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Supplementary Materials

Assessing the Impact of Site-Specific BMPs Using a Spatially Explicit, Field-Scale SWAT Model with Edge-of-Field and Tile Hydrology and Water-Quality Data in the Eagle Creek Watershed, Ohio

Supplementary Materials A

S.1. Data Collection and Processing

USGS collected extensive data at multiple gages within Eagle Creek watershed (Table S1). Similar methods of data collection, sample processing, and data analysis are described in Stuntebeck et al. [1]. Flow at the monitoring sites was recorded continuously during the study period. Water-quality samples were collected and analyzed for suspended sediment, chloride, nitrate plus nitrite (referred to through this paper as NO_3-N), ammonium, unfiltered total Kjeldahl nitrogen (TKN), orthophosphate, and total phosphorus (TP). Total nitrogen (TN), particulate P (PP), and organic nitrogen are calculated. Terminology substitution for analytically-determined orthophosphate [2] as dissolved reactive phosphorus, or DRP [3], is used in this paper.

Table S1. U.S. Geological Survey (USGS) gaging stations and National Climatic Data Center (NCDC) weather stations in or near the Eagle Creek, Ohio watershed.

Owner	Site ID	Station Name	Parameter	Period of Record *
USGS	04188496	Eagle Creek above Findlay, OH	Streamflow Water Quality	10/12/2007 to 9/30/2016 8/14/2012 to 9/30/2016
USGS	0405051083391201	Eagle Creek waterway 1 near Williamstown OH	Surface Runoff Water Quality	8/29/2012 to 9/30/2016 9/8/2012 to 9/30/2016
USGS	0405051083391001	Eagle Creek tile 1 near Williamstown, OH	Tile flow Water Quality	8/29/2012 to 9/30/2016 2/9/2012 to 9/30/2016
NCDC	USW00014825	Findlay Airport OH US	Precipitation Temperature	1/1/1942 to 9/30/2016
NCDC	USC00334189	Kenton, OH US	Precipitation Temperature	1/1/1893 to 9/17/2014
NCDC	US1OHHD0014	ADA 5.4 NE, OH US	Precipitation	5/18/2014 to 9/30/2016

* Period of record is the starting date of the station, while the ending date is the last date used in this study; Notes: USGS = U.S. Geological Survey; NCDC = National Climatic Data Center.

S.1.1. Stage and Streamflow

The water levels at all sites were measured every 15 min during zeroflow (base flow), and the sampling frequency increased during storm events to 5 min at the HUC12 outlet and 1 minute at the tile and EOF sites [1]. Measured stage and streamflow data were compiled and streamflows were computed from stage-discharge relations that were developed through standard USGS procedures [4,5] and are stored in the USGS National Water Information System [6]. Daily mean streamflows were computed from subhourly discharges at the HUC12 outlet site. Daily discharge volume is the conversion of daily mean discharge to daily sum discharge in cubic feet and calculated during cases of base flow discharge for a partial day. Individual storm volume is the total storm volume in cubic feet for the individual or subsplit storms at the EOF site or subsplit storm and base flow period at a tile site [1].

S.1.2. Water Quality

Water samples were collected by refrigerated automatic samplers at all sites. The frequency of samples varied throughout a given year through the hydrograph at each sampling location. At the EOF and tile sites, samplers were activated during storm events when thresholds were met and collected repeatedly during changes in stage for a given storm following procedures from Stuntebeck et al. [1]. Grab samples from the EOF and tile sites were collected one to two times per year for comparisons to triggered automated samples in the EOF and tile flumes. At the HUC12 outlet, quality-assurance water samples were collected four to six times per year using the equal-width-increment method [7].

All samples were analyzed by the Water and Environmental Analysis Laboratory at the University of Wisconsin in Stevens Point, Wisconsin or the USGS National Water Quality Laboratory in Lakewood, Colorado for comparative discrete quality assurance. Sample results for the HUC12 outlet are stored in the USGS National Water Information System [6].

At the EOF and tile sites, sample concentrations and the discharge record can be used to estimate sediment and nutrient concentrations of adjacent storm events and base flow during unsampled periods of discharge record. The combination of these sampled and estimated periods of record result in better representations of loads than would have been calculated using sampled concentrations alone. The total sampled and unsampled storm event and base flow loads are then used to calculate daily and annual loads. Loads were normalized by their respective drainage basin area to account for differences in drainage-area size. The EOF and tile daily loads were produced using the USGS Graphical Constituent Loading Analysis System (GCLAS) [8] and are available at Science Base [9].

