Supplementary Information

Life Cycle Assessment of a Water Quality Trading Approach for NPDES Nutrient Permit Compliance

**Appendix C – SWAT Model Development and Results**

# Methods

The Kickapoo River Watershed is located in the Driftless Area of southwestern Wisconsin (Figure 1) The Kickapoo River lies within a 768-square mile drainage basin in southwest Wisconsin. It begins in south central Monroe County and flows in a southerly direction for 130 miles through Vernon, Richland and Crawford Counties before reaching the Wisconsin River near the Village of Wauzeka. This landscape is highly eroded, stream bank erosion has been a major concern (Gaffield et al. 1998; Juckem et al. 2008). This watershed is relatively extensive forested landscape of 52% followed by pasture and crop land (Figure C1). Karst topography is found throughout the area, characterized by shallow carbonate bedrock, caves, sinkholes, springs, and cold streams (Gaffield et al. 1998). Soils are generalized as silty loams (loess) and sandy loams over sandstone residuum over dolomite. Soils have moderate permeability and high-water capacity making the land ideal for farming.

## Data

### Spatial and Climate

The input data used to set up the SWAT model for Kickapoo watershed and evaluate the model efficiency are listed in Table C1.

Table C1. List of SWAT input data, source, and resolution.

|  |  |  |
| --- | --- | --- |
| **Data** | **Scale/Extent** | **Source** |
| DEM | 30 m raster | [USGS National Elevation Dataset](National%20Elevation%20Dataset%20(http://ned.usgs.gov/) |
| Land use/land cover (2017) | 30 m raster | [USDA NASS Cropland Data Layer](https://nassgeodata.gmu.edu/CropScape/) |
| Soil database | 1:12,000 to 1:63,360 (30 m to 52 m) | [USDA Soil Survey Geographic Database (SSURGO)](https://www.nrcs.usda.gov/resources/data-and-reports/soil-survey-geographic-database-ssurgo) |
| Point Source data | Within Kickapoo watershed | [U.S. EPA Enforcement and Compliance History Online (ECHO)](https://echo.epa.gov/tools/data-downloads) |
| Weather | Daily | [PRISM (https://prism.oregonstate.edu/](PRISM%20(https://prism.oregonstate.edu/)) |
| Measured streamflow | Daily (2000-2020) | [UGSS Streamflow Data](https://waterdata.usgs.gov/nwis/rt) |
| Measured Sediment and Nutrient data | Discrete samplings (2000-2020) | [Wisconsin Department of Natural Resources Surface Water Quality](https://dnr.wisconsin.gov/topic/surfacewater) |

## Agricultural Management Data

To accurately predict nutrient load at the watershed scale, it is necessary to specify agricultural management practices for different agricultural land uses. However, obtaining detailed spatiotemporal information about field-scale management across watersheds can be challenging. To address this, generic practices that represent the agricultural land uses in the Kickapoo watershed (such as row crops, hay, and pasture) were defined through collaborative discussions involving stakeholders and extension agents familiar with the watershed. These practices were also informed by the NRCS Conservation Practice Standard Nutrient Management (code 590) and Wisconsin agronomy extension documents (<http://corn.agronomy.wisc.edu/Management/L003.aspx>). The generic crop rotation in the watershed is corn-soybean based on three years of crop rotation from Cropland data Layers (CDL). Table C2 provides a summary of the agricultural management practices (planting, fertilizer application, tillage, harvest) incorporated in model setup. The tillage practices were exclusively used for corn-soyabean rotation. In the case of intensive tillage, the field preparation after the fall harvest involved a process that included disking to disturb the top 200 mm of soil with an 85% efficiency mix of residue. Additionally, one month before planting, chisel plowing to disturb 200 mm of topsoil with 30% mixing of residue was conducted to prepare seed beds, followed by seed planting using a field cultivator. These tillage practices were implemented for both corn and soybean crops. For reduced tillage, only seed planting using field cultivator to disturb the top 150 mm soil with a 50% efficiency to mix the residue was implemented. Additionally, all pasture fields were assumed to be utilized as cow grazing lands and the hay lands were used to bale the alfalfa three times a year.

