# 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 predictions are sensitive to the resolution of the DEM used for model input and that prediction 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 predictions are relatively insensitive to subbasin size but recommend drainage area thresholds of less than 3% of the total modeled area for predicting sediment loads and less than 5% for predicting 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.

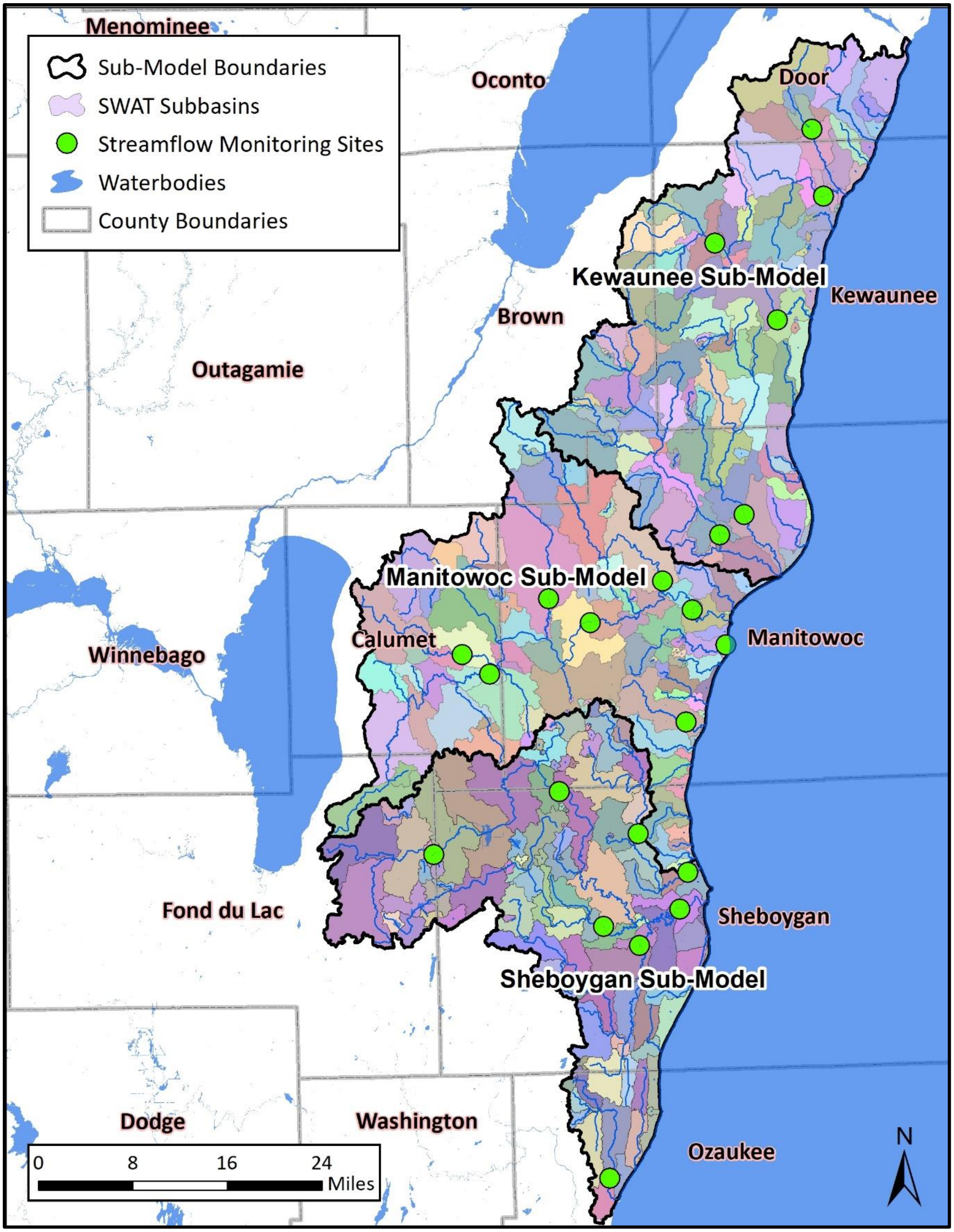


Figure 1. NEL SWAT model subbasins and sub-model boundaries.

