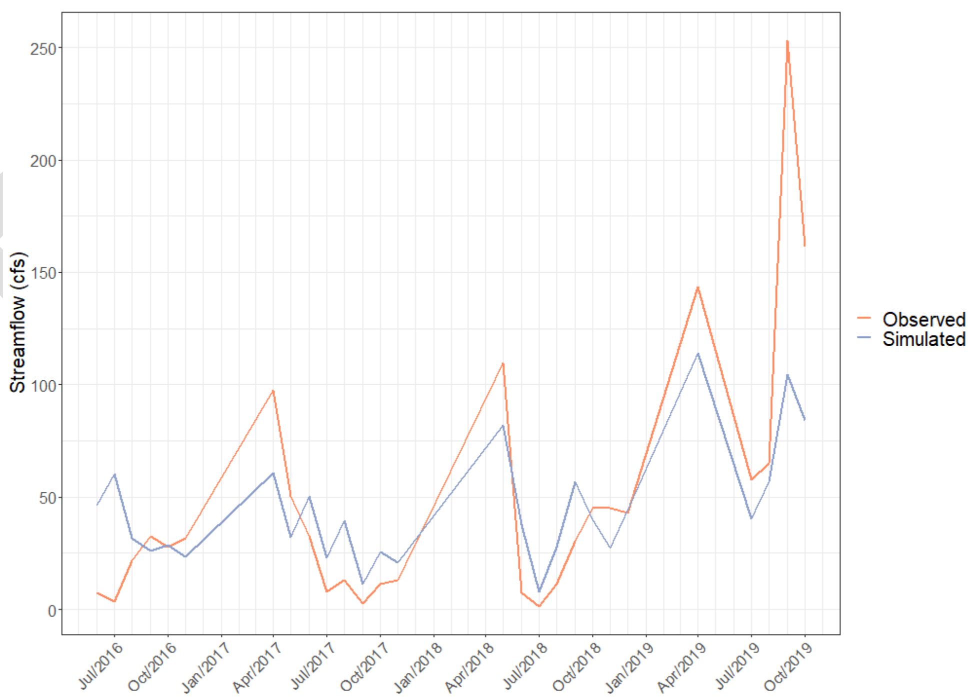

Figure A-15. Monthly streamflow calibration plot for WDNR site ID 10020779 (Silver Creek (Algoma) at Willow Drive).

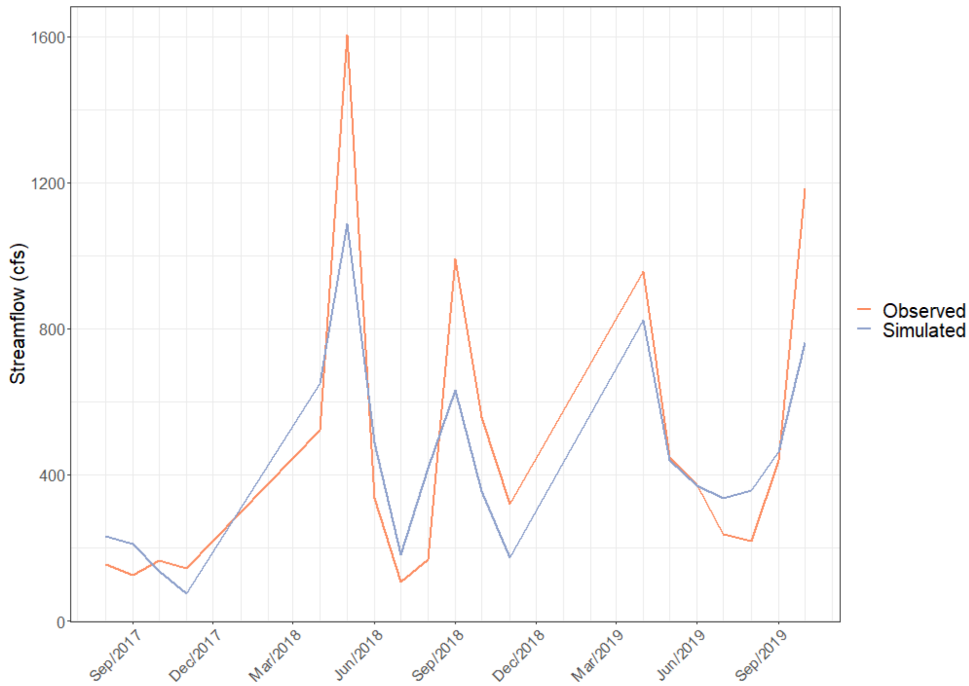

Figure A-16. Monthly streamflow calibration plot for WDNR site ID 10020782 (Manitowoc River at Leist).

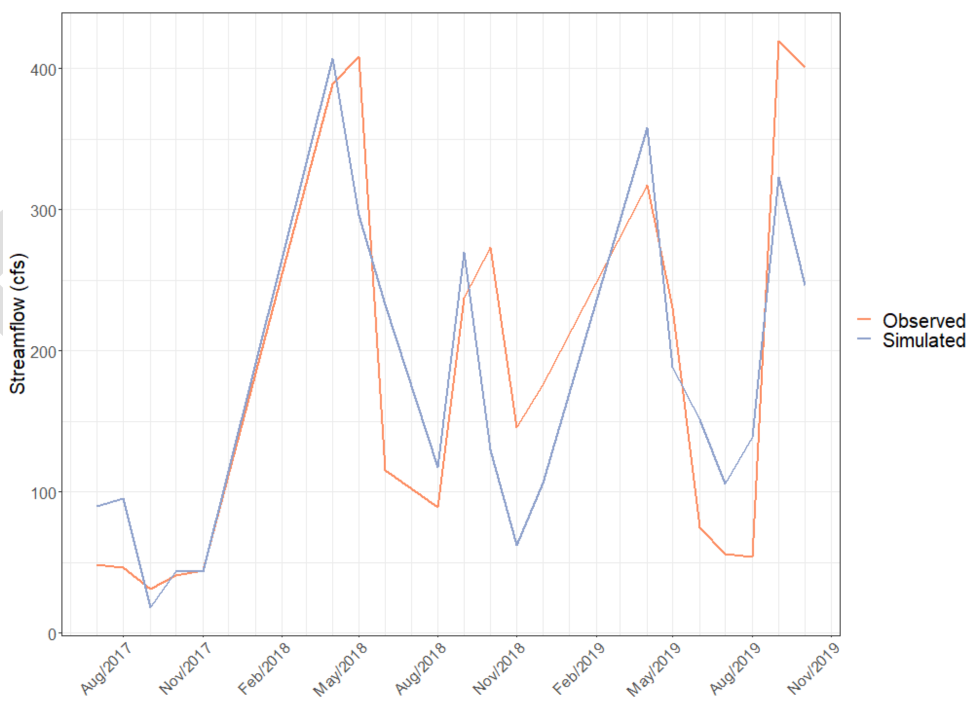

Figure A-17. Monthly streamflow calibration plot for WDNR site ID 10029482 (West Twin River at CTH V).

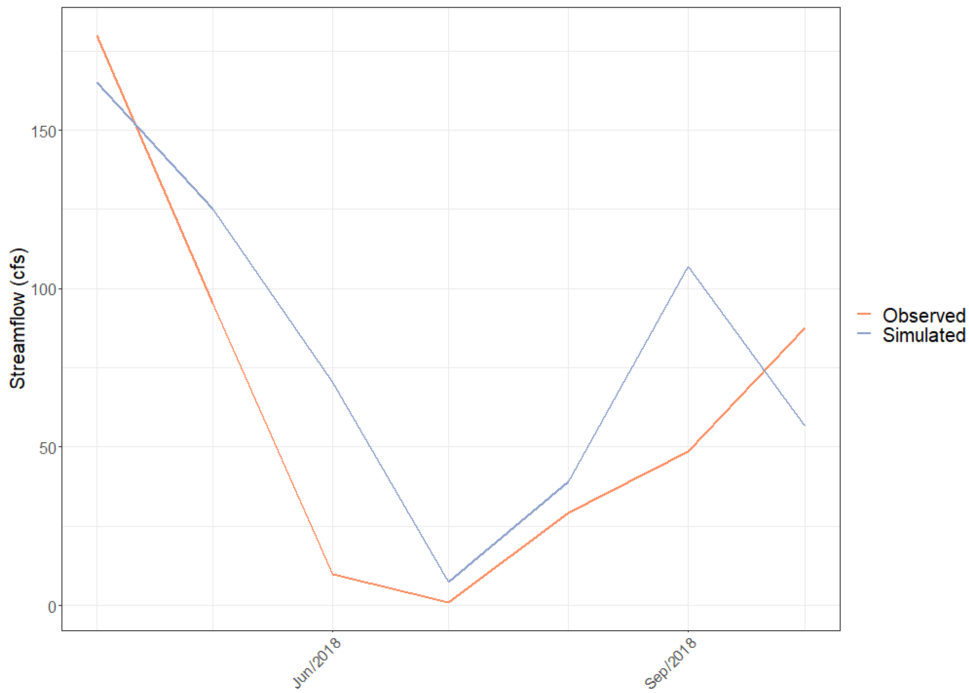

Figure A-18. Monthly streamflow calibration plot for WDNR site ID 10029954 (Kewaunee River at Hillside Rd.).

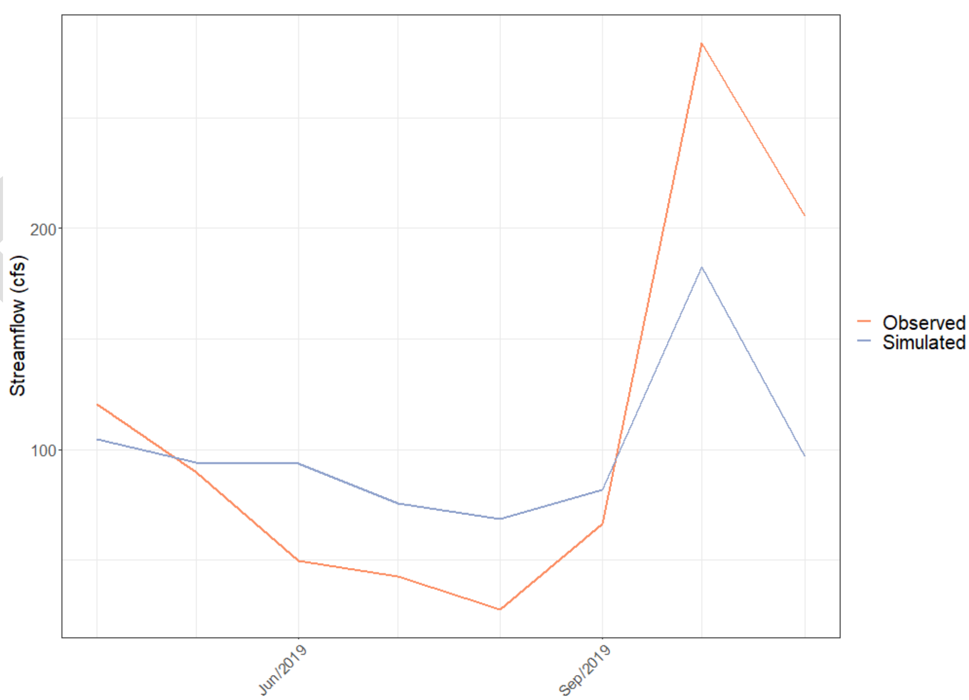

Figure A-19. Monthly streamflow calibration plot for WDNR site ID 10039440 (Sheboygan River at Palm Tree Rd.).

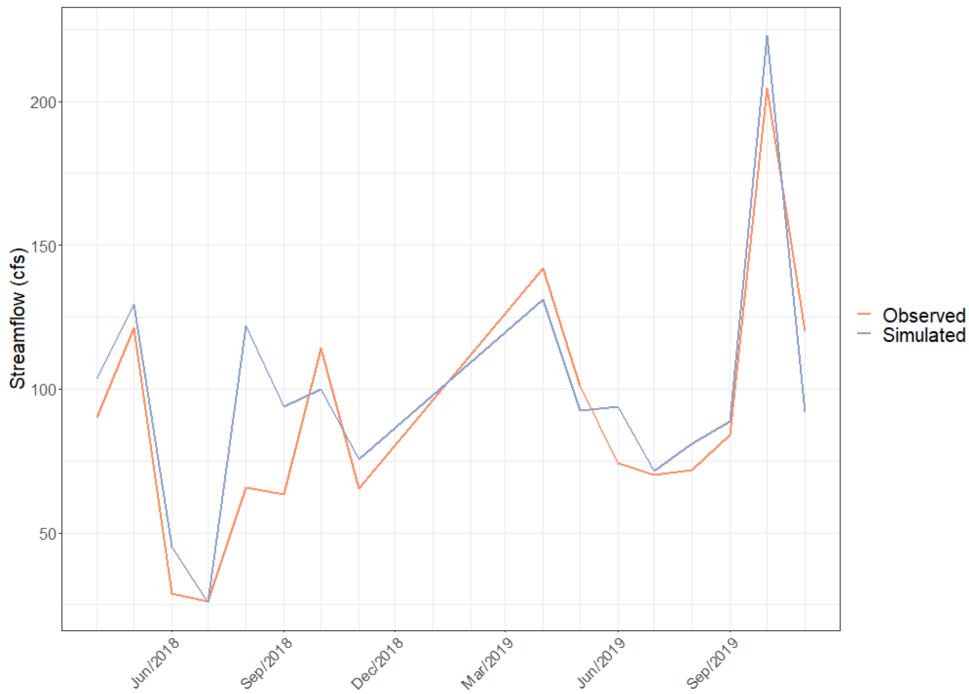

Figure A-20. Monthly streamflow calibration for WDNR site ID 10049358 (Mullet River at Sumac Rd.).

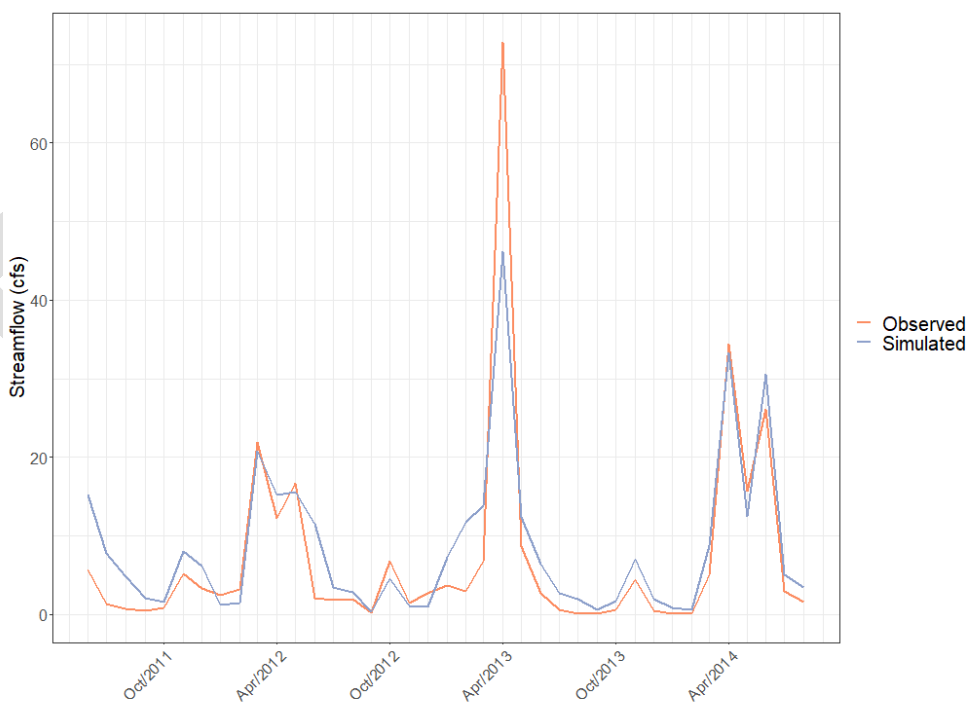

Figure A-21. Monthly streamflow calibration plot for USGS site ID 040854592 (Fisher Creek at Howards Grove, WI).