S.2. Development of Hydrologic Response Units

HRUs are the basic building blocks for the SWAT model where all landscape processes are computed. Through the ArcSWAT interface, land use, soil, and slope layers were overlaid to create unique combinations of HRUs by subbasin. By default in SWAT, all similar HRUs within a subbasin are lumped together [10]. For example, areas within subbasin 20 that have forested land use, with four soils, and 0–2% slopes are lumped into a single HRU even if they are not adjacent parcels, losing the field's spatially unique management characteristics [11]. A simple way to avoid this aggregation is to set HRU thresholds in the model to zero [12,13]. Daggupati et al. [12] and Kalcic et al. [14] presented a procedure to allow each agricultural field to remain its own HRU, thereby the user can control each field's management. This procedure was used for the SWAT model in this study with variations described below and in Section 2.2. on Model Development.

The land use layer was developed using the Common Land Unit (CLU) data layer [15], which outlines individual farm fields receiving NRCS assistance, provided by NRCS. The CLU did not cover the entire Eagle Creek watershed; there were gaps in it for residential, urban, forested areas, and wetlands. Urban areas, roads, forests, and fields not receiving NRCS assistance were manually delineated. Altogether, there were 2162 field parcels encompassing the study watershed. Using the procedure outlined in Kalcic et al. [14], majority values from the CDL 2013 were used to describe each outlined field.

The soil layer was developed using SSURGO soils GIS data layer [16]. The field parcel boundary outline created for land use also was used for the soils definition, where the majority soil present in each field was used. The slope layer was created using the "single slope option" in ArcSWAT, which assigned a uniform slope throughout the watershed, as slope in this basin did not very much.

Finally, the land use, soil, and uniform slope layers were used to generate HRUs. The majority of HRUs represented one farm field or contiguous land use; however, when a field contained a topographic divide and drained to multiple subbasins, then the field was separated into multiple HRUs. For example, a field cuts across three subbasins and hence the field parcel was divided into three individual HRUs—one in each subbasin. Fields divided by the watershed boundary were considered separately in the analysis.

S.3. Weather

Precipitation and temperature data were obtained from weather stations selected in the WLEB study (Figure 1 and Table S1) [17]. Solar radiation, wind speed, and relative humidity were calculated using the SWAT weather generator [18]. The precipitation station at ADA 5.4 NE, OH was only used for model validation as data collection started at this site late in the calibration period to replace the precipitation station at Kenton, OH as data collection at the Kenton, OH station ended just prior to the start of the validation period.

S.4. Point Sources

Three point sources with National Pollutant Discharge Elimination System (NPDES) permits were in the Eagle Creek watershed (Figure 1). Daily flow and sporadic water-quality data were provided by Ohio EPA (Richard Bouder, Ohio EPA, written communication, 2017), while older monthly data were obtained from the U.S. EPA Enforcement and Compliance History Online [19]. One of the sites, Camp Berry, a Boy Scout Camp, had its highest discharges during summer months and intermittently on weekends throughout the rest of the year. Point sources accounted for approximately 7% of the average annual flow at the HUC12 outlet.

S.5. Best Management Practice Selection

NCP BMPs conform to national and state standards specifying placement and its minimum application criteria [20]. NCP BMPs were evaluated as to the following modeling conditions:

1) Inability of being simulated in SWAT
2) Limited impact to nutrient or sediment loads
3) Failed USDA-NRCS privacy requirements (to maintain USDA-NRCS privacy requirements, a practice with less than five occurrences in the Eagle Creek watershed was not simulated.)
4) BMPs applied or planned prior to 2005: Practices planned or applied before 2005 were removed, as NCP database went through a major update and restructuring in 2005.

If any one of the four above conditions were met, the BMP(s) were removed from the dataset. A total of 1180 unique BMPs were considered in the model. A listing of conservation practices considered in the models are shown in (Table 3). Thirty-six BMPs (401 individual practices) were removed from the model data (Table S2).

Table S2. National Conservation Planning Database best management practices (BMPs) in Eagle Creek watershed, Ohio not modeled with SWAT.