Table C2. Agricultural Management Practices for crop rotation (Corn- Soyabean, Hay and Grazing Pasture)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Crops** | **Planting** | **Fertilizer** | **Tillage** | **Harvest date** |
| Corn | April 15th | 6-20-30 Starter 112.08 kg/ha  46-0-0 Urea | Intense Tillagea,  Reduce Tillageb ,  No tillagec | October 15th |
| Soybean | May 1st | 12 kg P/ha Starter | October 4th |
| **Hay** | | | | |
| Alfalfa | Perennial | No fertilizer | No tillage | 3 times of harvest per year  (June, August, October) |
| **Grazing Pasture** | | | | |
| Alfalfa | Perennial | No Fertilizer | No tillage | Grazing |
| **Grazing SWAT Inputs**   * Stocking rate: 1cow/1 acre * Grazing days: May – November * Biomass consumed: 20lb/day/ cow dry matter. * Excretion /Manure added: 12 lb/ day/cow dry matter. | | | | |

A: tillage practice for crop fields with <2% slope. b: 2-10 %. c: >10%. The classification of tillage practices based on slope is adopted from <https://uwdiscoveryfarms.org/>.

## Model Setup

Hydrologic and Water Quality System (HAWQS) on-line platform (HAWQS 2019), Version 2.0 DEV (dev.hawqs.tamu.edu) was used to set up and parameterize the Kickapoo watershed model. Pre-processed land use, soil data along with the DEM (Table C1) were used to construct sub basins and HRUs.

The watershed was partitioned into 92 sub basins considering the Hydrology Unit Codes (HUC 14) sub basin boundaries (Figure C2). These sub basins were further partitioned into HRUs (Hydrologic Response Unit) with similar land use, soil, and slope class. Three slope classes were defined (<2%, 2-10%, and >10%) to create HRUs according to the slope range suitable for tillage practices (Table C2). Following these criteria, a total of 11764 HRUs were delineated. The row crop fields selected for water quality trading were assumed to be under intense tillage category irrespective of the slope to assess nutrient load under extreme scenario. In the model, the initial concentration of labile P in the topsoil layer is assigned for row cropland and pasture HRUs, based on the soil test P value of wastewater treatment facility (WWTF) watersheds (which are based on county averages) as specified in Table B3. The wastewater treatment facility’s average discharge and effluent P concentration into the Kickapoo River, or its tributaries, was also included in the model.

## Model Calibration and Validation

A sequential method for watershed calibration was followed by first calibrating the stream flow parameters followed by nutrient (TP and TN) load (Santhi et al. 2006; Arnold et al. 2012), since nutrient load strongly depends on the accuracy of water flows (Lam et al. 2010; Ferrant et al. 2013; Epelde et al. 2015). Before calibration, a sensitivity analysis was performed to reduce uncertainty by identifying important parameters and their ranges that govern the system process as a further guidance for the calibration step of the study. In this study, the sensitivity analysis, calibration, and validation were conducted using the SUFI-2 algorithm in SWAT Calibration and Uncertainty Program (SWAT-CUP 2012) (Abbaspour 2015). The tested ranges of streamflow and nutrient parameters were selected within reasonable/expected limits based on the SWAT-CUP manual (Abbaspour 2015) and peer reviewed SWAT literature studies conducted in similar hydrological conditions (Tetra Tech 2015; Al Khoury et al. 2023; Ricci et al. 2023).

The watershed was calibrated and validated at a monthly time step for streamflow, beginning with the upstream station at LaFarge and subsequently moving to the downstream station at Steuben. The Kling Gupta Efficiency (KGE) (Gupta et al. 2009) calibration objective function was used to compare the simulated to observed variables. With the final calibrated values of the two gauging sites, the complete watershed model was run to check the statistics of the objective function and the interaction of parameters among the sub basins for streamflow. In addition to numeric calibration statistics (NSE, KGE, R2, and PBIAS), visual assessments of hydrographs between observed and simulated constituents were evaluated.

The calibration period was from 2000-2012 and validation from 2012-2020 with a warmup period of two years 1998-1999 to mitigate initial condition instabilities, including soil water and nitrate balances. Calibration of a large scale distributed hydrological model against river discharge alone may not be sufficient to reduce the uncertainty in prediction of all components of the water balance, so simulated actual evapotranspiration (Eta) at a monthly scale (Table C1) was compared with USGS ETa data. As ETa is directly related to plant growth and soil moisture fluctuation (FAO, 1986; Jensen, 1968), streamflow calibration using appropriate plant growth dynamics gives more confidence on the partitioning of water between soil storage, actual evapotranspiration, and aquifer recharge (Faramarzi et al. 2009; Faramarzi et al. 2010).