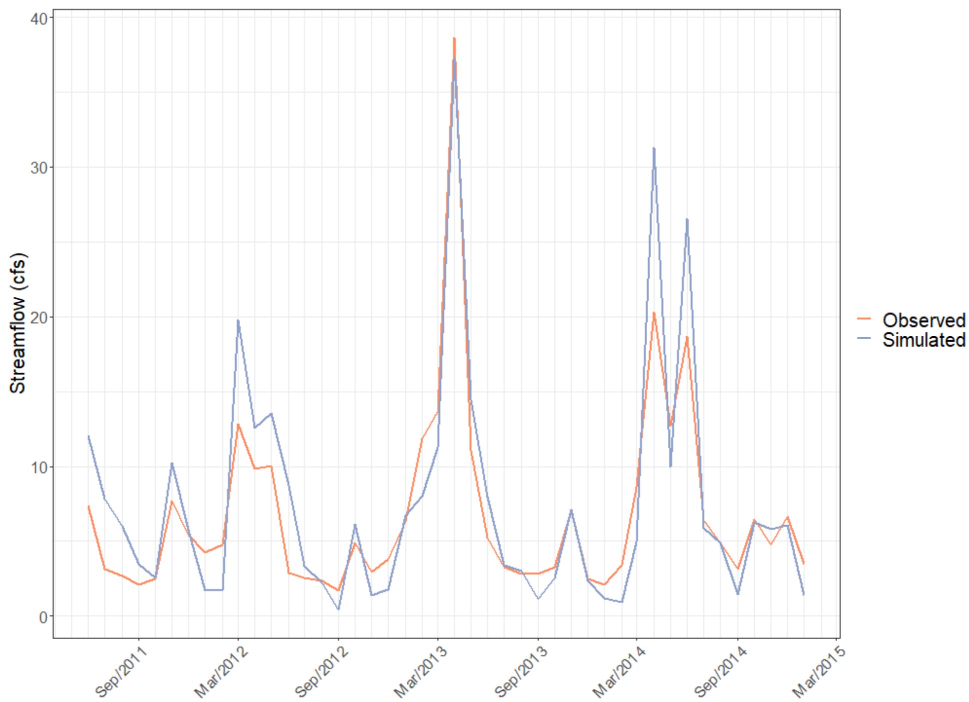

Figure A-22. Monthly streamflow calibration plot for site ID 040857005 (Otter Creek at Willow Road Near Plymouth, WI).

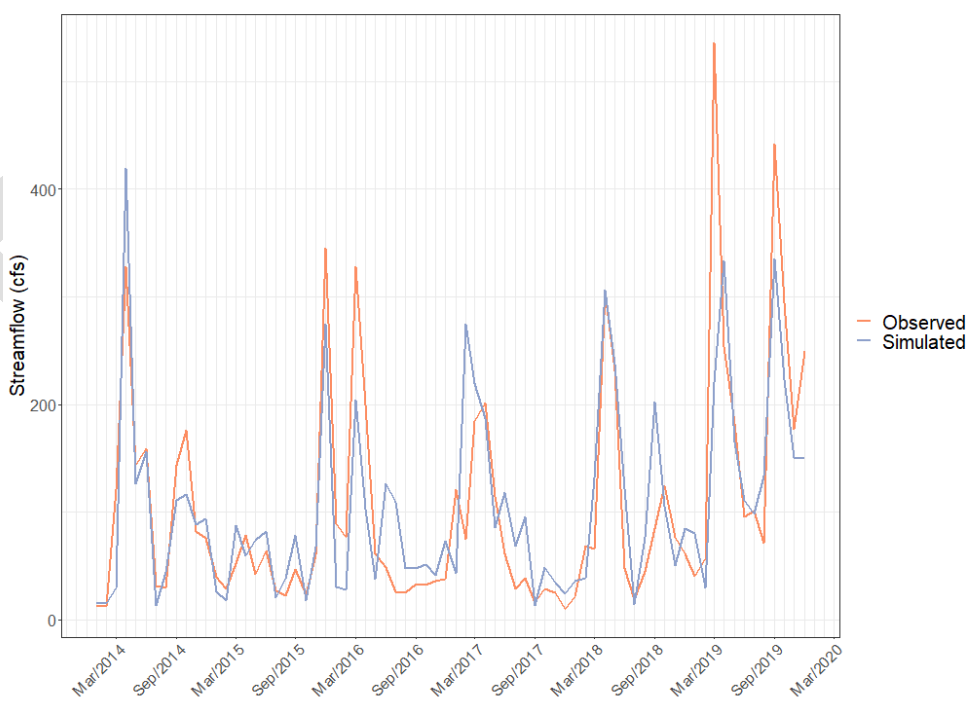

Figure A-23. Monthly streamflow validation plot for USGS site ID 04085200 (Kewaunee River Near Kewaunee, WI).

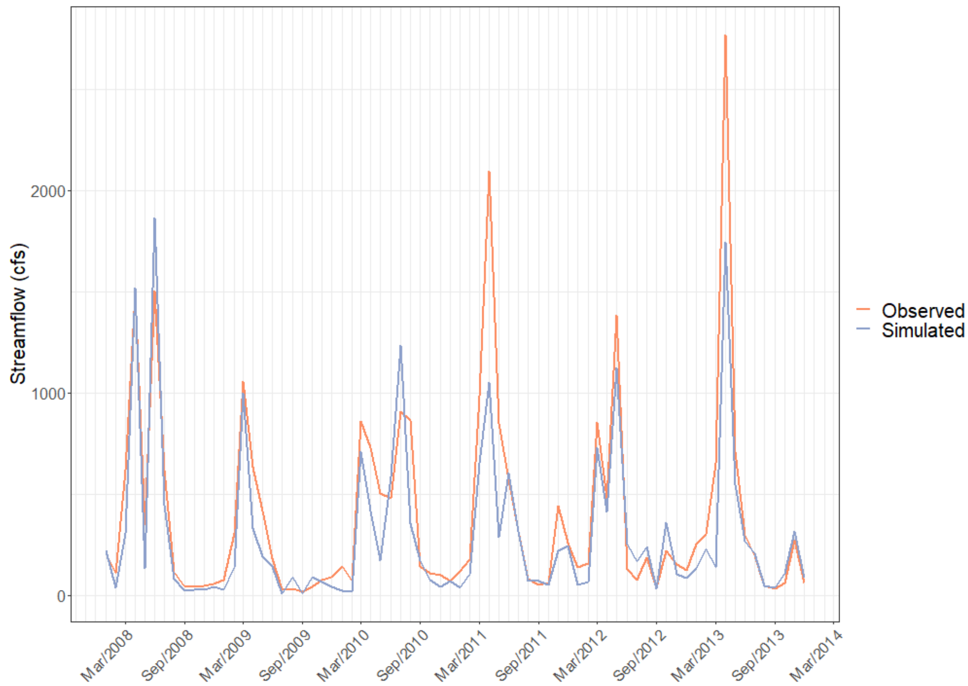

Figure A-24. Monthly streamflow validation plot for USGS site ID 04085427 (Manitowoc River at Manitowoc, WI).

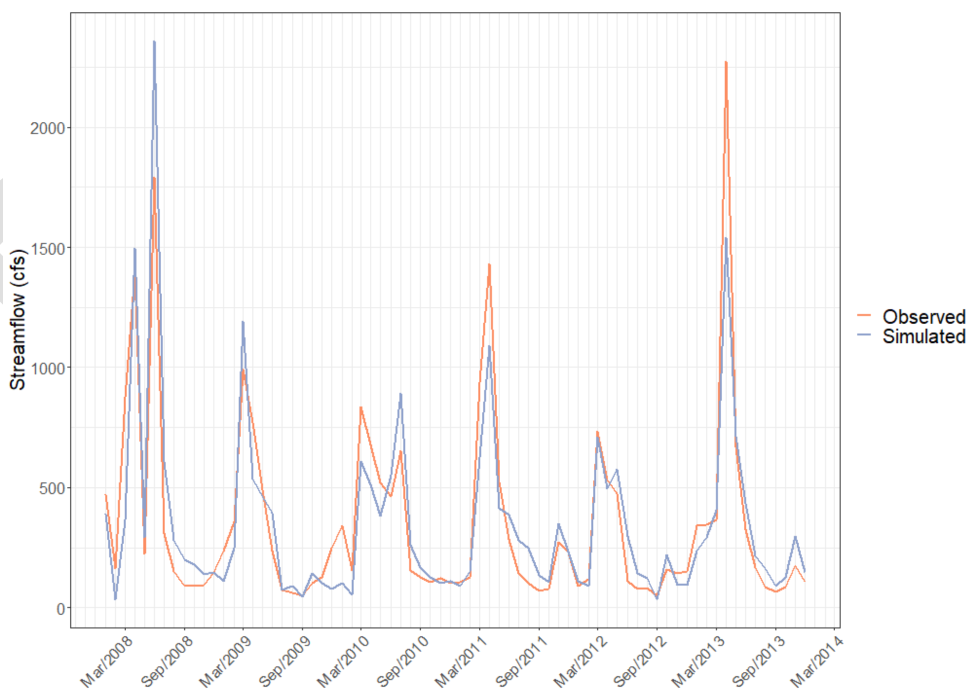

Figure A-25. Monthly streamflow validation plot for USGS site ID 04086000 (Sheboygan River at Sheboygan, WI).

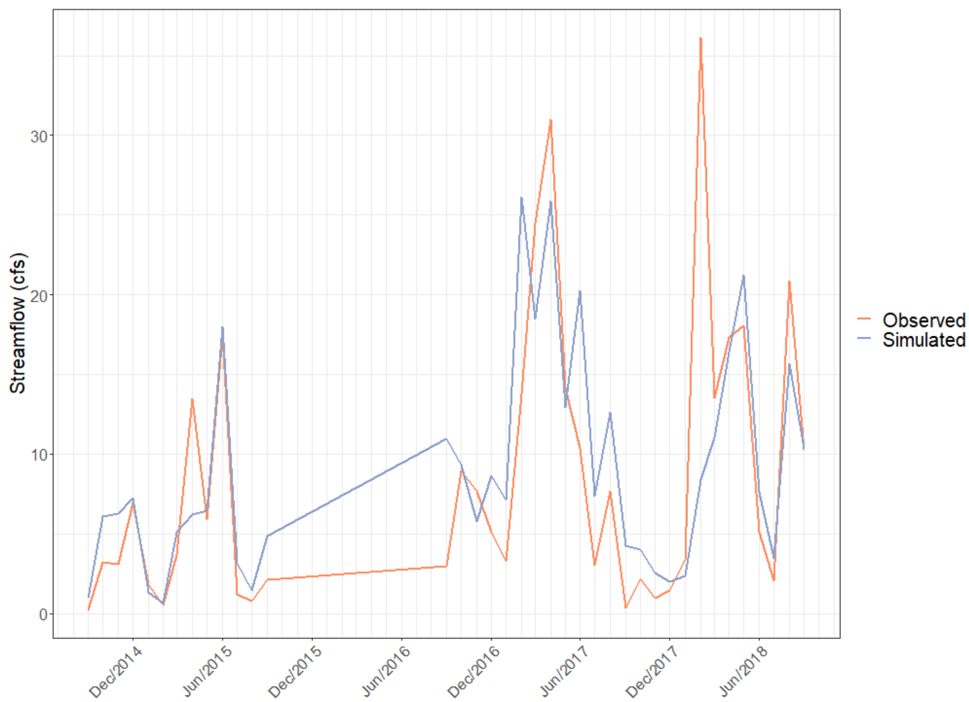

Figure A-26. Monthly streamflow validation plot for USGS site ID 040854592 (Fisher Creek at Howards Grove, WI).

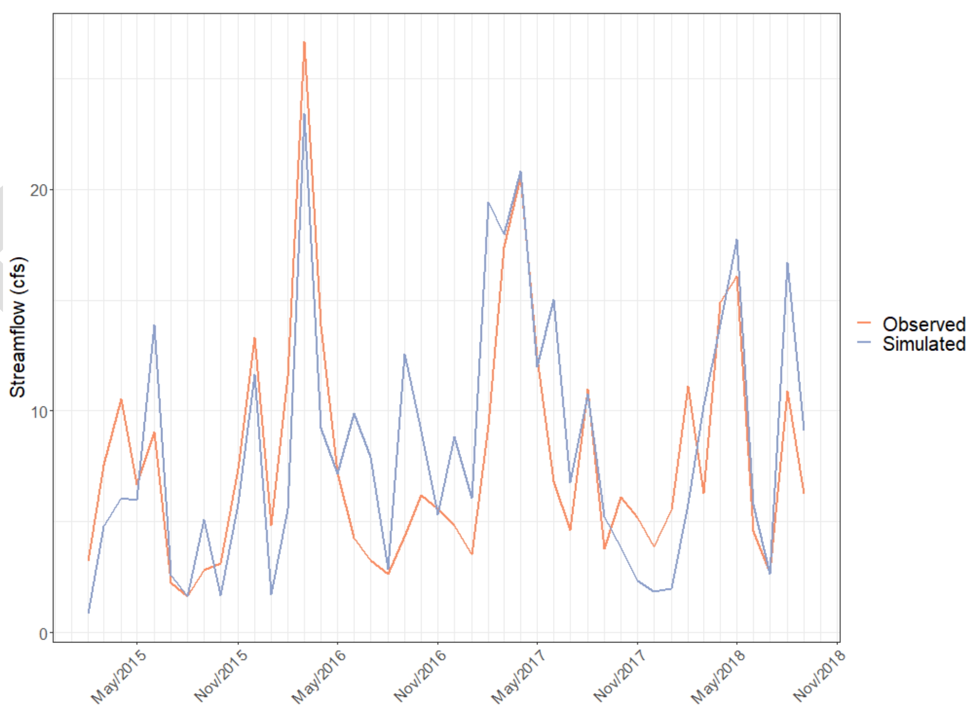

Figure A-27. Monthly streamflow validation plot for USGS site ID 040857005 (Otter Creek at Willow Road Near Plymouth, WI).

Appendix B. Sediment Calibration and Validation Time Series Plots

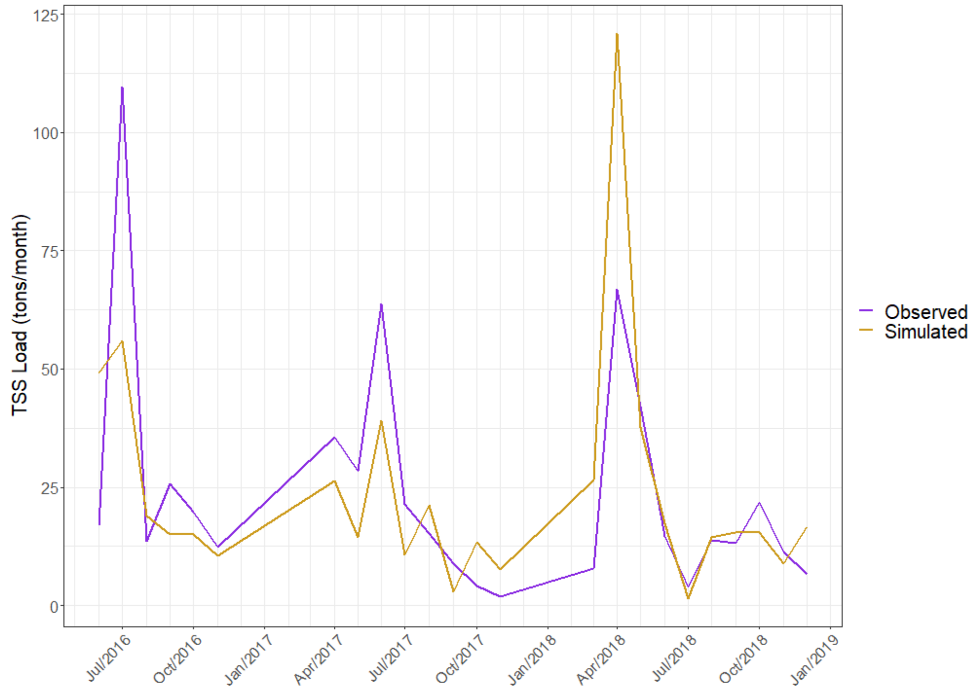

Figure B-1. Monthly sediment calibration plot for WDNR site ID 153027 (Ahnapee River at CTH J).

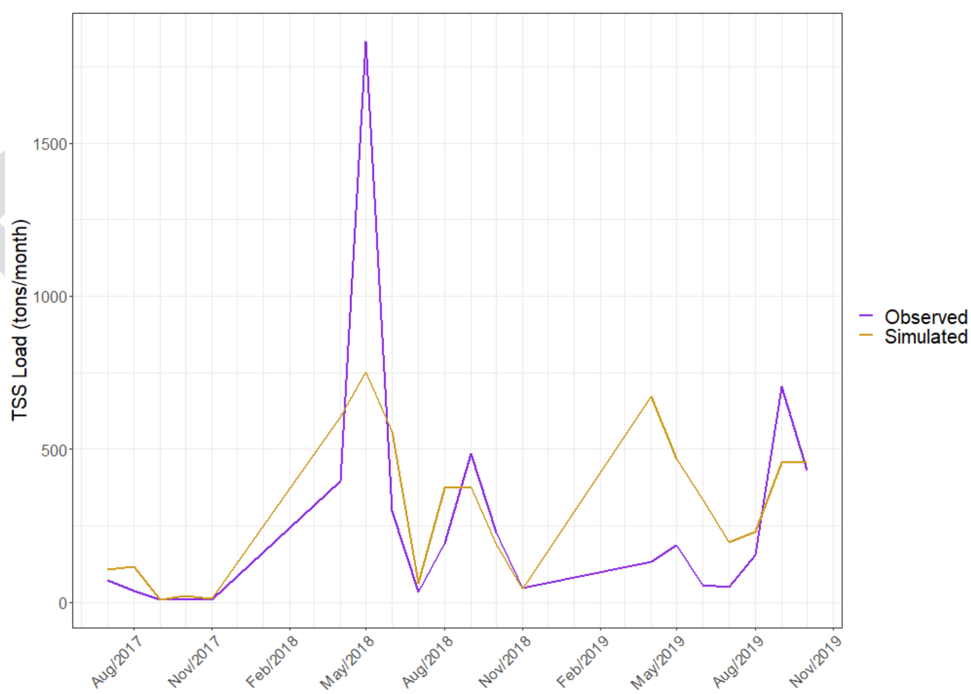

Figure B-2. Monthly sediment calibration plot for WDNR site ID 363313 (Branch River at Branch River Rd.).