## 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 document. 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 17 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 the Agricultural survey summary. Note that the 17 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.

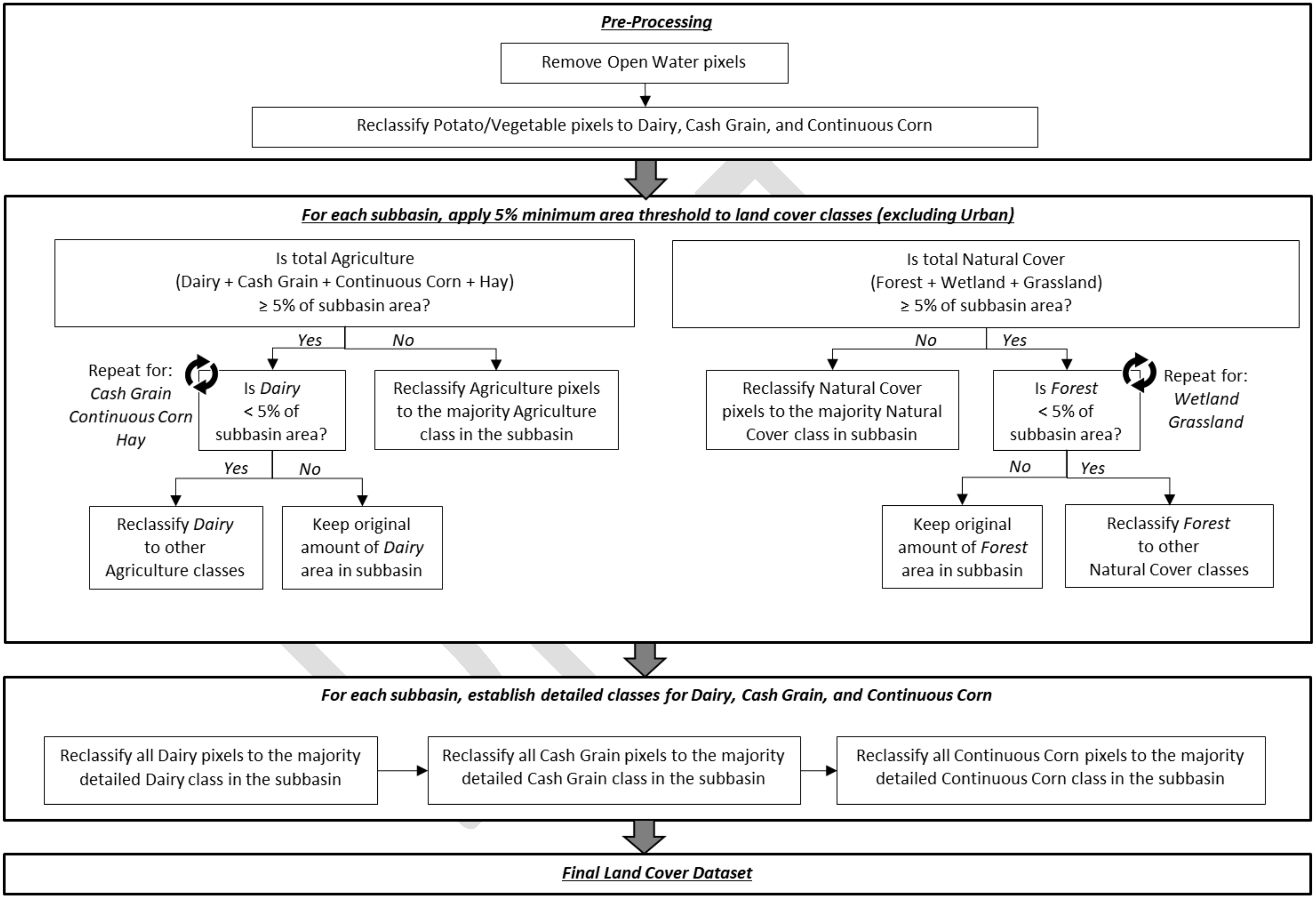


Figure 2. Flow chart describing the steps applied to the land cover map layer for HRU definition.