Following the streamflow evaluation, the calibration and validation of TP and TN load was carried out at Steuben since long term data was available only at Steuben. For the calibration of water quality parameters, the monthly total load of TP, TN, and TSS from 2000 to 2020, estimated using LOADEST, was utilized. Recognizing the uncertainties associated with the LOADEST estimated load, the calibrated nutrient load was cross verified with observed point load data. The USLE P-factor (erosion management practice factor varying 0–1) was set to 1.0 as it was assumed that currently no conservation practices were applied in the watershed model.

# Results and Discussion

Table C3 and Table C4 list the parameters, their descriptions within the model and their calibrated ranges for discharge, TP, and TN load calibration. Percentage-based variations (relative changes with respect to default value) of Curve Number moisture condition II (CN2), available water capacity (SOL\_AWC), and absolute changes to the ground water parameters were used to maintain their spatial variability.

SWAT performed well in capturing the streamflow trends at both the gauging stations (Table C5, Figure C3). However, all the processes such as baseflow, peaks, rising and falling limbs of hydrographs are better captured at La Farge. The consistent underestimation of baseflow at the Steuben station, stemming from groundwater contributions originating from karst structures near Steuben can be attributed to the simplified groundwater algorithm utilized in the SWAT model. Although flow at Steuben was consistently underestimated during the calibration period, improved predictions were observed during validation, and SWAT effectively captured the increasing trend of streamflow post 2014. Furthermore, Juckem et al. (2008) shows that prolonged changes in land use and climate since 1970 are the primary drivers for increased infiltration in the karst region of Kickapoo watershed and leading to significant rise in baseflow and which were cumbersome to address in the SWAT model. Additionally, the evaluation of actual evapotranspiration (ETa) at the monthly scale for the watershed yielded very good results of NSE (0.85), KGE (0.73), PBIAS (22.5) (Figure C4), confirming a robust upland water balance.

Overall, the monthly LOADEST estimated TP and TN load and the calibrated TP and TN load trends exhibit agreement for both the calibration and validation periods (Figure C5). Considering the uncertainty associated with the estimation from LOADEST model, the calibrated TP load with the point-observed load was also compared and it shows a bias of -9.6% (Figure C7), indicating a satisfactory calibration.

Table C3. Hydrology parameters used for streamflow calibration in SWAT.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Hydrology Parameters** | | | | |
|  | ***Parameter*** | ***Description*** | ***Tested Range*** | ***Value Used*** |
| Sub basins contributing to Lafarge | r\_CN2.mgt | Initial SCS runoff curve number for moisture condition II | -0.10 - 0.10 | -0.05 |
| v\_EPCO.hru | Plant uptake compensation factor | 0.1 - 1 | 0.77 |
| v\_ESCO.hru | Soil evaporation compensation factor | *0.5 - 1* | *0.9* |
| a\_GW\_DELAY.gw | Ground water delay time (days) | *-20 - -5* | *-7* |
| r\_SOL\_AWC ().sol | Available water capacity of the soil layer (mm H20/mm soil) | *-0.05 - 0.05* | *-0.02* |
| v\_\_CANMX.hru  ( Forest Land uses) | Maximum canopy storage | *0 - 10* | *9.5* |
| v\_\_SLSOIL.hru | Slope length for lateral subsurface flow | *0 - 150* | *31.08* |
| v\_\_LAT\_TTIME.hru | Lateral flow travel time | *0 - 180* | *11.65* |
| a\_\_GWQMN.gw | Threshold depth of water in the shallow aquifer required for return flow to occur | *-100 - 100* | *-73.28* |
| v\_\_GW\_REVAP.gw | Ground water revap coefficient | *0.02-0.2* | *0.02* |
| a\_\_RCHRG\_DP.gw | Aquifer percolation coefficient | *-0.03 - 0.03* | *-0.034* |
| a\_\_ALPHA\_BF.gw | Baseflow alpha factor | *0.001 - 0.7* | *0.003* |
| a\_\_REVAPMN.gw | Threshold water level in shallow aquifer for revap | *-700 - 700* | *700* |
| v\_\_OV\_N.hru | Manning's "n" value for overland flow | *0.01-1* | *0.048* |
| Sub basins contributing to Steuben | r\_CN2.mgt | Initial SCS runoff curve number for moisture condition II | -0.10 - 0.10 | -0.096 |
| v\_EPCO.hru | Plant uptake compensation factor | 0.1 - 1 | 0.98 |
| v\_ESCO.hru | Soil evaporation compensation factor | *0.5 - 1* | *0.947* |
| a\_GW\_DELAY.gw | Ground water delay time (days) | *-20 - -5* | *-11.179* |
| r\_SOL\_AWC().sol | Available water capacity of the soil layer (mm H20/mm soil) | *-0.05 - 0.05* | *-0.016* |
| v\_\_CANMX.hru (Forest Landuses) | Maximum canopy storage | *0 - 10* | *3.77* |
| v\_\_SLSOIL.hru | Slope length for lateral subsurface flow | *0 - 150* | *56.43* |
| v\_\_LAT\_TTIME.hru | Lateral flow travel time | *0 - 180* | *11.61* |
| a\_\_GWQMN.gw | Treshold depth of water in the shallow aquifer required for return flow to occur | *-200 - 200* | *-182.03* |
| v\_\_GW\_REVAP.gw | Ground water revap coefficient | *0.02-0.2* | *0.02* |
| a\_\_RCHRG\_DP.gw | Aquifer percolation coefficient | *-0.05 - 0.05* | *-0.04* |
| v\_\_ALPHA\_BF.gw | Baseflow alpha factor | *0.001 - 0.7* | *0.003* |
| a\_\_REVAPMN.gw | Threshold water level in shallow aquifer for revap | *-700 - 700* | *670.89* |
| v\_\_OV\_N.hru | Manning's "n" value for overland flow | *0.01-0.1* | *0.058* |
| Snow parameters | v\_\_SMTMP.bsn | Snow melt base temperature | *- 5 - 5* | *1.25* |
| v\_\_SFTMP.bsn | Snowfall temperature | *-5 - 5* | *0.75* |
| v\_\_SMFMX.bsn | Maximum melt rate for snow during year | 0 - 5 | 3.5 |
| v\_\_SMFMN.bsn | Minimum melt rate for snow during the year | 0 - 5 | 0.75 |
| v\_\_TIMP.bsn | Snowpack temperature lag factor | 0 - 1 | 0.4 |
| v\_\_CNCOEF.bsn | Plant ET curve number coefficient | 0.5 -1 | 0.616 |
| v\_\_SURLAG.bsn | Surface runoff lag time | 0 - 5 | 4.03 |