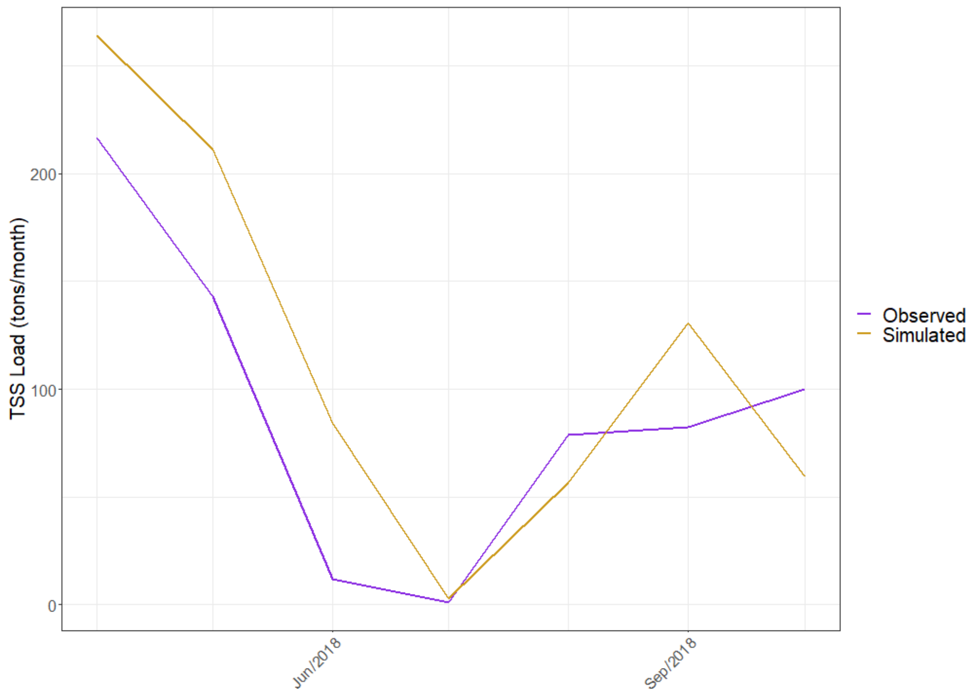

Figure B-3. Monthly sediment calibration plot for WDNR site ID 10029482 (Kewaunee River at Hillside Rd.).

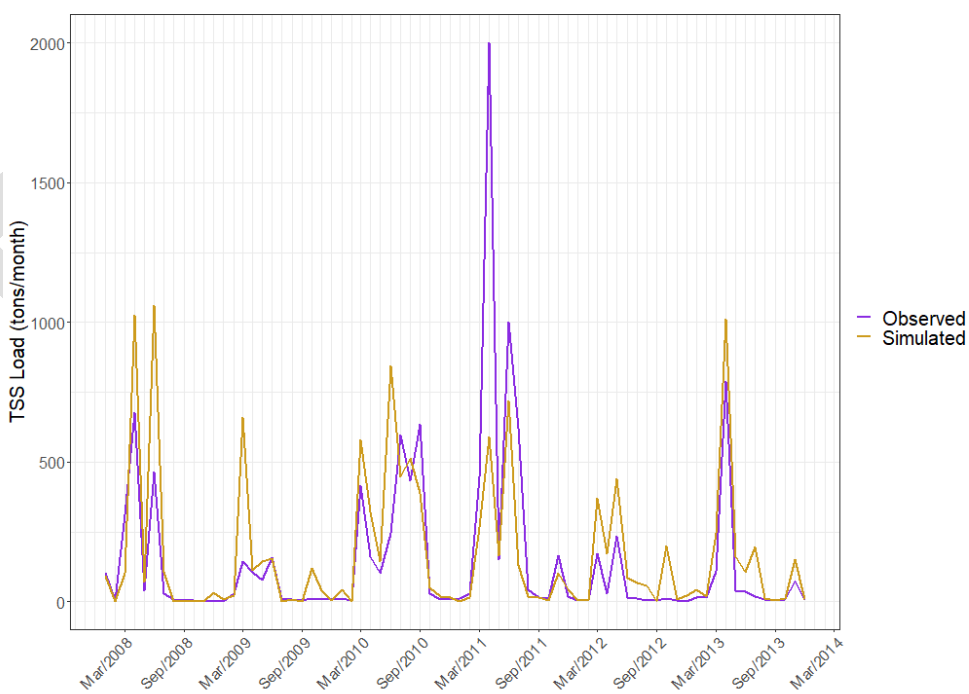

Figure B-4. Monthly sediment calibration plot for USGS site ID 04085200 (Kewaunee River Near Kewaunee, WI).

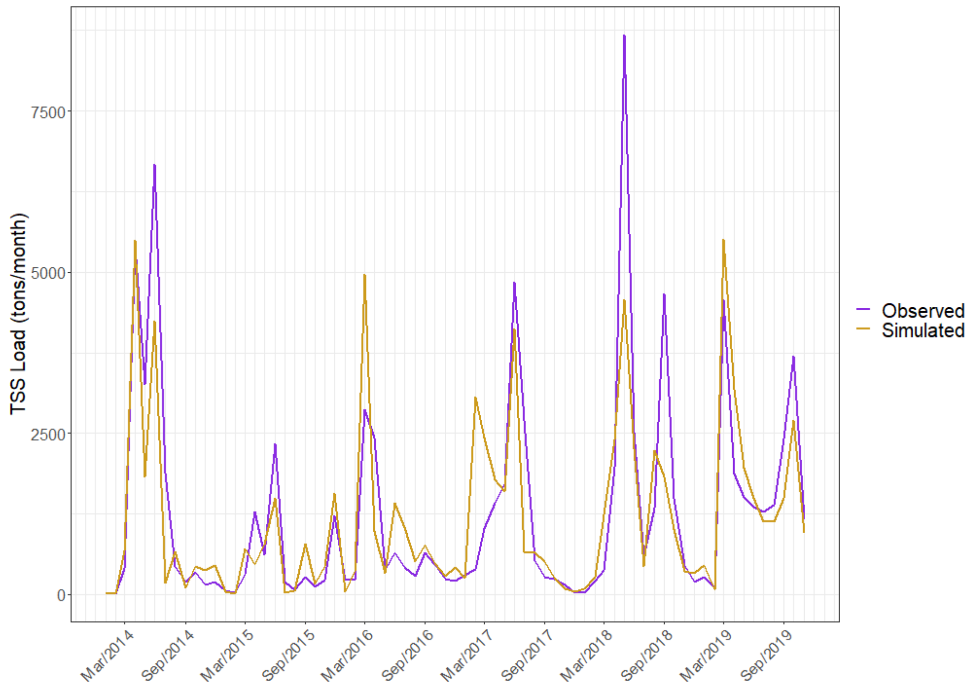

Figure B-5. Monthly sediment calibration plot for USGS site ID 04085427 (Manitowoc River at Manitowoc, WI).

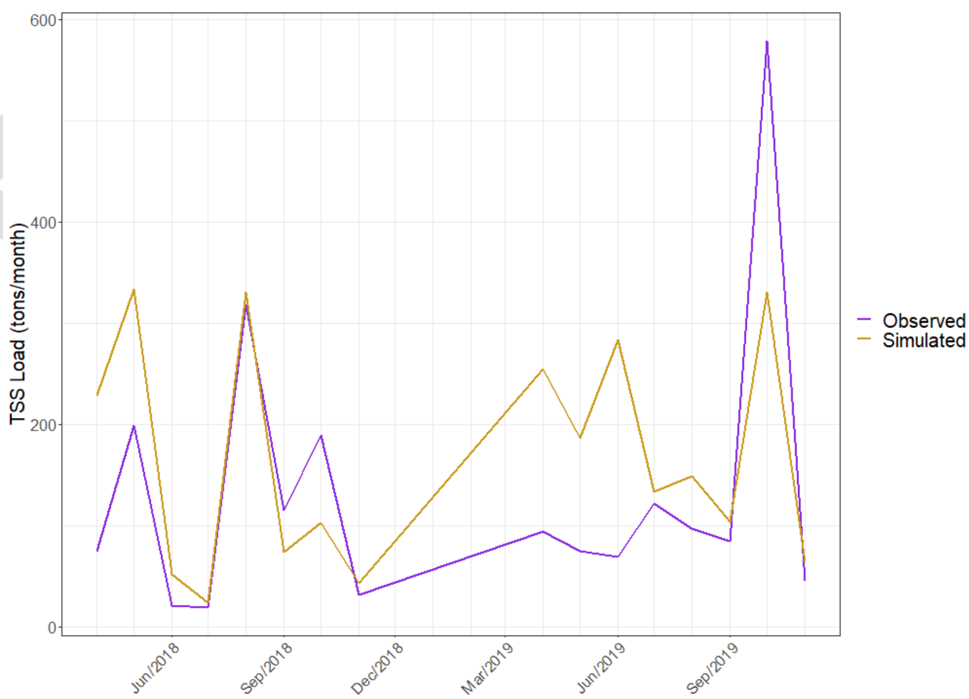

Figure B-6. Monthly sediment calibration plot for WDNR site ID 10049358 (Mullet River at Sumac Rd.).

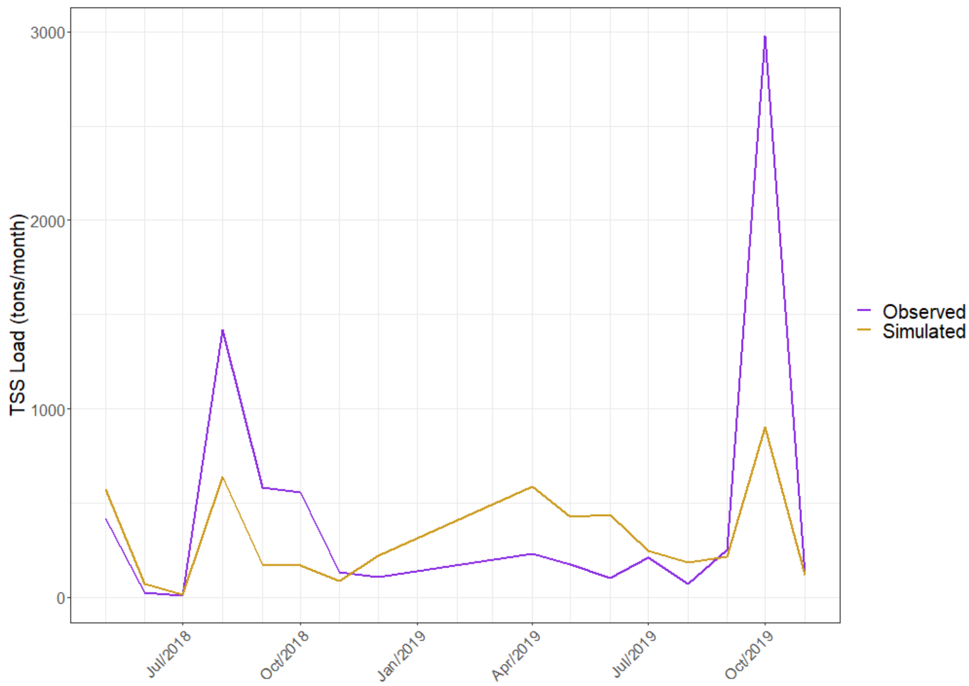

Figure B-7. Monthly sediment calibration plot for WDNR site ID 603304 (Onion River at Ourtown Rd. 5m Bi).

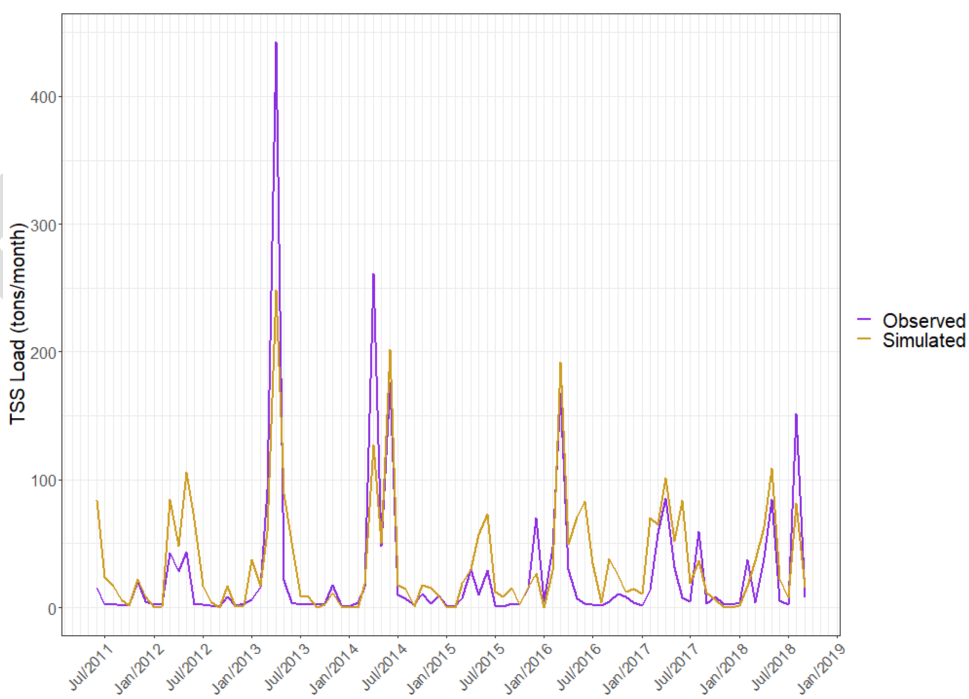

Figure B-8. Monthly sediment calibration plot for USGS site ID 040857005 (Otter Creek at Willow Road Near Plymouth, WI).

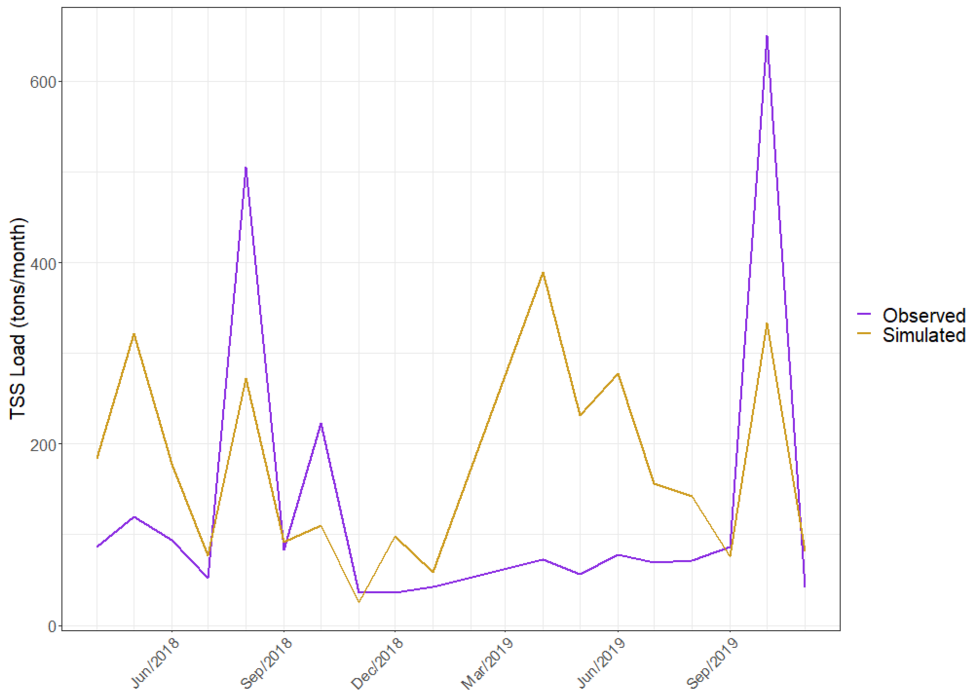

Figure B-9. Monthly sediment calibration plot for WDNR site ID 603295 (Pigeon River at Cth A -And River Rd.).