USDA-NRCS Code *	Practice Name	Modeling Condition Failed (Described in Section 5 in Text)
102	Comprehensive Nutrient Management Plan	1
OH202	Conservation Plan Development	1
OH204	Conservation Plan Implementation	1
334	Controlled Traffic Farming	1, 3
356	Dike	3
554	Drainage Water Management	3
382	Fence	1
394	Firebreak	1, 3
386	Field Border	1
512	Forage and Biomass Planting	1
666	Forest Stand Improvement	3, 4
410	Grade Stabilization Structure	3
110	Grazing Management Plan	3
561	Heavy Use Area Protection	1
595	Integrated Pest Management	1, 2
516	Livestock Pipeline	1
AIR02	N-stabilizers for air emissions control	1
WQL11	Precision application of nutrients	1

USDA-NRCS Code *	Practice Name	Modeling Condition Failed (Described in Section 5 in Text)
338	Prescribed Burning	1
391	Riparian Forest Buffer	3
558	Roof Runoff Structure	1, 3
367	Roofs and Covers	1, 3
646	Shallow Water Development and Management	3
587	Structure for Water Control	3
606	Subsurface Drain	3, 4
612	Tree/Shrub Establishment	3
620	Underground Outlet	3
633	Waste Recycling	1
313	Waste Storage Facility	3, 4
642	Water Well	3
614	Watering Facility	1
658	Wetland Creation	3
657	Wetland Restoration	3
644	Wetland Wildlife Habitat Management	3
648	Wildlife Watering Facility	1, 3
650	Windbreak/Shelterbelt Establishment	1

*USDA-NRCS BMPs conform to standards that are available online. Natural Resources Conservation Service (NRCS) n.d.; Modeling Conditions: (1) Inability of being simulated in SWAT; (2) limited impact to nutrient or sediment loads, (3) practice did not have five or more occurrences in the Eagle Creek watershed, and/or (4) BMPs certified prior to 2005.

Supplementary Materials B

Table S3. SWAT parameters and their final values used in calibration for the Eagle Creek watershed, Ohio SWAT model.

Parameter Type	Parameter	File Type	Description	Default Value	Model Range	Eagle Creek
Snow	SMTMP	.bsn	Snow melt base temperature (°C)	0.5	−5 to 5	0.292
Snow	SFTMP	.bsn	Snowfall temperature (°C)	1	−5 to 5	0.5
Snow	SMFMX	.bsn	Maximum snowmelt factor for June 21 (mm H2O °C^{-1} day^{-1})	4.5	0 to 20	10
Snow	SMFMN	.bsn	Minimum snowmelt factor for Dec. 21 (mm H2O °C^{-1} day^{-1})	4.5	0 to 20	0.8
Snow	SNOCOVMX	.bsn	Minimum snow water content that corresponds to 100% snow cover (mm)	1	0 to 500	91
Snow	SNO50COV	.bsn	Fraction of snow volume that corresponds to 50% snow cover	1	0 to 1	0.9
Hydrology	ICN	.bsn	Daily curve number calculation method (calculate daily CN as a function of 0 = soil moisture; 1 = plant evapotranspiration)	0	0 or 1	0
Hydrology	IPET	.bsn	Potential evapotranspiration method (0 = Priestly-Taylor method, 1 =Penman/Monteith method, 2 = Hargreaves, 3 = user defined)	1	0, 1, 2 or 3	2
Hydrology	R2ADJ	.hru	Curve number retention parameter adjustment factor to adjust surface runoff for flat slopes	1	0 to 1	0.1
Hydrology	CN2	.mgt	Initial SCS runoff curve number for moisture condition II	Varies *	49 to 99	−4% *
Hydrology	ESCO	.hru	Soil Evaporation compensation factor	0.95	0 to 1	0.788
Hydrology	EPCO	.hru	Plant uptake compensation factor	1	0 to 1	0.7
Hydrology	OV_N	.hru	Manning's "n" value for overland flow	Varies *	0.01 to 30	0.2
Hydrology	CH_N2	.rte	Manning's coefficient for channel	0.014	−0.01 to 0.3	0.084
Hydrology	SURLAG	.hru	Surface runoff lag time in the HRU (days)	2	0 to 24	1
Hydrology	GWQMN	.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	1000	0 to 5,000	50
Hydrology	RCHRG_DP	.gw	Deep aquifer percolation fraction	0	0 to 1	0.2
Hydrology	GW_DELAY	.gw	Groundwater delay (days)	31	0 to 2000	1000
Hydrology	ALPHA_BF	.gw	Base flow recession constant	0.048	0 to 1	0.135
Tile Drainage	ITDRN	.bsn	Tile drainage method; 0 = lag time method; 1 = Hooghoudt and Kirkham tile drain equations	0	0 or 1	1
Tile Drainage	DEP_IMP	.hru	Depth to impervious layer in soil profile in tile drained fields (mm)	6,000	0 to 6000	1100