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 the 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. Does not include direct discharges to Lake Michigan.

| **Facility Name** | **Permit Number** | **Outfall Number** | **SWAT Sub-Model** | **SWAT Subbasin** |
|---|---|---|---|---|
| Agropur Inc. Luxemburg | 0050237 | 9 | | 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 | Kewaunee | 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 | | 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 | Manitowoc | 10 |
| Morrison Sanitary District No. 1 | 0036773 | 1 | | 47 |
| 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 | | 98 |
| Belgium Wastewater Treatment Facility | 0023353 | 1 | | 17 |
| Bemis Manufacturing Company Plant D | 0027456 | 1 | | 30 |
| Cedar Grove Wastewater Treatment Facility | 0020711 | 1 | Sheboygan | 9 |
| Cedar Valley Cheese Inc. | 0051535 | 11 | | 20 |
| Gibbsville Sanitary District | 0031577 | 1 | | 22 |
| Howards Grove Wastewater Treatment Facility | 0021679 | 1 | | 41 |

| Facility Name | Permit Number | Outfall Number | SWAT Sub-Model | SWAT Subbasin |
|---|---|---|---|---|
| Johnsonville LLC | 0001759 | 2 | Sheboygan | 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 |
| 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 233,00 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 | |

| Facility Name | County | Permit Number | Sub-Model |
|---|---|---|---|
| Ebert Dairy Enterprises | Kewaunee | 0062235 | Kewaunee |
| 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 | |
| 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 | |

| Facility Name | County | Permit Number | Sub-Model |
|---|---|---|---|
| Wolfgang Dairy | Manitowoc | 0061808 | Manitowoc |
| 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 | |
| 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 were assumed to be 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 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 assumed to provide a reasonable estimate for non-agricultural HRUs.

Table 7. Initial soil phosphorus summary statistics for agricultural HRUs, by SWAT sub-model.

| SWAT Sub-Model | Agricultural Soil Phosphorus Value (parts per million) | | | |
|---|---|---|---|---|
| | Minimum | Maximum | Mean | Standard Deviation |
| Kewaunee River | 15.95 | 69.97 | 32.02 | 9.83 |
| Manitowoc River | 18.58 | 74.86 | 38.11 | 10.60 |
| Sheboygan River | 11.39 | 87.89 | 38.12 | 12.93 |

## 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.

## 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 stream gaging 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 gage sites with continuous streamflow in the NEL study area. Calculated using the BFLOW baseflow separation program (Arnold et. al 1999).

| USGS ID | Gage 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.

## 2.10 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.

## 2.11 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.

## 2.12 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.

## 2.13 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<br>Model Hydrography Definition |
| 2018 (approved) and 2020 (draft) 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.pdfhttps://dnr.wisconsin.gov/sites/default/files/topic/TMDLs/NEL_ag_survey_summary.pdf | Land Use (HRU Definition)<br>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/NEL_ag_survey_summary.pdf | Initial Soil Phosphorus Concentration for Agricultural HRUs |
| WDNR MS4 Boundaries Dataset | WDNR | https://p.widencdn.net/5ry0aa/NEL_Shapefiles | Land Use (HRU Definition) |
| 2010 US Census County Subdivisions Layer | US Census Bureau | https://www2.census.gov/geo/tiger/TIGER2010/COUSUB/2010/ | Land Use (HRU Definition) |
| WDNR Point Sources Dataset | WDNR | https://p.widencdn.net/5ry0aa/NEL_Shapefiles | Point Source Locations, Flow, TSS, & TP Discharges |
| Daymet 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<br>Internal Drainage Definition |