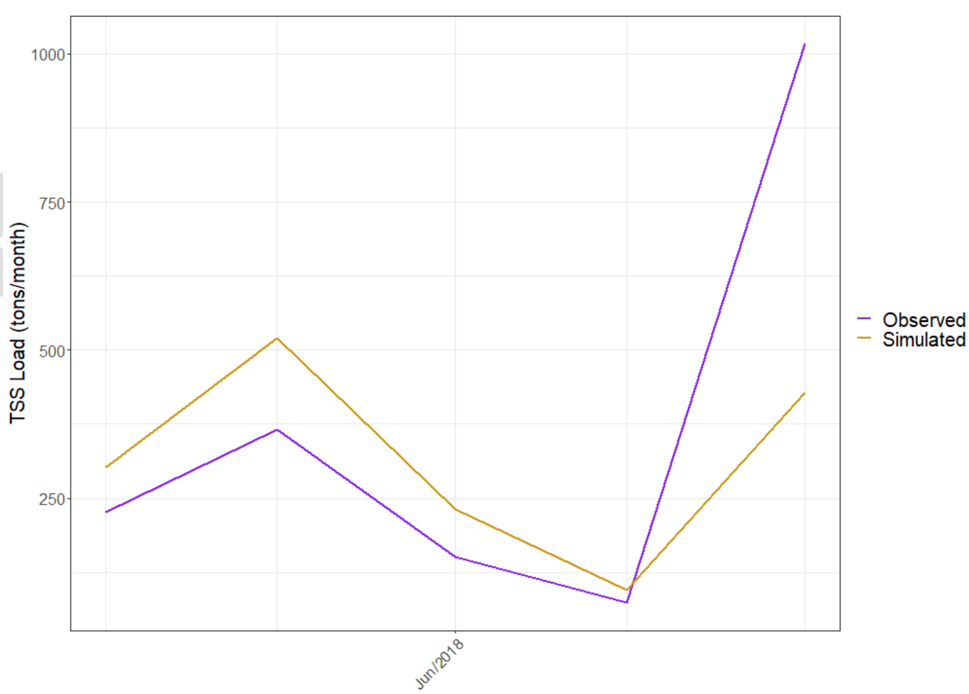

Figure B-1010. Monthly sediment calibration plot for WDNR site ID 603051 (Pigeon River at Mill Rd.).

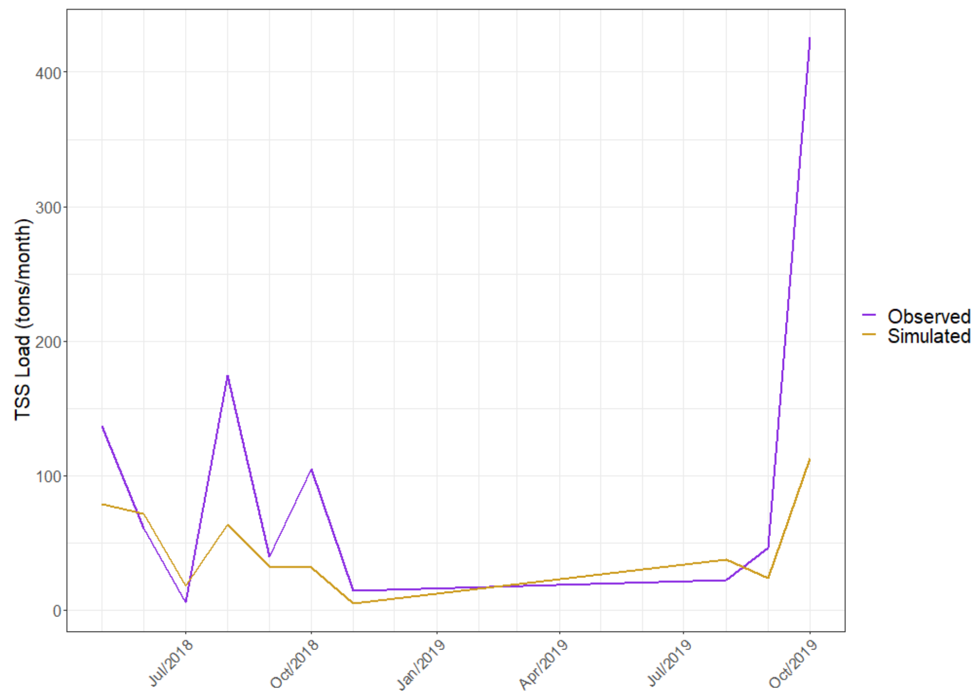

Figure B-1111. Monthly sediment calibration plot for WDNR site ID 363368 (Point Creek at Centerville Rd.).

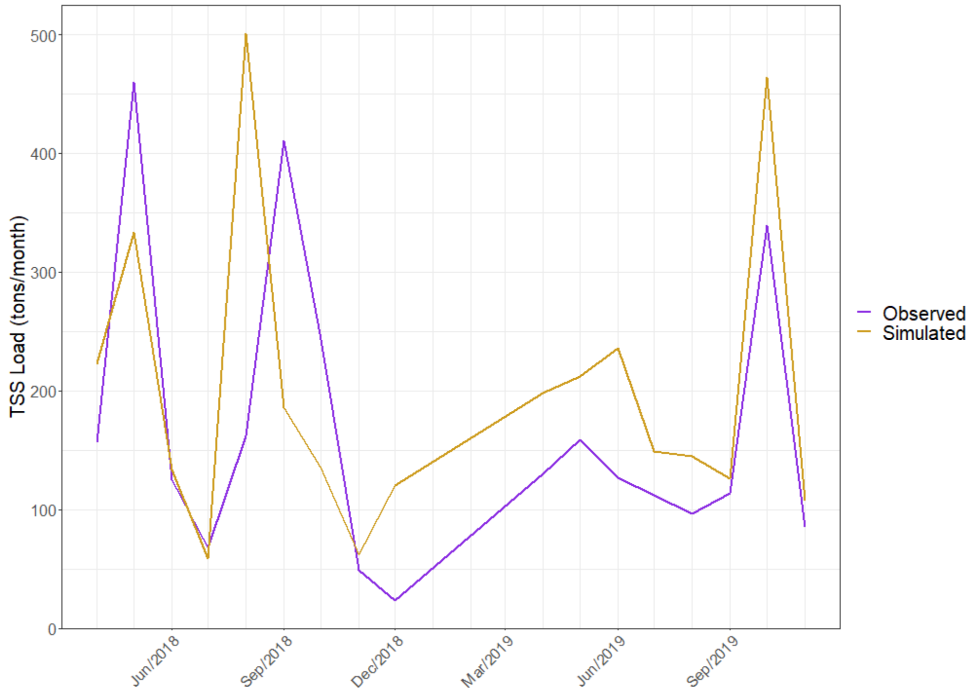

Figure B-12. Monthly sediment calibration plot for WDNR site ID 10016139 (Sheboygan R. - Hwy 57 Crossing).

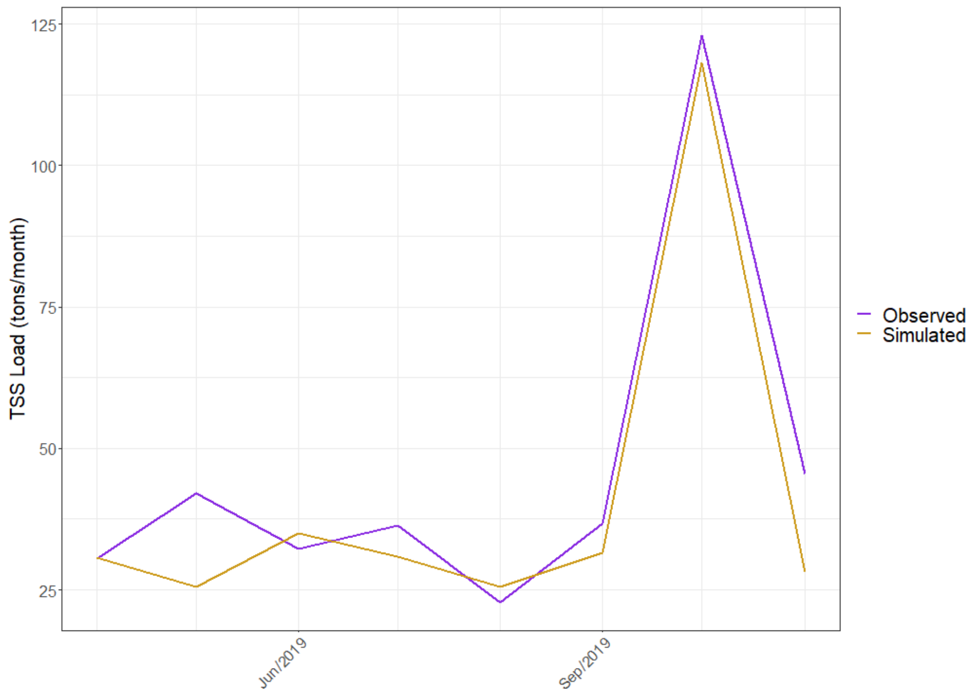

Figure B-13. Monthly sediment calibration plot for WDNR site ID 10039440 (Sheboygan River at Palm Tree Rd.).

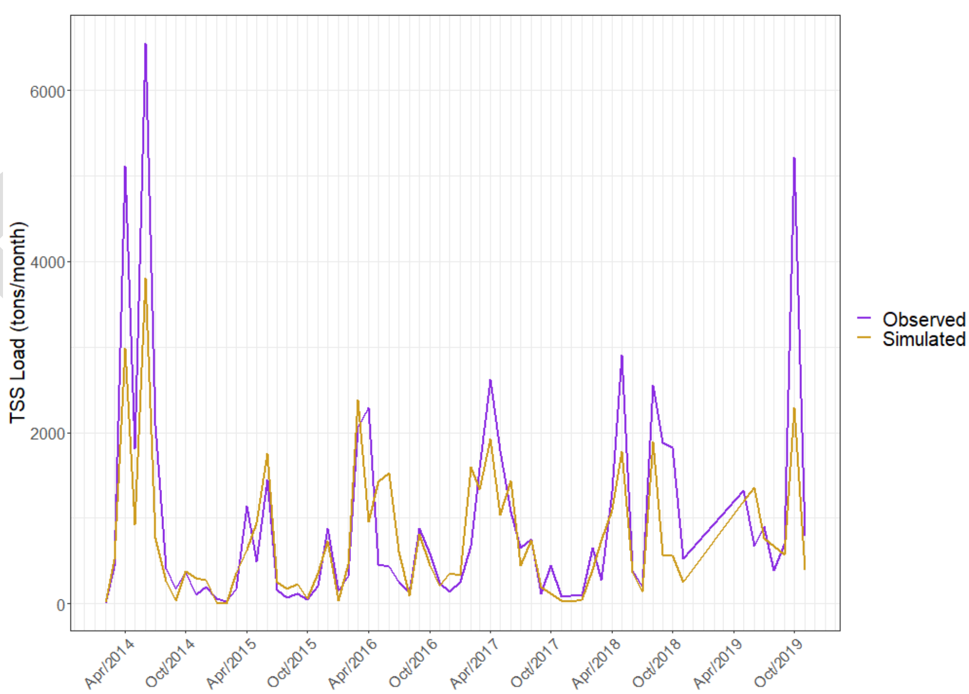

Figure B-14. Monthly sediment calibration plot for USGS site ID 04086000 (Sheboygan River at Sheboygan, WI).

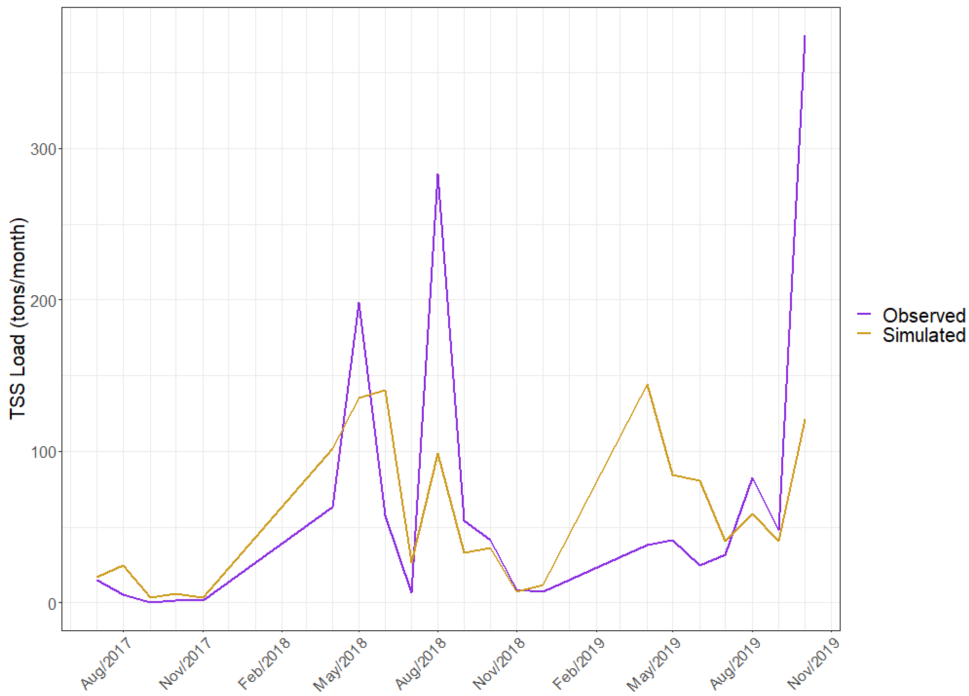

Figure B-15. Monthly sediment calibration plot for WDNR site ID 363228 (Silver Creek (Manitowoc) at Cth Ls).

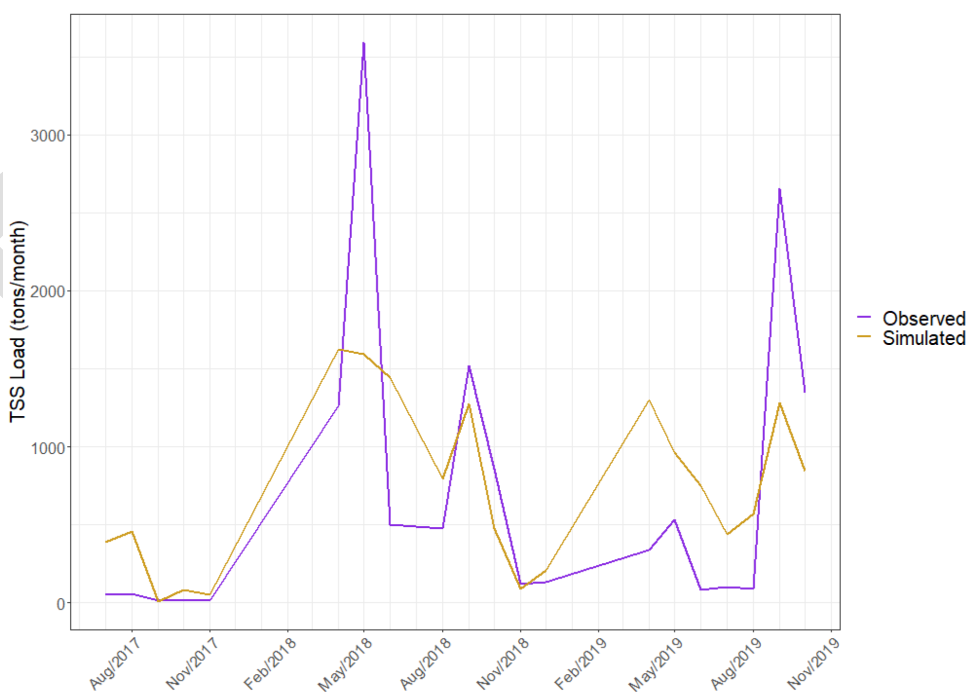

Figure B-1612. Monthly sediment calibration plot for WDNR site ID 10029482 (West Twin River at CTH V).

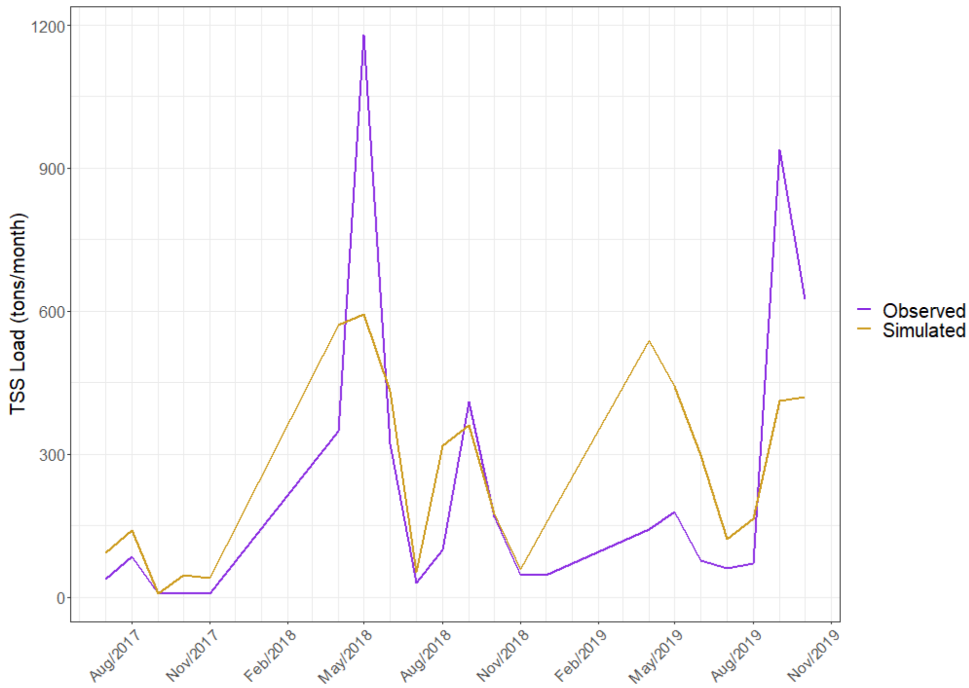

Figure B-17. Monthly sediment validation plot for WDNR site ID 10008207 (East Twin River at Steiners Corners Rd.).