Parameter Type	Parameter	File Type	Description	Default Value	Model Range	Eagle Creek
Tile Drainage	DEP_IMP	.hru	Depth to impervious layer in soil profile in undrained fields (mm)	6000	0 to 6000	6000
Tile Drainage	DDRAIN	.mgt	Depth to drains (mm); must be >0 to initiate tile drainage	0	0 to 2000	1000
Tile Drainage	LATKSATF	.sdr	Multiplication factor	1	0.01 to 4	4
Tile Drainage	SDRAIN	.sdr	Distance between two drain tubes or tiles (mm)	0	7600 to 30,000	20,000
Tile Drainage	PC	.sdr	Pump capacity	1	0 to 5	0
Sediment	SPCON	.bsn	Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing	0.0001	0.0001 to 0.01	0.003
Sediment	SPEXP	.bsn	Exponent parameter for calculating sediment reentrained in channel sediment routing	1	1.0 to 2.0	1.1
Phosphorus	SOL_P_MODEL	.bsn	Soil Phosphorus Model (0= original; 1 = new soil P model)	0	0 or 1	1
Phosphorus	PSP	.bsn	Phosphorus availability index	0.4	0 to 1	0.84
Phosphorus	PPERCO	.bsn	Phosphorus percolation coefficient (10 m^3 Mg^{-1})	10	10.0 to 17.5	14.965
Phosphorus	PHOSKD	.bsn	Phosphorus soil partitioning coefficient (m^3 Mg^{-1})	175	100 to 200	112.023
Phosphorus	P_UPDIS	.bsn	Phosphorus uptake distribution parameter	20	0 to 400	200.726
Phosphorus	SOL_CRK	.sol	Maximum crack volume of soil profile (fraction)	0.5	0 to 1	0.11
Phosphorus	SOL_LABP	.chm	Initial soluble P concentration in the soil layer (mg kg^{-1})	5	0 to 1000	20
Phosphorus	SOL_ORGP	.chm	Initial organic P concentration in the soil layer (mg kg^{-1})	0	0 to 1000	100
Phosphorus	RS2	.swq	Benthic (sediment) source rate for dissolved phosphorus in the reach at 20 °C (mg dissolved P (m^2 day^{-1})$^{-1}$)	0.05	0.001 to 0.1	0.089714
Phosphorus	RS5	.swq	Benthic (sediment) source rate for dissolved phosphorus in the reach at 20 °C (mg dissolved P (m^2 day^{-1}) $^{-1}$)	0.05	0.001 to 0.1	0.051759
Phosphorus	BC4	.swq	Rate constant for mineralization of organic P to dissolved P in the reach at 20 °C (day^{-1})	0.35	0.01 to 0.7	0
Phosphorus	AI2	.wwq	Fraction of algal biomass that is phosphorus	0.015	0.01 to 0.02	0.078569
Nitrogen	FIXCO	.bsn	Nitrogen fixation coefficient	0.5	0 to 1	1
Nitrogen	NFIXMX	.bsn	Maximum daily Nitrogen fixation (kg ha^{-1})	20	1 to 20	18
N/P	RSDCO	.bsn	Residue decomposition coefficient	0.05	0.02 to 0.1	0.063
Nitrogen	RCN	.bsn	Concentration of nitrogen in rainfall (mg N L^{-1})	1.0	0 to 15	1.85
Nitrogen	CMN	.bsn	Rate factor for humus mineralization of active organic nutrients	0.0003	0.0001 to 0.003	0.002
Nitrogen	NPERCO	.bsn	Nitrate percolation coefficient	0.2	0 to 1	0.993
Nitrogen	CDN	.bsn	Denitrification exponential rate coefficient	1.4	0.0 to 3.0	0.1
Nitrogen	SDNCO	.bsn	Denitrification threshold water content	1.1	0 to 1	0.995
Nitrogen	N_UPDIS	.bsn	Nitrogen uptake distribution parameter	20	0 to 100	5

Parameter Type	Parameter	File Type	Description	Default Value	Model Range	Eagle Creek
Nitrogen	ANION_EXCL	.sol	Fraction of porosity (void space) from which anions are excluded	0.5	0 to 1	0.36
Nitrogen	SOL_ORGN	.chm	Initial organic N concentration in the soil layer (mg kg^{-1})	0	0 to 1000	28.12
Nitrogen	ERORGN	.hru	Organic N enrichment ratio	0	0 to 5	3.8
Crop growth	BIO_E (winter wheat)	Plant.dat	Plant radiation use efficiency (MJ m^{-2})	30	10 to 90	25
Crop growth	BLAI (corn)	Plant.dat	Maximum leaf area index	3	0.5 to 10	6

* CN2 and OV_N is dependent on soils and land use. CN2 was only changed for tile drained HRUs. N = nitrogen; P = phosphorus.