v\_ means that the existing parameter value is to be replaced by a given value; r\_ means that an existing parameter value is multiplied by (1+ a given value); a\_ means that the existing parameter value is added or subtracted by the default value.

Table C4: Parameters used for TP and TN load calibration in SWAT.

|  |  |  |  |
| --- | --- | --- | --- |
| **TN Calibration** | | | |
| ***Parameter*** | ***Description*** | ***Tested Range*** | ***Value Used*** |
| v\_CDN\* | Denitrification exponential rate coefficient | 0.45-2 | 1.12 |
| v\_CMN | Rate factor for humus mineralization of active organic N | 0.0001-0.002 | 0.0002 |
| v\_\_N\_UPDIS.bsn | Nitrogen uptake distribution parameter | 20-100 | 89.84 |
| v\_NPERCO | Nitrogen percolation coefficient | 0.18-0.65 | 0.55 |
| v\_BIOMIX | Biological mixing efficiency | 0.2-0.4 | 0.2 |
| v\_RSDCO | Residue decomposition coefficient | 0.05-0.08 | 0.05 |
| v\_SDNCO\* | Denitrification threshold water content | 0.85-1.1 | 0.99 |
| v\_HLIFE\_NGW\* | Half-life of N in groundwater (days) | 850-2500 | 1000 |
| **TP Calibration** | | | |
| v\_P\_UPDIS. bsn | Phosphorus uptake distribution parameter | 20-100 | 68.5 |
| SOL\_P\_MODEL.bsn | Soil Phosphorus Model (0 = original; 1 = new soil P model) |  | 1 |
| v\_PPERCO.bsn | Phosphorus percolation coefficient | 10 - 17.5 | 10.19 |
| v\_PHOSKD.bsn | Phosphorus soil partitioning coefficient | 100 - 200 | 163 |
| v\_PSP.bsn | Phosphorus sorption coefficient | 0.01 - 0.7 | 0.687 |
| v\_ERORGP.hru | Organic P enrichment ratio | 0 - 5 | 0.8 |
| v\_\_GWSOLP.gw  (CORN, SOYB) | Concentration of soluble phosphorus in groundwater contributing to reach (mg/l) | 0.01 – 0.35 | 0.1 |
| v\_\_GWSOLP.gw  (FRSD, PAST, HAY) | 0.01 – 0.35 | 0.05 |
|  | **TSS Calibration** |  |  |
| v\_\_SPCON.bsn | Linear parameter for calculating the maximum amount of sediment that can be re entrained during channel sediment routing | 0.0001 – 0.01 | 0.00157 |
| v\_\_SPEXP.bsn | Exponent parameter for calculating sediment re entrained in channel sediment routing | 1 – 1.5 | 1.5 |
| v\_\_ADJ\_PKR.bsn | Peak rate adjustment factor for sediment routing in the subbasin (tributary channels) | 0.5 - 2 | 1.19 |
| v\_\_PRF\_BSN.bsn | Peak rate adjustment factor for sediment routing in the main channel | 0 - 2 | 1.85 |