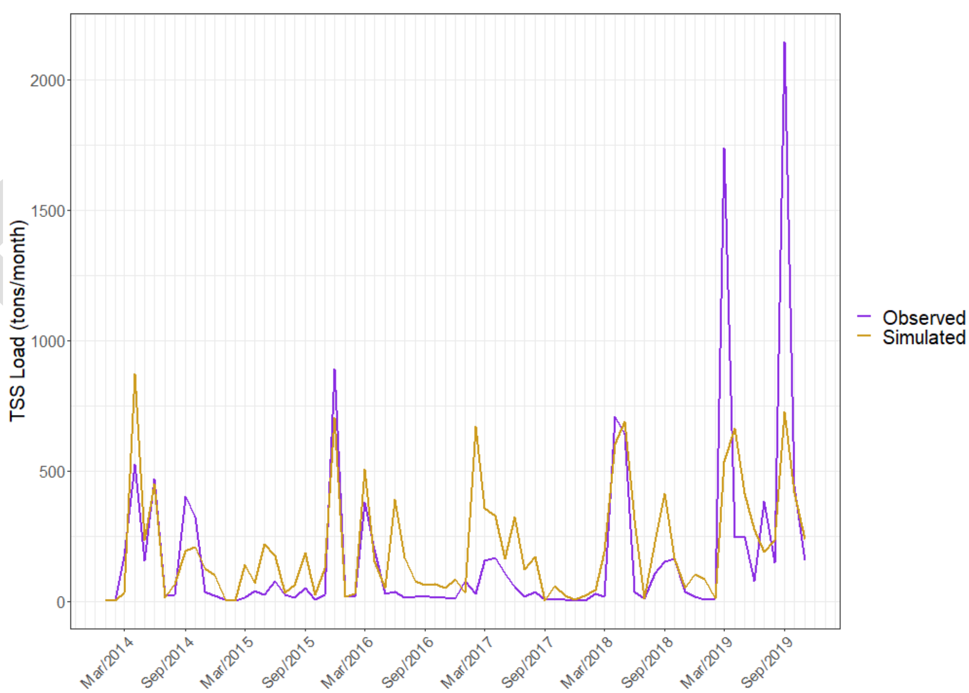

Figure B-18. Monthly sediment validation plot for USGS site ID 04085200 (Kewaunee River Near Kewaunee, WI).

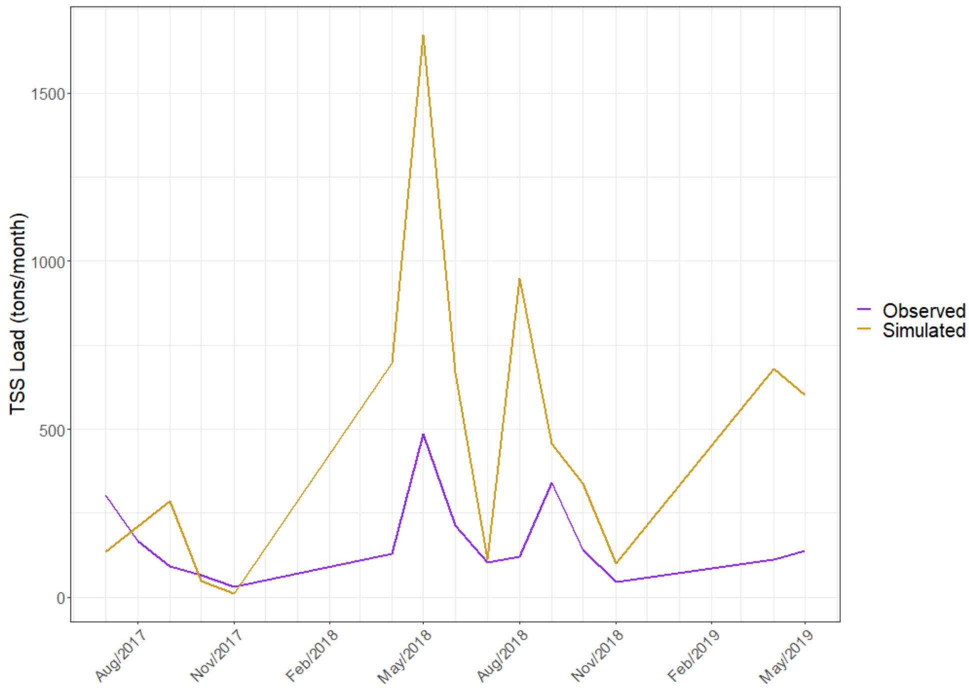

Figure B-19. Monthly sediment validation plot for WDNR site ID 363375 (Manitowoc River South Branch at Lemke Rd.).

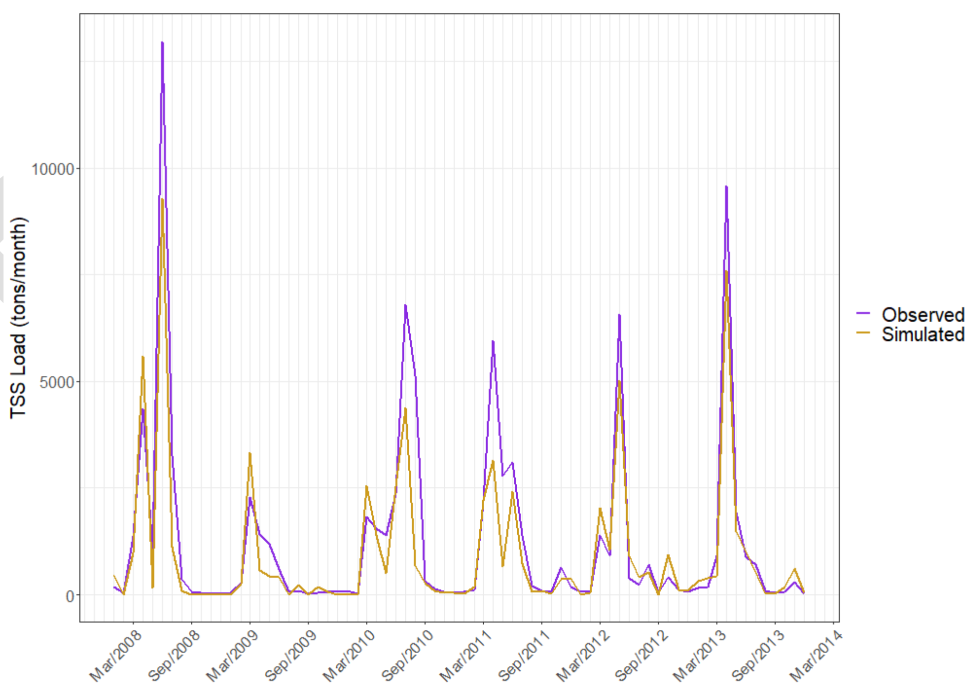

Figure B-20. Monthly sediment validation plot for USGS site ID 04085427 (Manitowoc River at Manitowoc, WI).

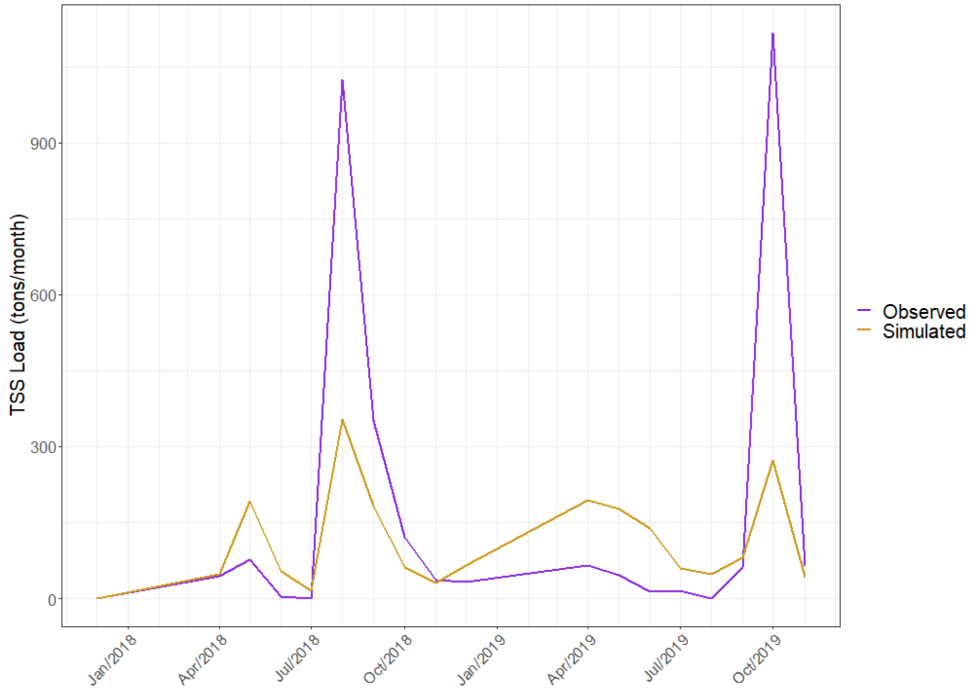

Figure B-21. Monthly sediment validation plot for WDNR site ID 463070 (Sauk Creek at Mink Ranch Rd. (Bi)).

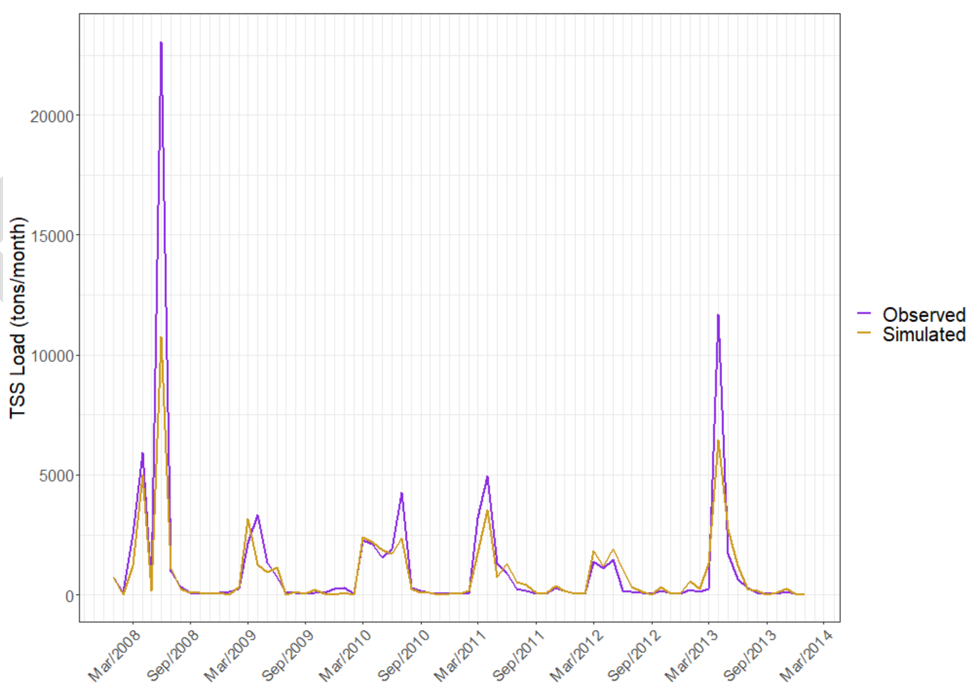

Figure B-22. Monthly sediment validation plot for USGS site ID 04086000 (Sheboygan River at Sheboygan, WI).

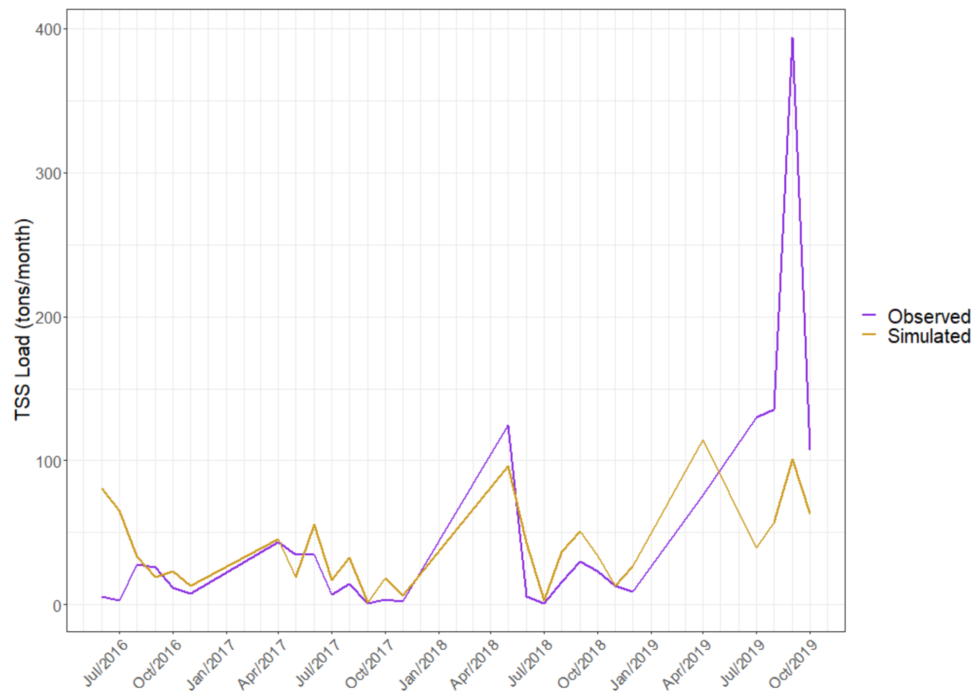

Figure B-23. Monthly sediment validation plot for WDNR site ID 10020779 (Silver Creek (Algoma) at Willow Drive).

Appendix C. Total Phosphorus Calibration and Validation Time Series Plots

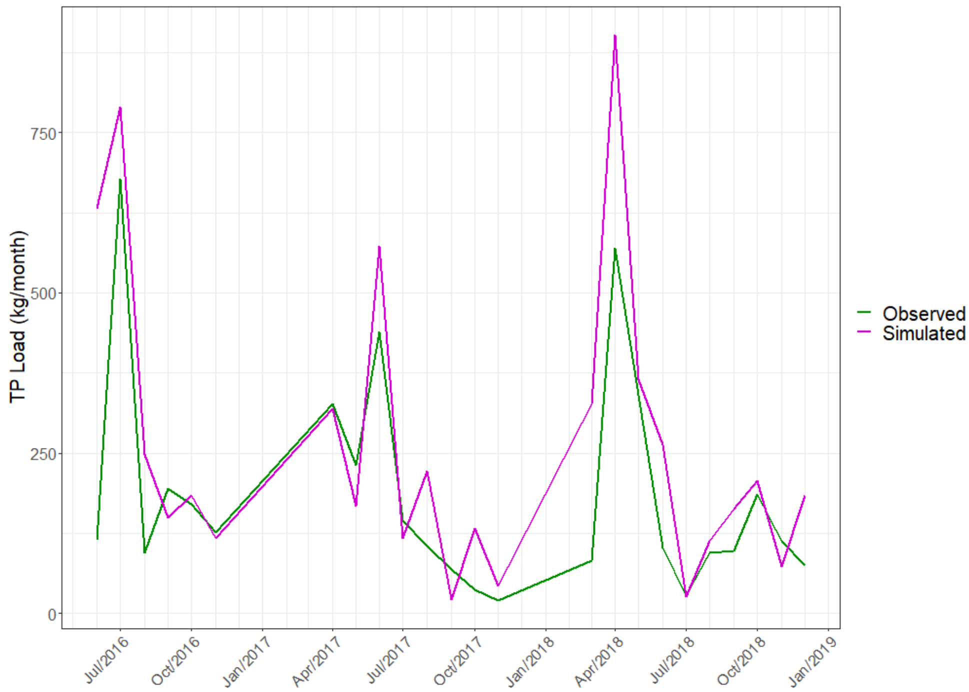

Figure C-1. Monthly total phosphorus calibration plot for WDNR site ID 153027 (Ahnapee River at CTH J).