Supplementary Materials C

Impact of Air Temperature Modification

SWAT does not simulate tile flow when the soil temperature of the first layer of the soil profile is frozen (soil temperature less than 0 °C) [10]. The input air temperature maximum and minimum (TMAX and TMIN, respectively) were modified to ensure that soil temperature did not drop below 0 °C, thus permitting tile flow. An average of 14% of input air temperatures were modified each WY, with more TMIN values modified (19% of TMIN values were modified) than TMAX values (10% TMAX values were modified). To assess the potential impact of these modifications, the original (unmodified) air temperatures were inserted into the calibrated model.

Figure S1 shows simulated values at the EOF, tile, and HUC12 outlet using the unmodified air temperatures compared to the observed (when available) and simulated flow components from the calibrated model (from Figures 4A, 5A, and 6A). The impact of the air temperature modifications to simulated tile drainage was most prominent from December 2013 through March 2014. Simulated tile flow from the unmodified temperatures (QtileUT) ranged from 0 to 0.01 mm due to frozen soils, while at the same time the observed data ranged from 0.58 to 1.10 mm. A large overestimation of observed tile flow in QileUT of almost 300% occurred in April 2014 just after the frozen water thaws and drains; a similar effect is seen in January and February of 2013. Winter peaks (December 2013 to March 2014) in surface runoff simulated from the unmodified temperatures (SURQUT) more closely matched the observed data at the EOF site than the simulated surface runoff (Figure S1); however, during this period QtileUT values were very low or 0 when the monitoring data showed the tile flowing. QtileUT and SURQUT during summer months were similar to simulated tile flow as everything else in the model is the same. At the HUC12 outlet, the simulated flow with the unmodified temperatures (QUT) simulated less flow than the calibrated model in the months of January and February and QUT increased in April and May in the calibration period.

The soil-water content and percolation were different due to temperature modifications in the winter months (January to March; Figure S1). When the temperatures drop beneath 0˚C, soil-water content simulated from the unmodified temperature input data (SW_{UT}) was greater than the calibrated soil-water content because frozen soils do not allow water to move or percolate, thus there was more water held in the soils. Groundwater contributions to streamflow were greater with the temperature modifications due to greater water availability.

At the tile monitoring station, the water quality loads were generally lower in the unmodified temperature simulation than when temperature was modified (Figure S2). NO_3-N and DRP loads in QtileUT were very small or zero in winter months when tiles were not flowing. Correspondingly, at the EOF site (Figure S3) in the winter, DRP and NO_3-N loads in SURQUT were higher to compensate for the nutrients not leaving through the tile drain. When unmodified temperatures were used at the watershed outlet (Figure S4), exported NO_3-N loads were lower in winter months when soils were frozen and then higher in the following spring months once the soils thawed than the simulated loads.

The impact to the hydrologic cycle was examined (Table S4). The overall water balance was affected due to the temperature modification. The total water yield without temperature modifications increased 1.4 mm from the calibrated model. QtileUT was decreased 4.8 mm while SURQUT was increased 7.2 mm compared to the calibrated model. With the unmodified temperatures, smaller decreases in lateral soil flow, groundwater flow, aquifer recharge, and percolation were also found compared to the calibrated model. The ratio of simulated tile flow to rainfall was 18.6%, while QtileUT to rainfall was 15.8%.

It is important to note that the model was calibrated with the modified temperatures. Calibration parameters (Table S3) may have been different if the unmodified temperatures were used in calibration. The tile monitoring shows that in some situations, tiles flow when air temperatures are below 0 °C. SWAT's soil temperature was not reacting with the unmodified air temperature keeping the soil frozen and thus not simulating tile flow. This simple modification allows for the correct tiles response without altering major hydrological components. More research is needed in terms of developing a physically-based soil-temperature module.

Table S4. Annual average hydrological cycle components from the calibrated and unmodified air input temperatures simulations in the Eagle Creek watershed, Ohio SWAT model.

Annual Average	Calibrated	Unmodified Temperatures
Surface Runoff (mm)	138.46	145.69
Lateral soil flow (mm)	7.09	6.92
Tile flow (mm)	161.76	156.98
Groundwater, shallow aquifer (mm)	14.76	14.05
Groundwater, deep aquifer (mm)	3.64	3.47
Revap (mm)	12.61	12.61
Aquifer Recharge (mm)	18.47	17.58
Percolation (mm)	20.98	19.71
Water Yield (mm)	325.71	327.12