## 3 Model Calibration

TO BE ADDED…

## 4 Model Validation

TO BE ADDED…

## 5 Discussion of Model Performance

TO BE ADDED…

## 6 Summary of Model Results

TO BE ADDED…

## 7 References


Arnold, J., Allen, P., Muttiah, R., & Bernhard, G. (1999). Baseflow Filter Program. Retrieved from Soil and Water Assessment Tool: http://swat.tamu.edu/media/70814/baseflow_inst_2006-06.pdf

Arnold, J., Kiniry, J., Srinivasan, R., Williams, J., Haney, E., & Neitsch, S. (2012). *SWAT Documentation.* Retrieved from Soil and Water Assessment Tool (SWAT) Website: http://swat.tamu.edu/media/69296/SWAT-IO-Documentation-2012.pdf

Baumgart, P. (2005). Lower Green Bay and Lower Fox Tributary Modeling Report.

The Cadmus Group (2018). SWAT Model Setup, Calibration, and Validation for the Upper Fox-Wolf Basins TMDL. The Cadmus Group. Retrieved from https://dnr.wi.gov/topic/TMDLs/documents/UFW/DraftAppendixC.pdf

Cotter, A. S., Chaubey, I., Costello, T. A., Soerens, T., & Nelson, M. A. (2003). Water Quality Model Output Uncertainty as Affected by Spatial Resolution of Input Data. *JAWRA Journal of the American Water Resources Association*, 39, 977–986.

Heathman, G. C., Flanagan, D. C., Larose, M., & Zuercher, B. W. (2008). Application of the soil and water assessment tool and annualized agricultural non-point source models in the St. Joseph River watershed. Journal of Soil and Water Conservation, 63(6), 552-568.

Her, Y., Frankenberger, J., Chaubey, I., & Srinivasan, R. (2015). Threshold Effects in HRU Definition of the Soil and Water Assessment Tool. Transactions of the ASABE Vol. 58(2): 367-378. American Society of Agricultural and Biological Engineers.

Jha, M., Gassman, P. W., Secchi, S., Gu, R., & Arnold, J. (2004). Effect of Watershed Subdivision on SWAT Flow, Sediment, and Nutrient Predictions. *JAWRA Journal of the American Water Resources Association*, 40, 811–825.

Kirsch, K., Kirsch, A., & Arnold, J. G. (2002). Predicting sediment and phosphorus loads in the Rock River basin using SWAT. Transactions of the ASAE, 45(6), 1757-1769.

Larose, M., Heathman, G. C., Norton, L. D., & Engel, B. (2007). Hydrologic and atrazine simulation of the Cedar Creek watershed using the SWAT model. Journal of Environmental Quality, 36(2), 521-531.

Vadas, P., & White, M. (2010). Validating soil phosphorus routines in the SWAT model. *Transactions of the ASABE*, 53(5), 1469-1476.

WDNR (2016). Estimations of Sources of Water Quality Impairments at Ungaged Sites in the Upper Wisconsin River Basin. Department of Natural Resources. Retrieved from https://dnr.wi.gov/topic/TMDLs/documents/WisconsinRiver/Report/AppendixD.pdf

WDNR (2018). Wisconsin's 2018 Impaired Waters List. Department of Natural Resources. Retrieved from https://dnr.wi.gov/topic/impairedwaters/2018IR_IWList.html/Final2018IWL_23March2018.xlsx

WDNR and The CADMUS Group, LLC (2020). NE Lakeshore TMDL: Agriculture Practice Summary. https://dnr.wisconsin.gov/sites/default/files/topic/TMDLs/NEL_ag_survey_summary.pdf

WDNR (2020). NE Lakeshore TMDL: Calculation of manure and associated phosphate spreading for development of a SWAT model. https://dnr.wisconsin.gov/sites/default/files/topic/TMDLs/Manure_analysis.pdf