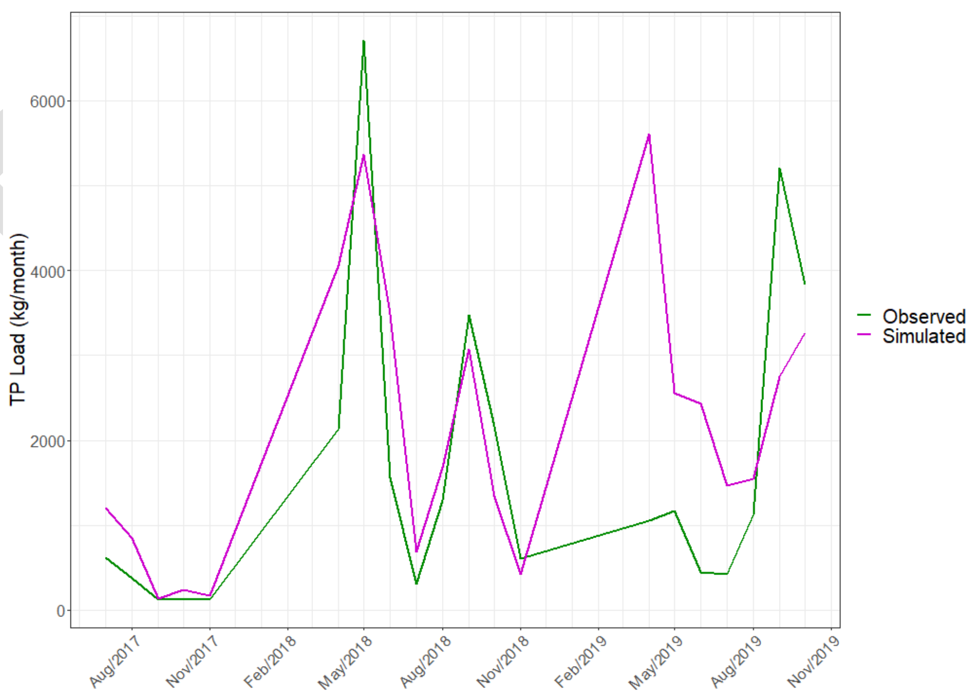

Figure C-2. Monthly total phosphorus calibration plot for WDNR site ID 363313 (Branch River at Branch River Rd.)

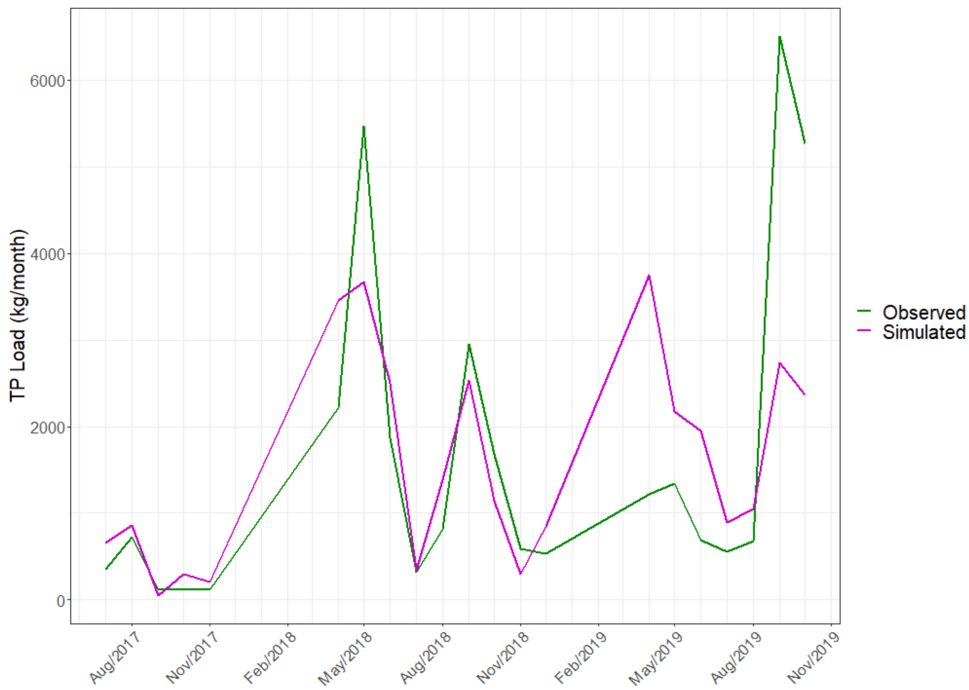

Figure C-3. Monthly total phosphorus calibration plot for WDNR site ID 10008207 (East Twin River at Steiners Corners Rd.).

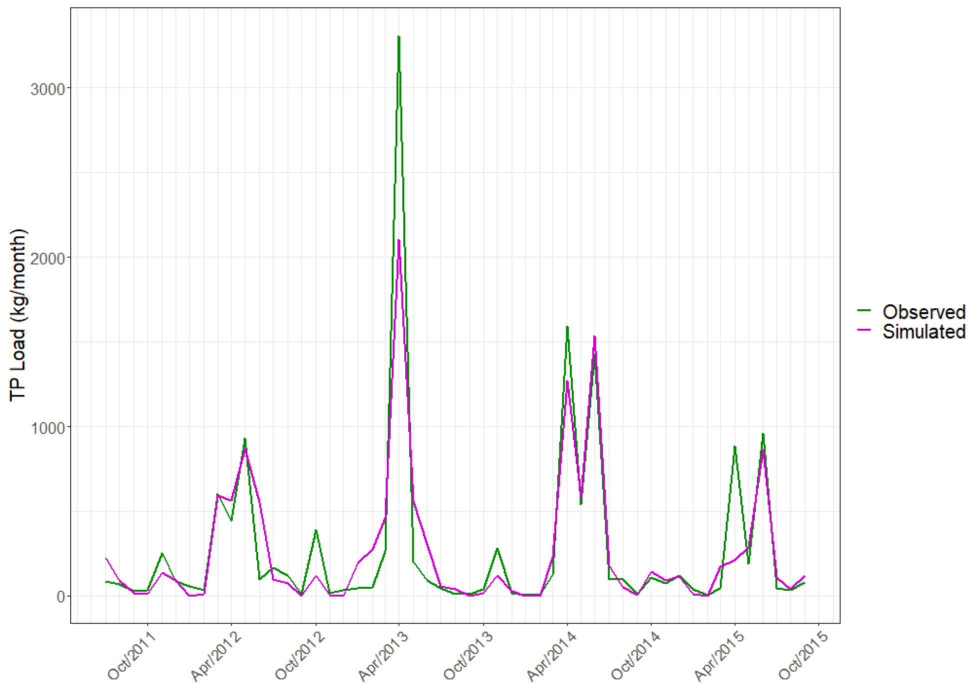

Figure C-4. Monthly total phosphorus calibration plot for USGS site ID 040854592 (Fisher Creek at Howards Grove, WI).

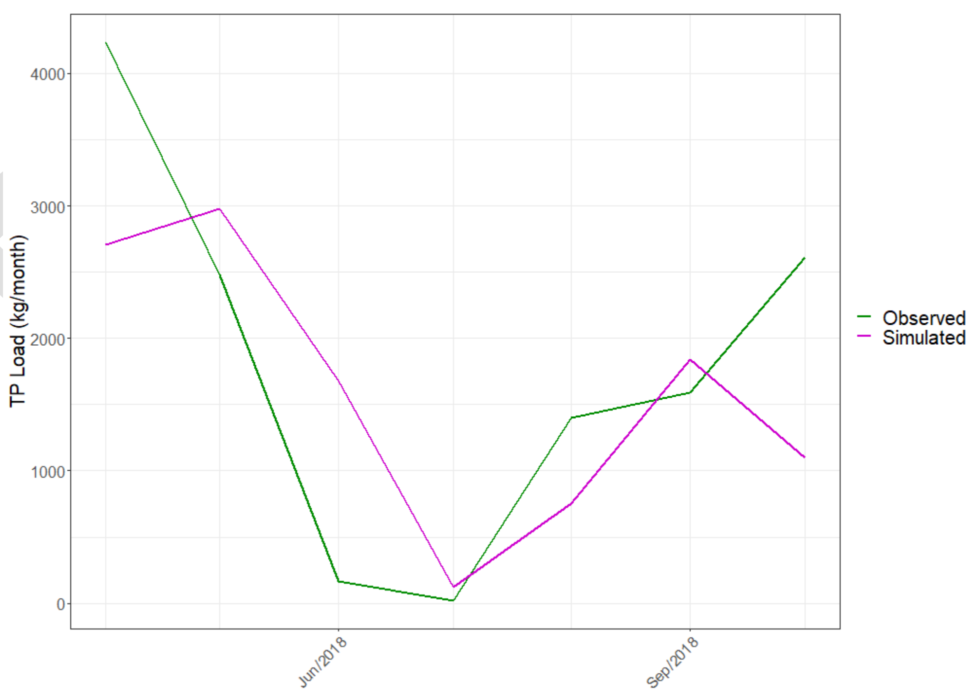

Figure C-5. Monthly total phosphorus calibration plot for WDNR site ID 10029954 (Kewaunee River at Hillside Rd.).

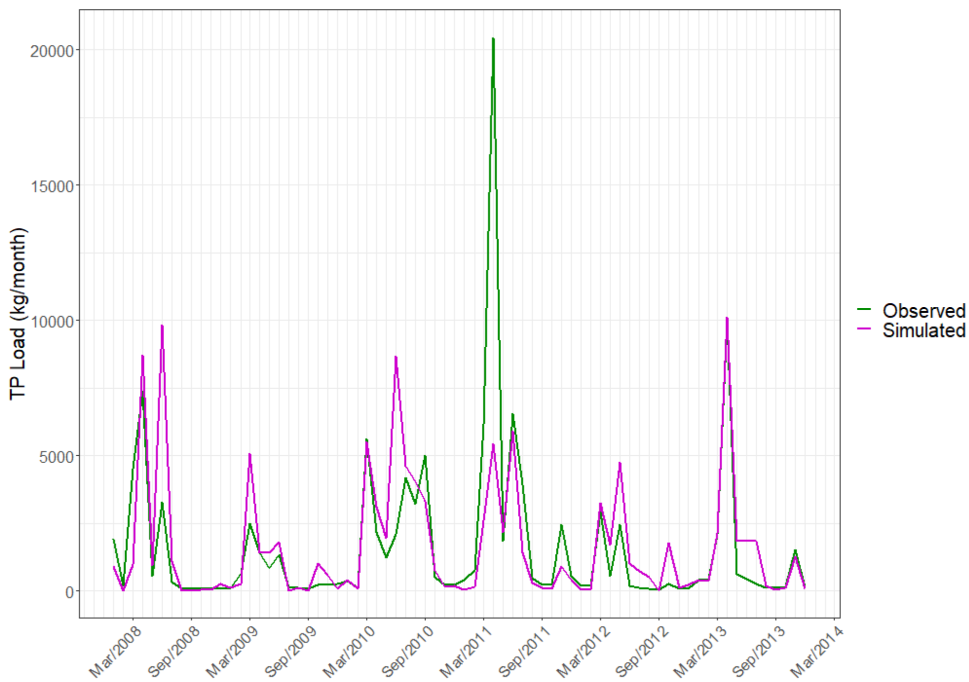

Figure C-6. Monthly total phosphorus calibration plot for USGS site ID 04085200 (Kewaunee River Near Kewaunee, WI).

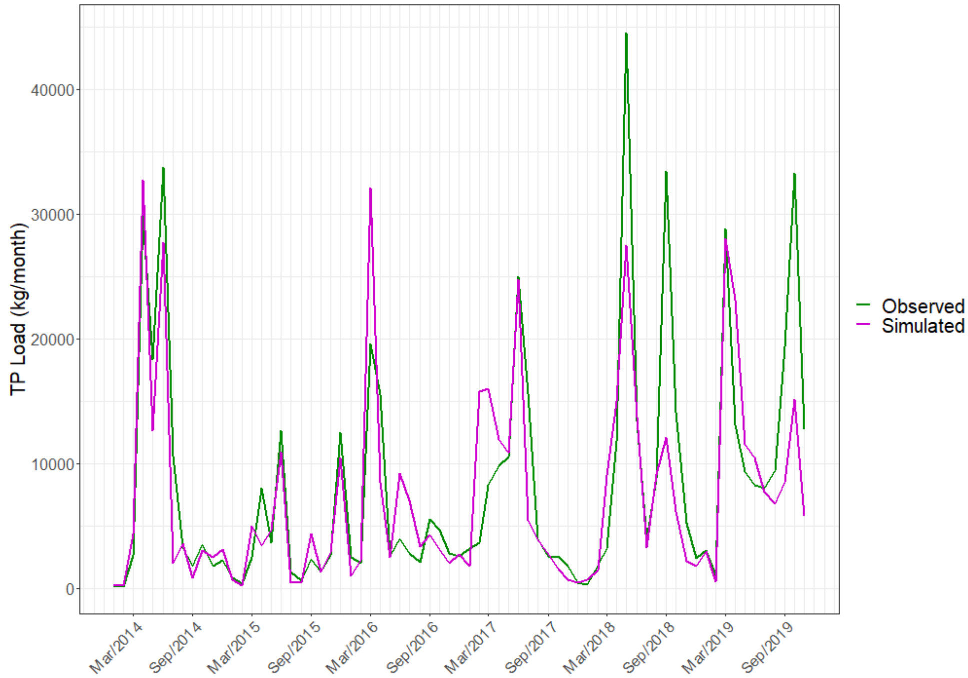

Figure C-7. Monthly total phosphorus calibration plot for USGS site ID 04085427 (Manitowoc River at Manitowoc, WI).

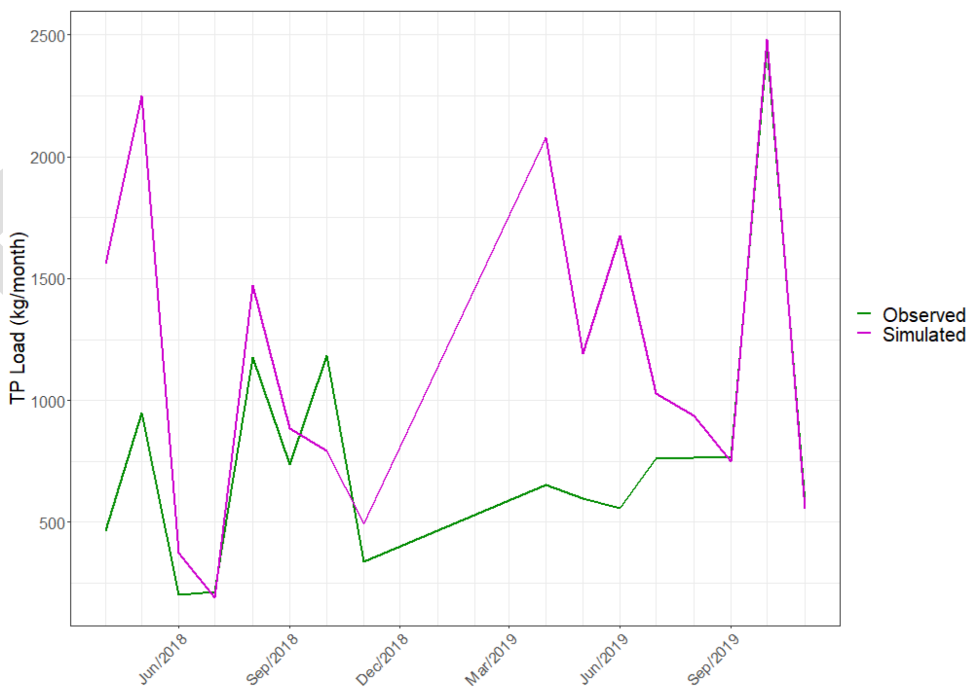

Figure C-813. Monthly total phosphorus calibration plot for WDNR site ID 10049358 (Mullet River at Sumac Rd.).

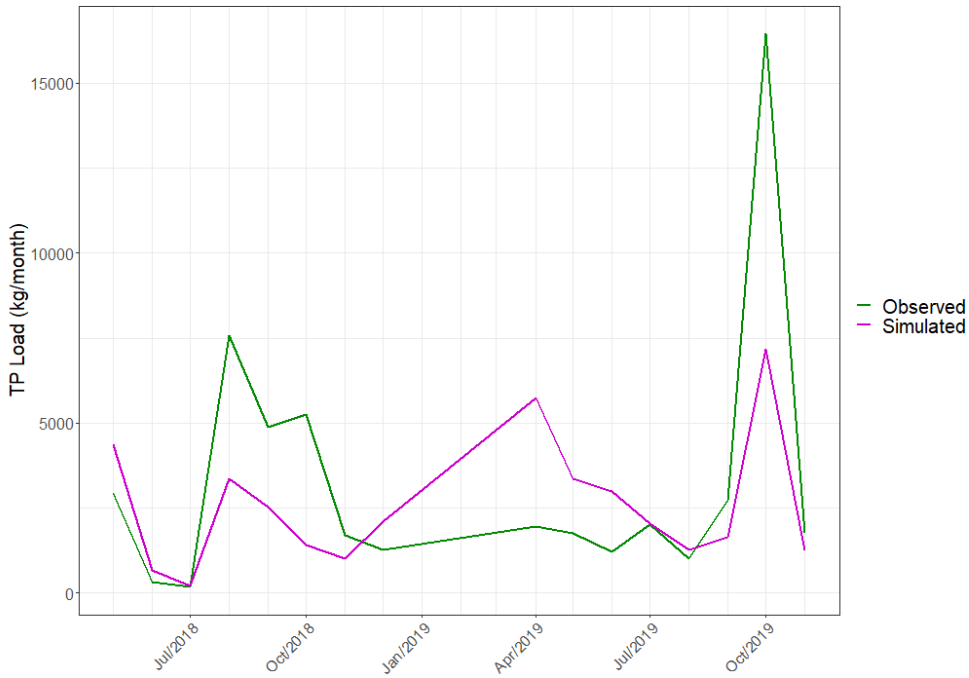

Figure C-9. Monthly total phosphorus calibration plot for WDNR site ID 603304 (Onion River at Ourtown Rd. 5m Bi).