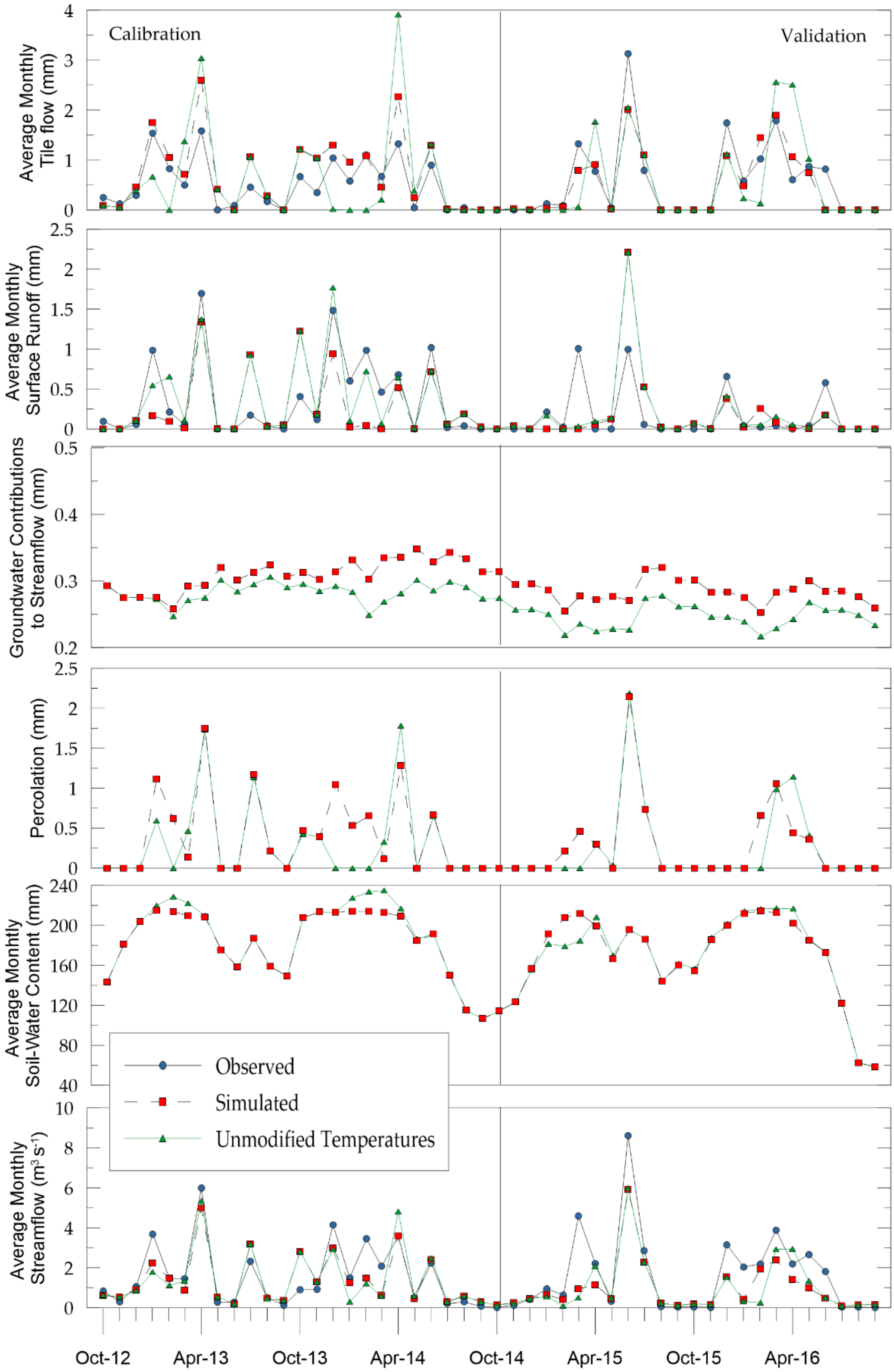

Figure S1. Comparison of with observed (where available), simulated, and simulated without modified input air temperature in tile flow, surface runoff, groundwater contributions to streamflow, percolation, soil-water content, and streamflow in tile, edge-of-field (EOF), and HUC12 outlet monitoring stations in the Eagle Creek watershed, Ohio.