Table C5: Evaluation of the goodness of fit of the streamflow, TP, and TN load at monthly scale.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Monthly** | | | | | | | |
| ***Category*** | ***Gauging Site*** | ***Calibration (2000-2011)*** | | | | ***Validation (2012-2020)*** | | | |
|  |  | ***NSE*** | ***R2*** | ***PBIAS (%)*** | ***KGE*** | ***NSE*** | ***R2*** | ***PBIAS (%)*** | ***KGE*** |
| Flow | La Farge | 0.50 | 0.89 | 16 | 0.46 | 0.52 | 0.89 | 15.8 | 0.46 |
| Steuben | 0.36 | 0.85 | 24 | 0.51 | 0.48 | 0.78 | 10.8 | 0.56 |
|  |  | **Monthly** | | | | | | | |
|  |  | ***NSE*** | ***R2*** | ***PBIAS (%)*** | ***KGE*** | ***NSE*** | ***R2*** | ***PBIAS (%)*** | ***KGE*** |
| TP Load | Steuben | 0.74 | 0.75 | 19.8 | 0.73 | 0.74 | 0.75 | 17.77 | 0.73 |
|  |  | **Monthly** | | | | | | | |
|  |  | ***NSE*** | ***R2*** | ***PBIAS (%)*** | ***KGE*** | ***NSE*** | ***R2*** | ***PBIAS (%)*** | ***KGE*** |
| TN Load | Steuben | 0.78 | 0.79 | -0.8 | 0.77 | 0.80 | 0.82 | 12.30 | 0.77 |

A map and a diagram

Description automatically generated

Figure C1. Kickapoo watershed with WWTF and land use distribution

A map of different colors

Description automatically generated

**B**

**A**

Figure C2. Inputs for SWAT model setup; slope, land use, and soil (A). SWAT model setup with discharge and water quality gauge site (B).

A graph with numbers and lines

Description automatically generated

A graph of blue and orange lines

Description automatically generated

Figure C3. Observed and simulated hydrographs for gauging station La Farge and Steuben.

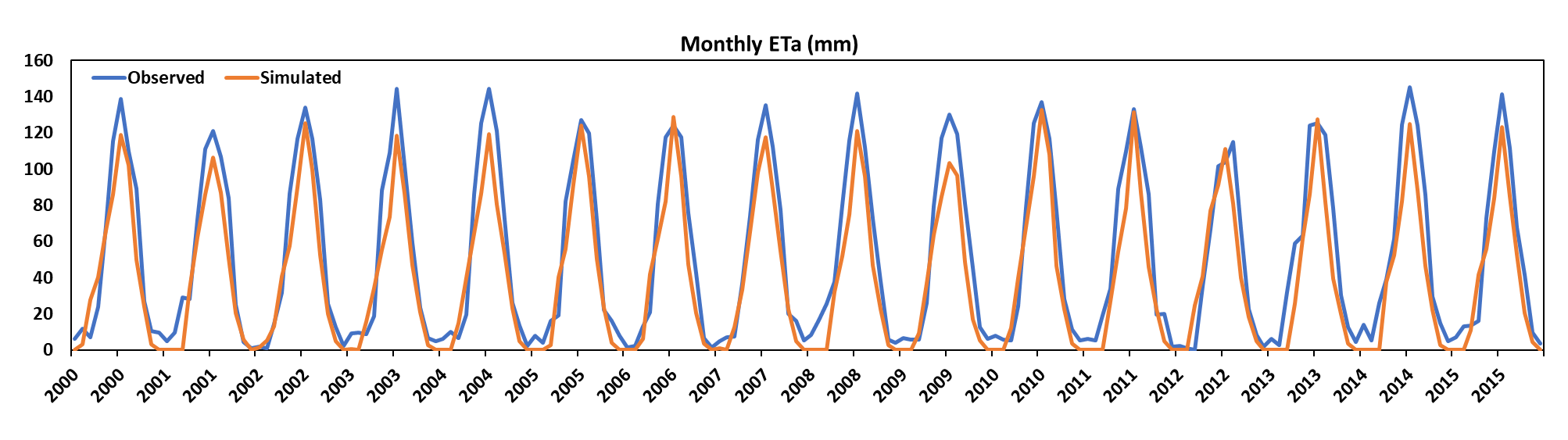


Figure C4: Monthly ETa comparison between MODIS ETa (observed) and SWAT at watershed scale.