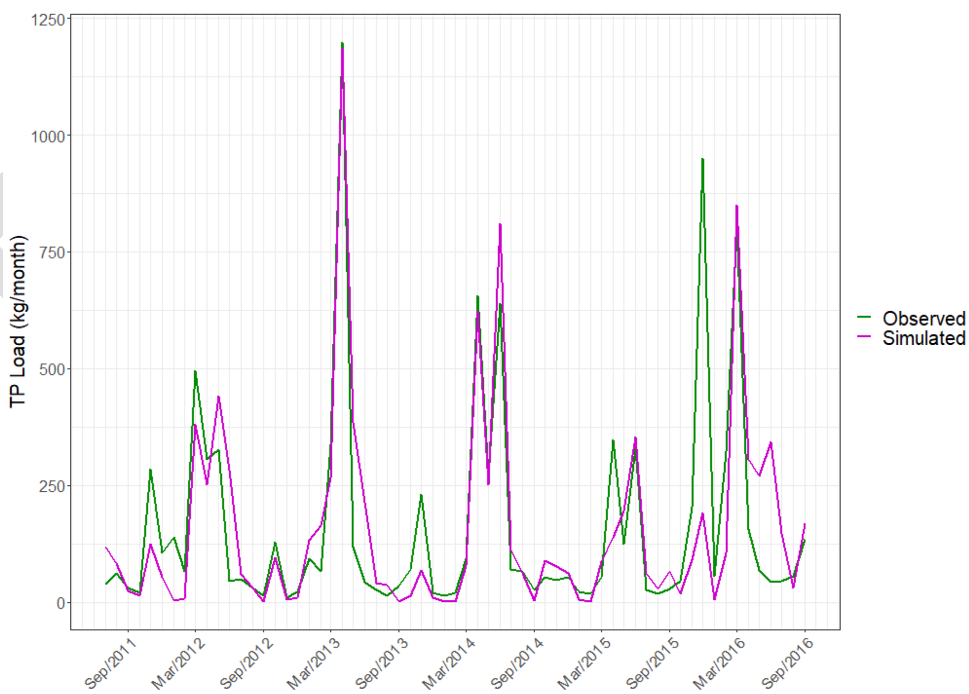

Figure C-10. Monthly total phosphorus calibration plot for USGS site ID 040857005 (Otter Creek at Willow Road Near Plymouth, WI).

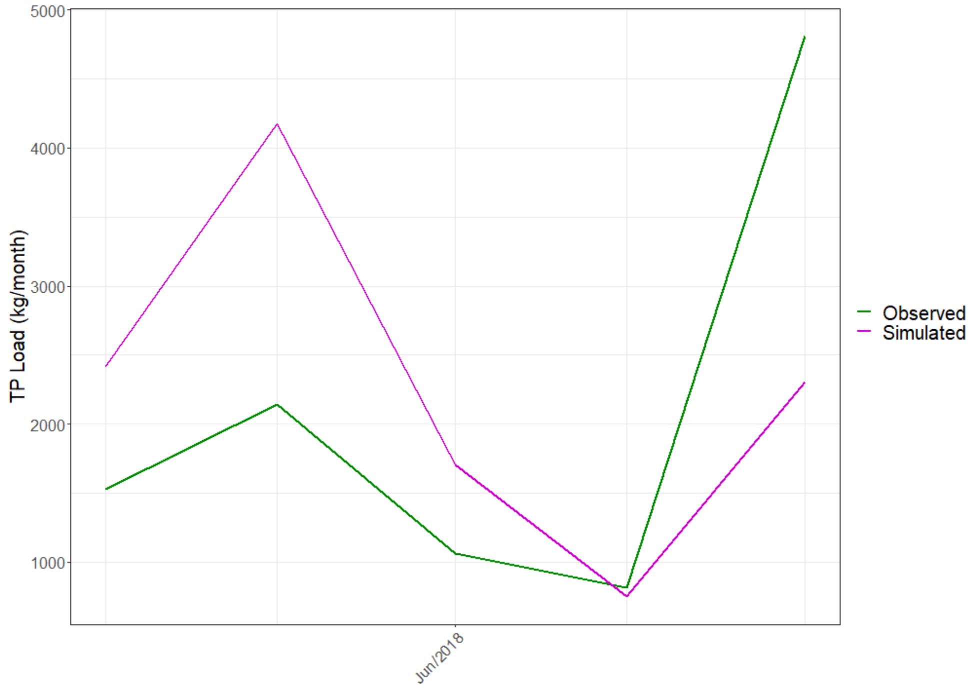

Figure C-11. Monthly total phosphorus calibration plot for WDNR site ID 603051 (Pigeon River at Mill Rd.).

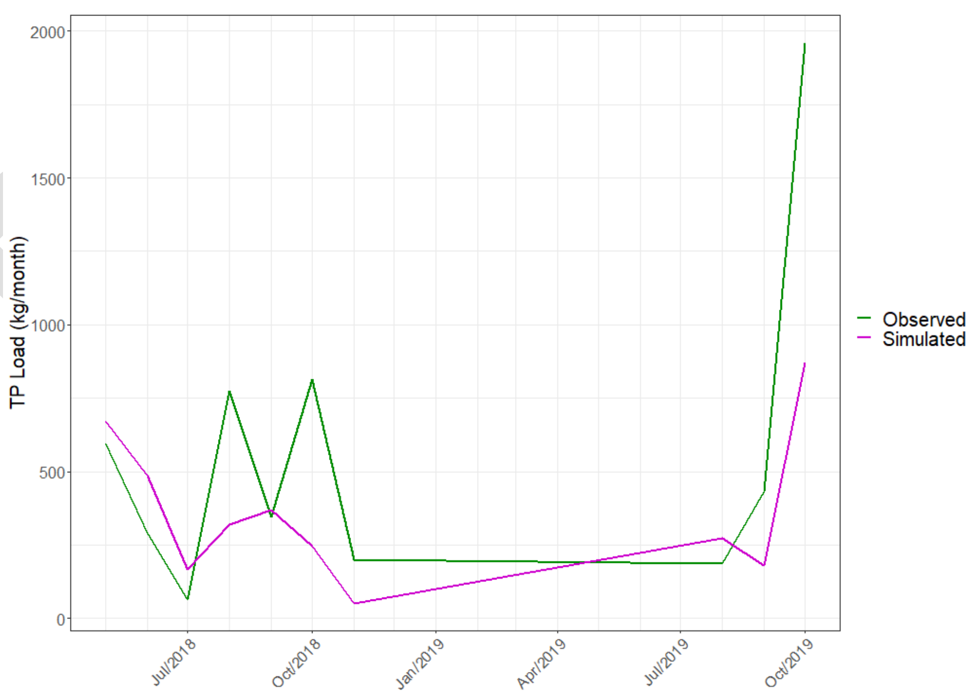

Figure C-12. Monthly total phosphorus calibration plot for WDNR site ID 363368 (Point Creek at Centerville Rd.).

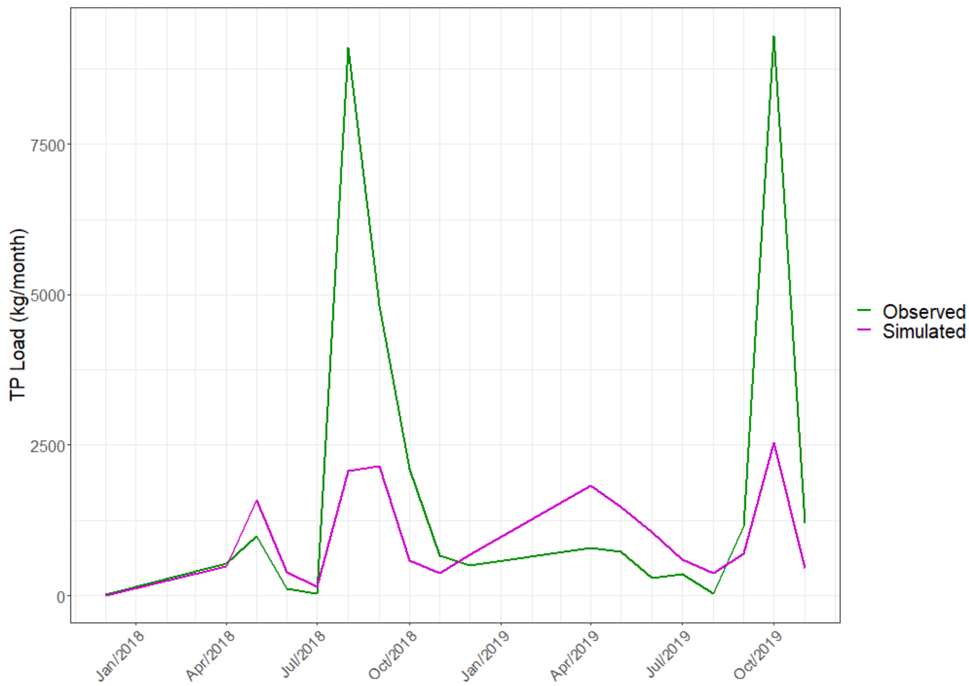

Figure C-13. Monthly total phosphorus calibration plot for WDNR site ID 463070 (Sauk Creek at Mink Ranch Rd. (Bi)).

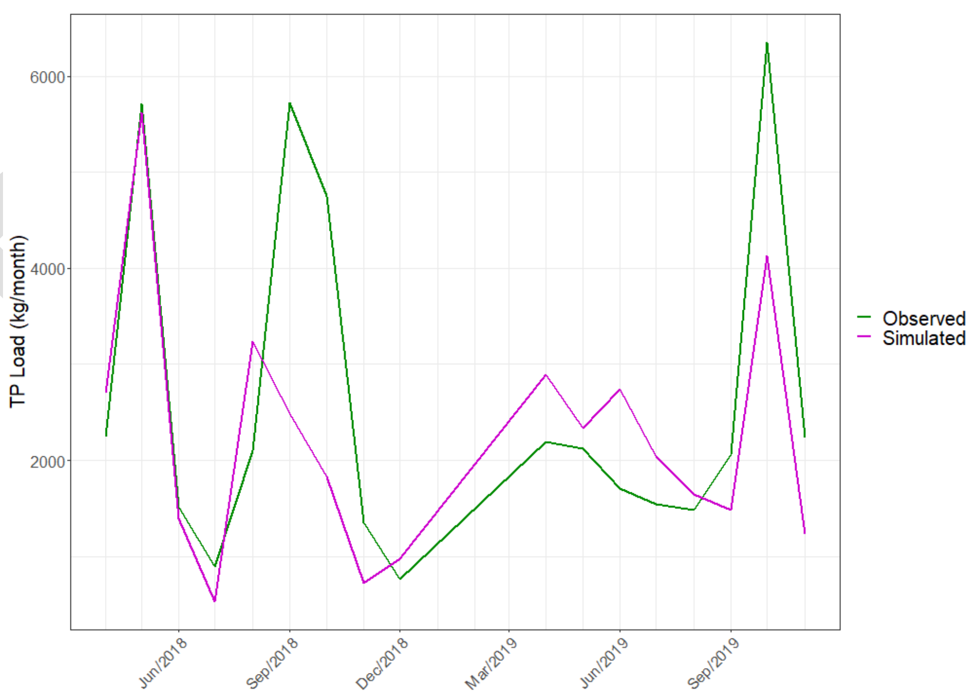

Figure C-14. Monthly total phosphorus calibration plot for WDNR site ID 10016139 (Sheboygan River - Hwy 57 Crossing).

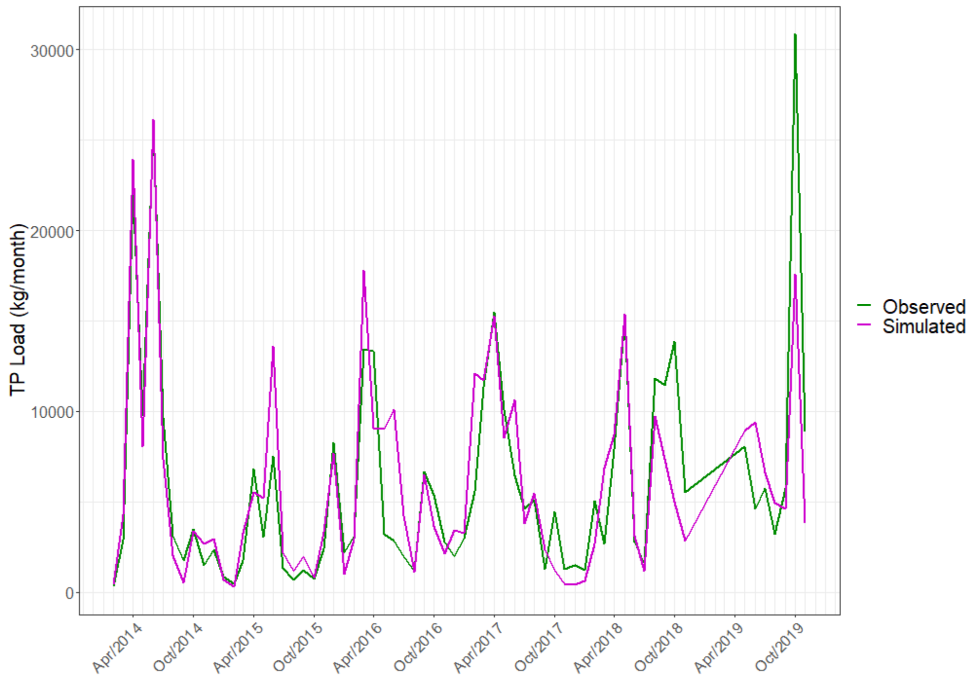

Figure C-15. Monthly total phosphorus calibration plot for USGS site ID 04086000 (Sheboygan River at Sheboygan, WI).

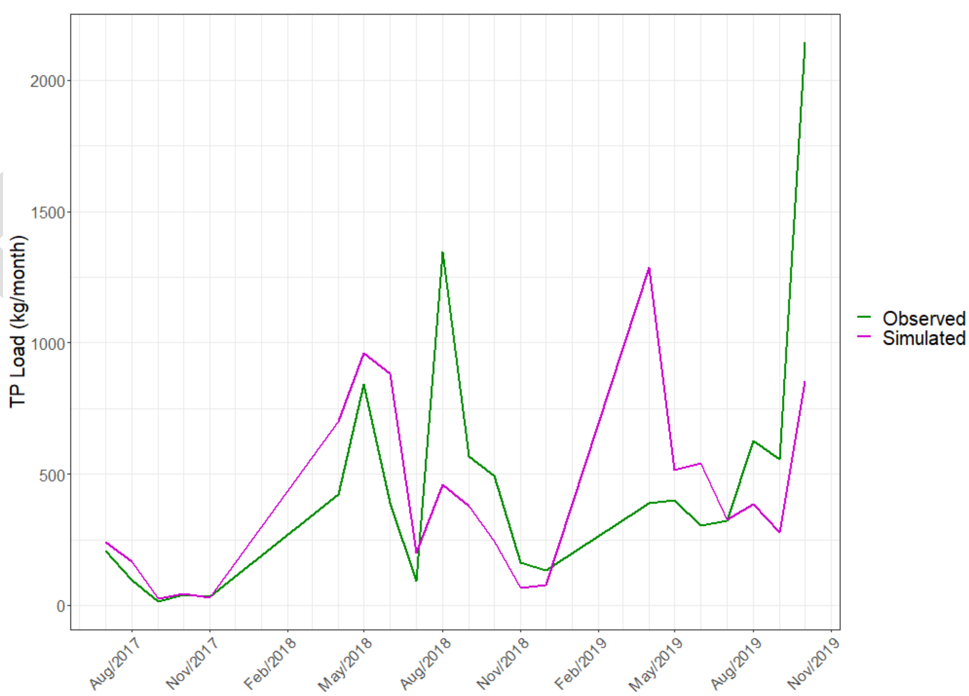

Figure C-16. Monthly total phosphorus calibration plot for WDNR site ID 363228 (Silver Creek (Manitowoc) at Cth Ls).