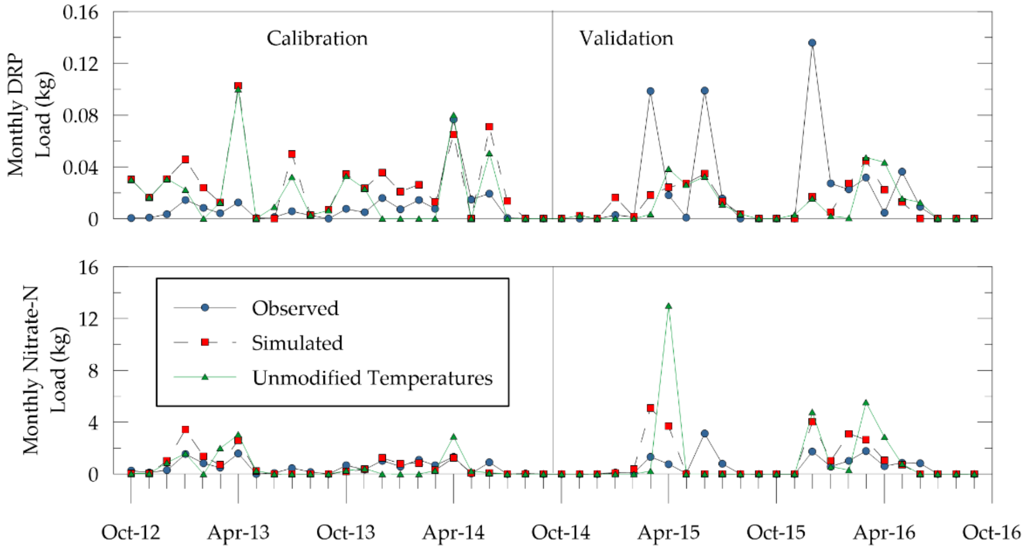

Figure S2. Comparison of monthly observed, simulated, and simulated without input air temperature modifications in nitrate-nitrogen and dissolved reactive phosphorus (DRP) in tile flow at the tile monitoring station in Eagle Creek watershed, Ohio.