A screen shot of a graph

Description automatically generated

Figure C5. Comparison of LOADEST (observed) and simulated TP load at Steuben.

A graph of a graph

Description automatically generated with medium confidence

Figure C6. Comparison of monthly LOADEST (observed) and simulated TN load at Steuben.

A graph of a graph of data

Description automatically generated

Figure C7. Comparison of measured load (point load) and simulated daily TP load at Steuben.

# References

Abbaspour, K. C. 2015. SWAT calibration and uncertainty programs—a user manual. *Swiss Federal Institute of Aquatic Science and Technology: Eawag, Switzerland*.

Al Khoury, I., L. Boithias, and D. Labat. 2023. A review of the application of the soil and water assessment tool (SWAT) in karst watersheds. *Water* 15. MDPI: 954.

Arnold, J. G., D. N. Moriasi, P. W. Gassman, K. C. Abbaspour, M. J. White, R. Srinivasan, C. Santhi, R. D. Harmel, et al. 2012. SWAT: Model use, calibration, and validation. *Transactions of the ASABE* 55. American Society of Agricultural and Biological Engineers: 1491–1508.

Epelde, A. M., I. Cerro, J. M. Sánchez-Pérez, S. Sauvage, R. Srinivasan, and I. Antigüedad. 2015. Application of the SWAT model to assess the impact of changes in agricultural management practices on water quality. *Hydrological Sciences Journal*: 1–19. doi:10.1080/02626667.2014.967692.

Faramarzi, M., K. C. Abbaspour, R. Schulin, and H. Yang. 2009. Modelling blue and green water resources availability in Iran. *Hydrological Processes* 23: 486–501. doi:10.1002/hyp.7160.

Faramarzi, M., H. Yang, J. Mousavi, R. Schulin, C. R. Binder, and K. C. Abbaspour. 2010. Analysis of intra-country virtual water trade strategy to alleviate water scarcity in Iran. *Hydrology and Earth System Sciences* 14. Copernicus GmbH: 1417–1433.

Ferrant, S., P. Durand, E. Justes, J.-L. Probst, and J.-M. Sanchez-Perez. 2013. Simulating the long term impact of nitrate mitigation scenarios in a pilot study basin. *Agricultural Water Management* 124. Elsevier: 85–96.

Gaffield, S. J., K. R. Bradbury, and K. W. Potter. 1998. *Hydrologic assessment of the Kickapoo Watershed, southwestern Wisconsin*. Wisconsin Geological and Natural History Survey.

Gupta, H. V., H. Kling, K. K. Yilmaz, and G. F. Martinez. 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of hydrology* 377. Elsevier: 80–91.

HAWQS. 2019. HAWQS System and Data to model the lower 48 conterminous U.S using the SWAT model (version V1). Texas Data Repository. doi:10.18738/T8/XN3TE0.

Juckem, P. F., R. J. Hunt, M. P. Anderson, and D. M. Robertson. 2008. Effects of climate and land management change on streamflow in the driftless area of Wisconsin. *Journal of Hydrology* 355: 123–130. doi:10.1016/j.jhydrol.2008.03.010.

Lam, Q. D., B. Schmalz, and N. Fohrer. 2010. Modelling point and diffuse source pollution of nitrate in a rural lowland catchment using the SWAT model. *Agricultural Water Management* 97: 317–325. doi:10.1016/j.agwat.2009.10.004.

Ricci, G. F., M. Centanni, A. M. DeGirolamo, and F. Gentile. 2023. Modelling daily streamflow in a temporary karst river system: comparing three approaches using the SWAT model. *Hydrological Sciences Journal* 68: 462–473. doi:10.1080/02626667.2023.2174027.

Santhi, C., R. Srinivasan, J. G. Arnold, and J. R. Williams. 2006. A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas. *Environmental modelling & software* 21. Elsevier: 1141–1157.

Tetra Tech. 2015. Lake Champlain Basin SWAT Model Configuration, Calibration and Validation. *Prepared for EPA Region 1*.