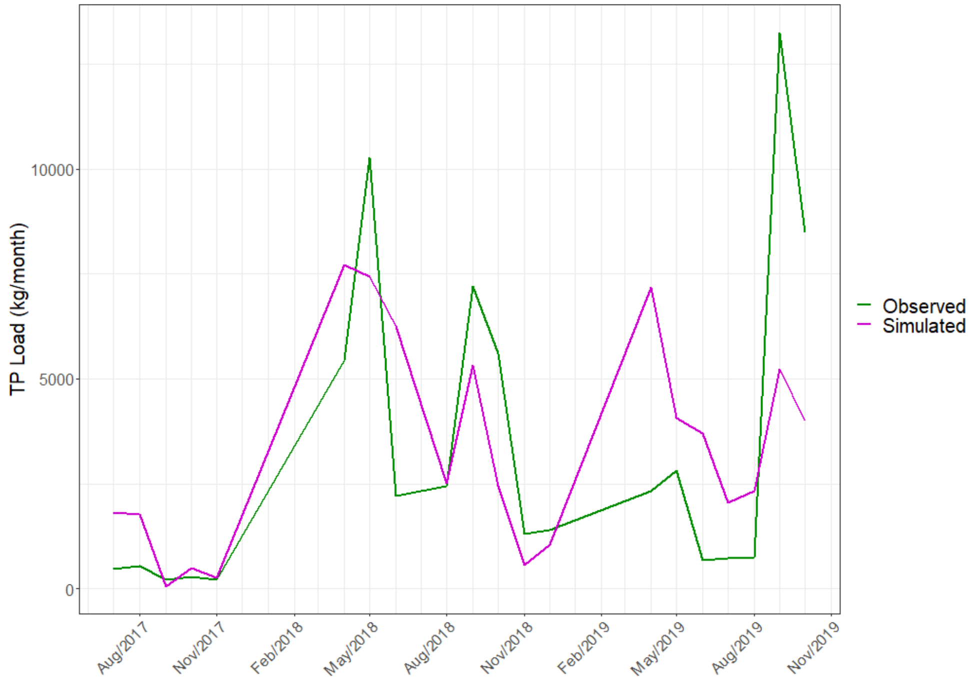

Figure C-17. Monthly total phosphorus calibration plot for WDNR site ID 10029482 (West Twin River at CTH V).

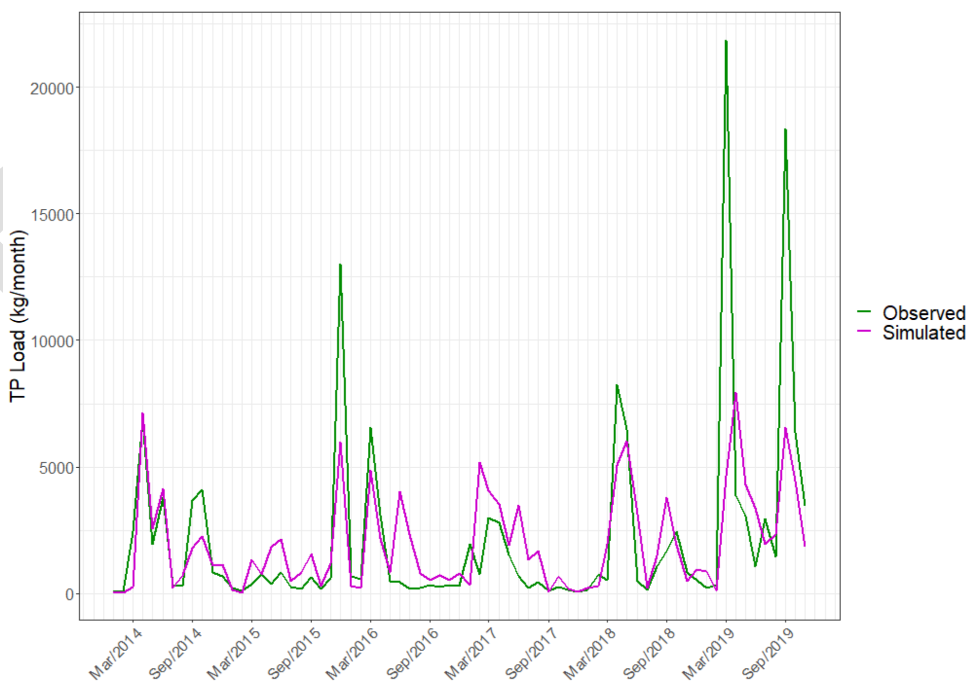

Figure C-18. Monthly total phosphorus validation plot for USGS site ID 04085200 (Kewaunee River Near Kewaunee, WI).

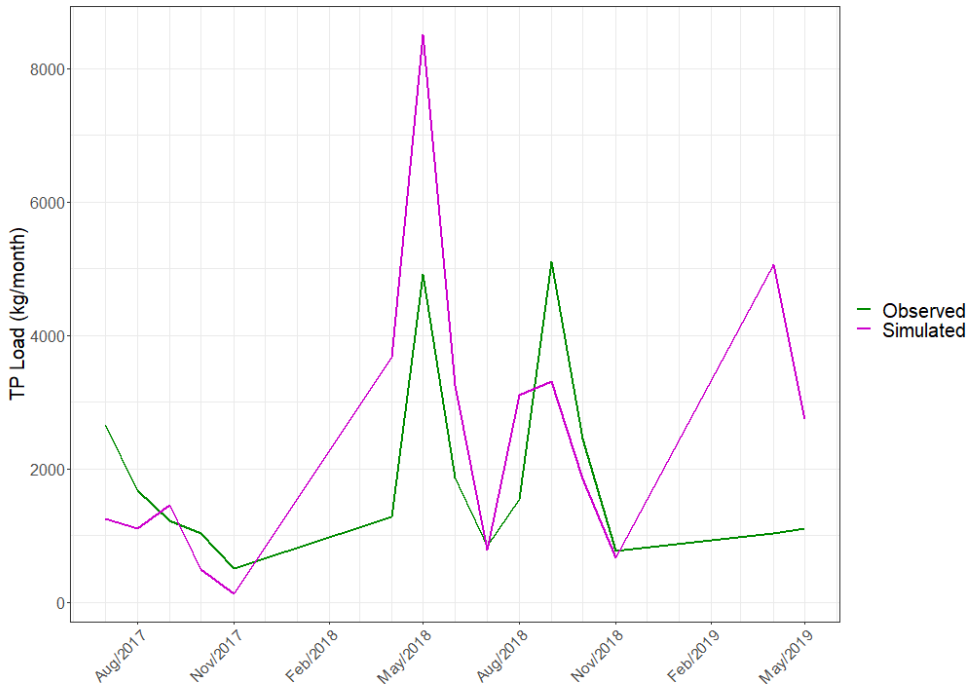

Figure C-19. Monthly total phosphorus validation plot for WDNR site ID 363375 (Manitowoc River South Branch at Lemke Rd.).

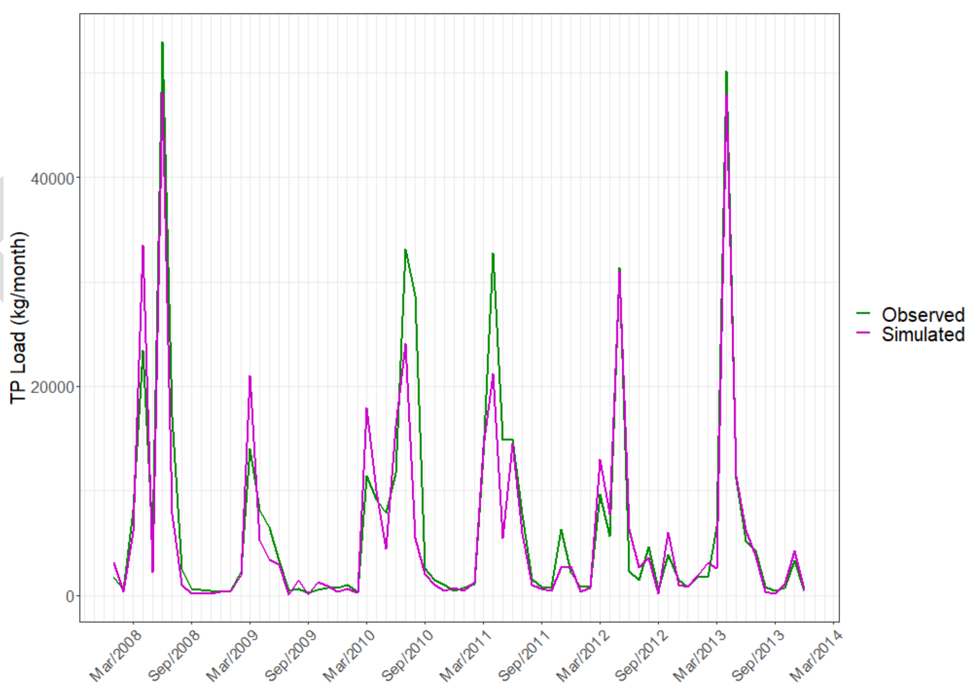

Figure C-20. Monthly total phosphorus validation plot for USGS site ID 04085427 (Manitowoc River at Manitowoc, WI).

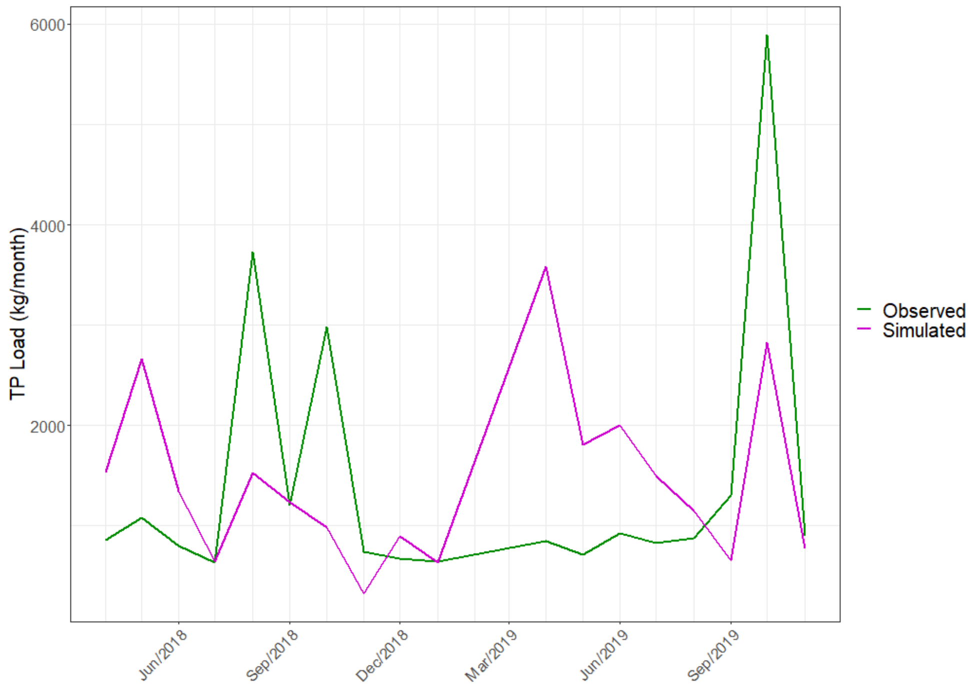

Figure C-21. Monthly total phosphorus validation plot for WDNR site ID 603295 (Pigeon River at Cth A - and River Rd.).

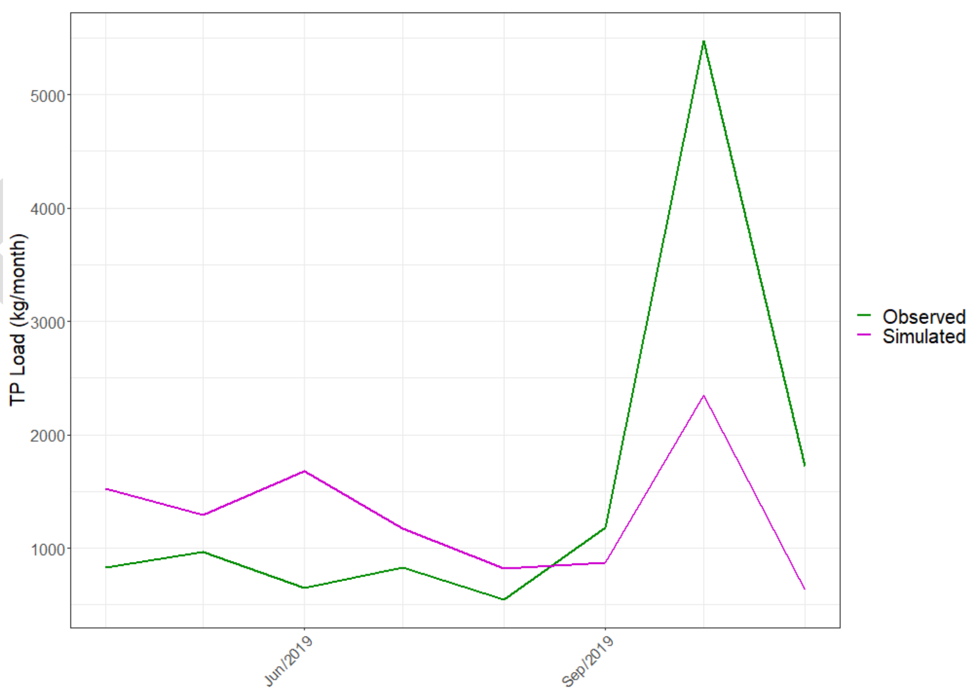

Figure C-22. Monthly total phosphorus calibration plot for WDNR site ID 10039440 (Sheboygan River at Palm Tree Rd.).

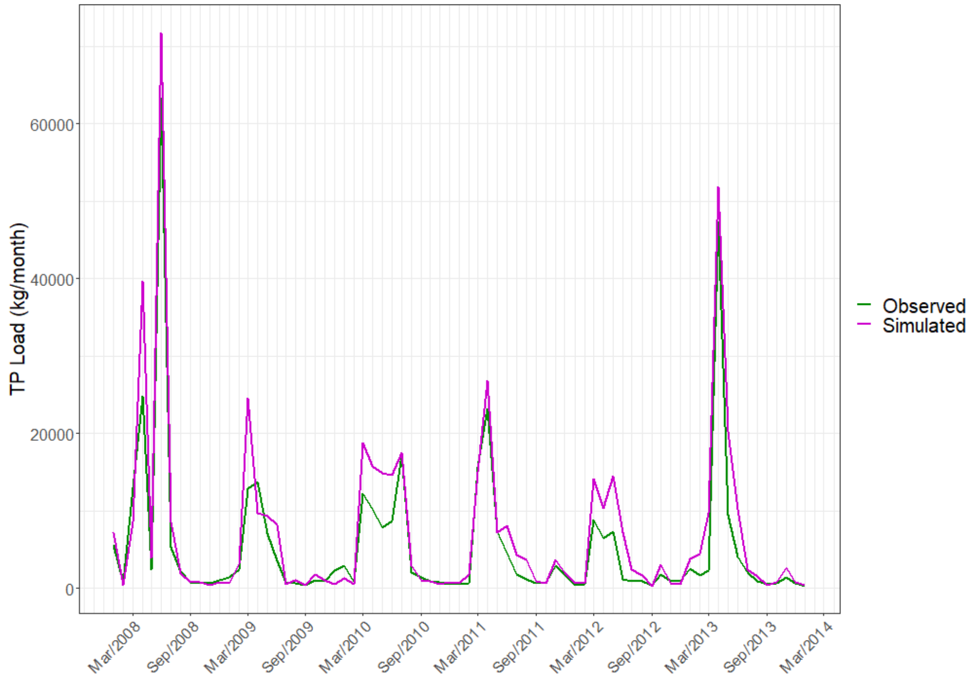

Figure C-23. Monthly total phosphorus validation plot for USGS site ID 04086000 (Sheboygan River at Sheboygan, WI).

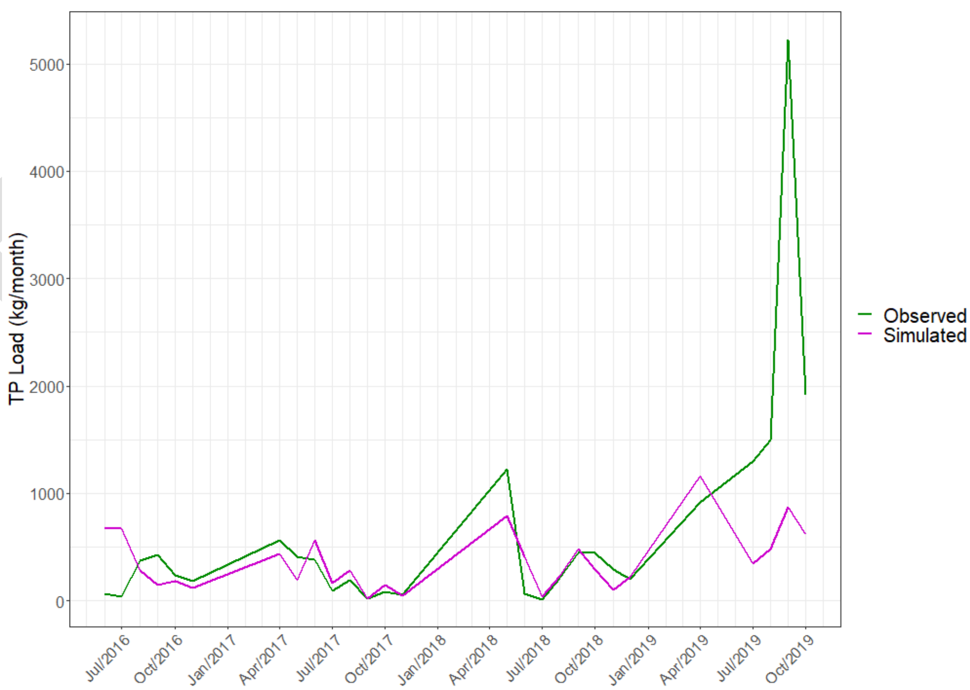

Figure C-24. Monthly total phosphorus validation plot for WDNR site ID 10020779 (Silver Creek (Algoma) at Willow Drive).