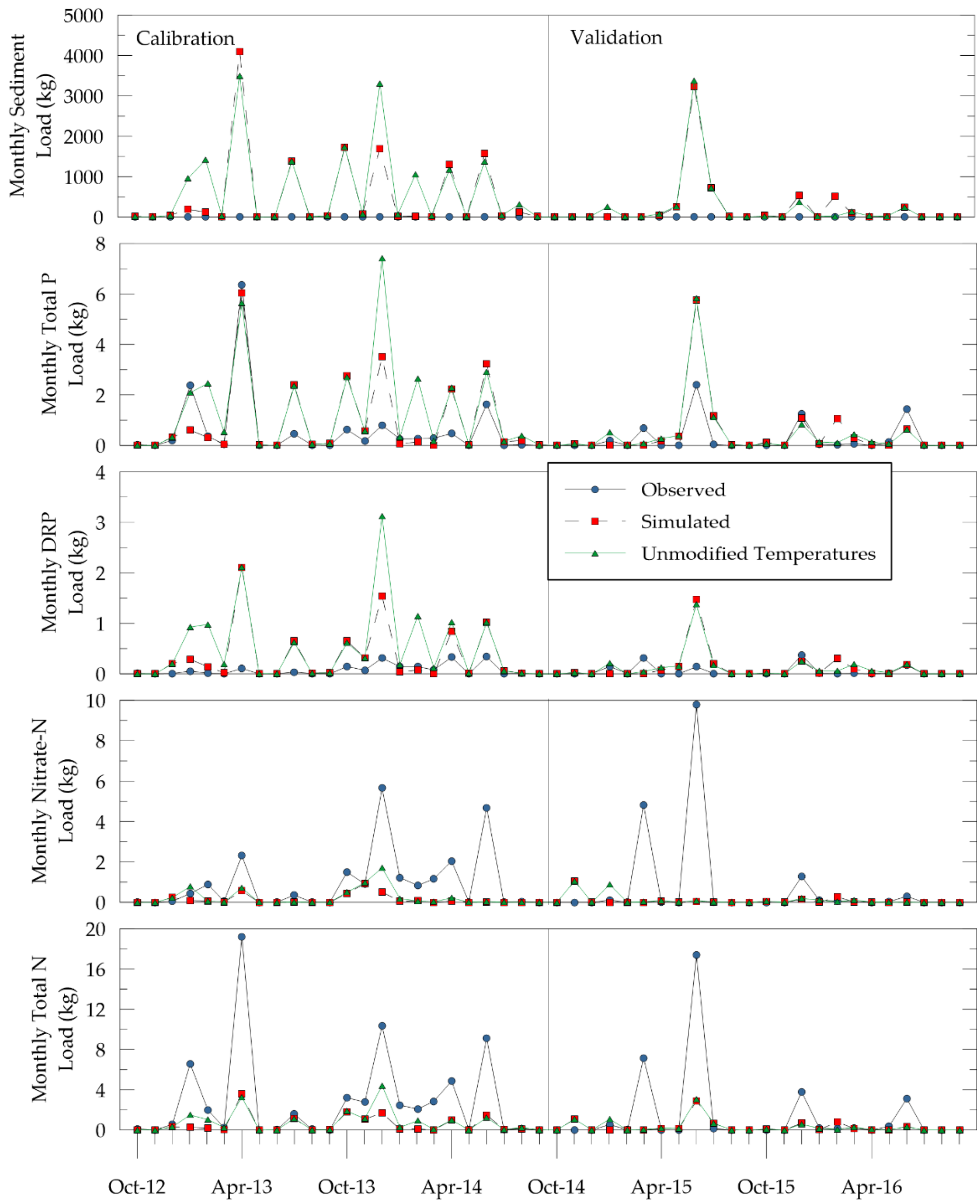

Figure S3. Comparison of monthly observed, simulated, and simulated without input air temperature modifications in sediment, total phosphorus, dissolved reactive phosphorus (DRP), nitrate-nitrogen, and total nitrogen at the edge-of-field (EOF) monitoring station in Eagle Creek watershed, Ohio.

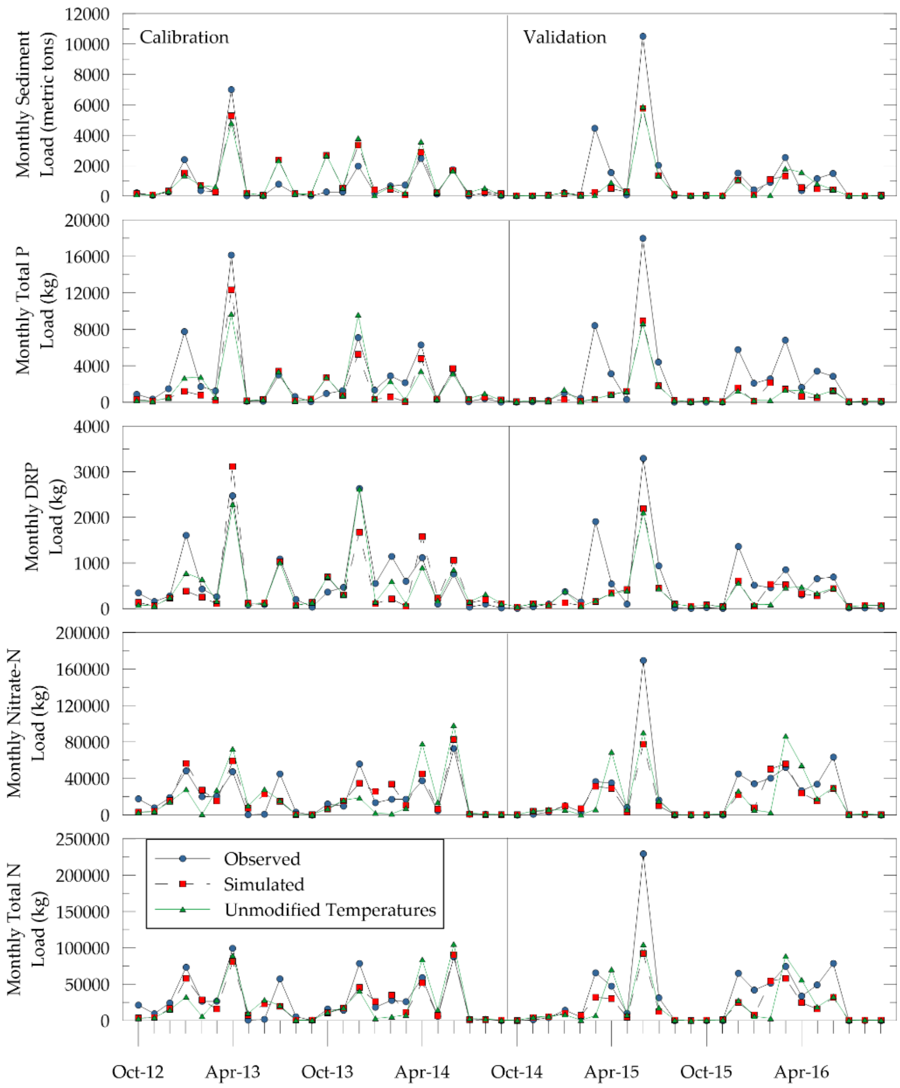

Figure S4. Comparison of monthly observed, simulated, and simulated without input air temperature modifications in sediment, total phosphorus, dissolved reactive phosphorus (DRP), nitrate-nitrogen, and total nitrogen at the HUC12 outlet, Eagle Creek, Ohio.

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