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IMPORTANCE OF CROP YIELD IN CALIBRATING WATERSHED WATER QUALITY SIMULATION TOOLS[1]

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ABSTRACT: Watershed-scale water-quality simulation tools provide a convenient and economical means to evaluate the environmental impacts of conservation practices. However, confidence in the simulation tool's ability to accurately represent and capture the inherent variability of a watershed is dependent upon high quality input data and subsequent calibration. A four-stage iterative and rigorous calibration procedure is outlined and demonstrated for Soil Water Analysis Tool (SWAT) using data from Upper Big Walnut Creek (UBWC) watershed in central Ohio, USA. The four stages and the sequence of their application were: (1) parameter selection, (2) hydrology calibration, (3) crop yield calibration, and (4) nutrient loading calibration. Following the calibration, validation was completed on a 10 year period. Nash-Sutcliffe efficiencies for streamflow over the validation period were 0.5 for daily, 0.86 for monthly, and 0.87 for annual. Prediction efficiencies for crop yields during the validation period were 0.69 for corn, 0.54 for soybeans, and 0.61 for wheat. Nitrogen loading prediction efficiency was 0.66. Compared to traditional calibration approaches (no crop yield calibration), the four-stage approach (with crop yield calibration) produced improved prediction efficiencies, especially for nutrient balances.

(KEY TERMS: SWAT; modeling; nutrients; crop yield; biomass; runoff.)

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INTRODUCTION

The success of any non-point source (NPS) pollution reduction program in agriculture depends on availability of suitable methods and tools to evaluate the effectiveness of the proposed programs in improving water quality. In this context, computer-based watershed-scale biophysical process models can be a useful tool to assess the effectiveness of conservation practices in watersheds. However, it is essential that these models allow representation of a wide variety of crops and technology combinations for evaluation and provide reasonable estimates of crop yield and environmental impact of crop production.

During the last couple of decades, several watershed models have been developed to understand NPS pollutant fate and transport processes on a heterogeneous landscape. The Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998) is a basin-scale computer

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model designed for assessing watershed-scale impacts of conservation management, particularly for agricultural dominated watersheds (Arnold and Fohrer, 2005; Gassman *et al.*, 2007). SWAT was selected because of its proven worthiness as a tool for understanding watershed-scale management impacts on nutrient loading from agriculture (Gassman *et al.*, 2007). Additionally, Borah and Bera (2004) reviewed several watershed models for their usefulness in modeling nutrient export with different land management strategies at a watershed scale and suggested that SWAT was a suitable and promising model for long-term continuous simulations in agricultural watershed compared to other evaluated models.

In general, calibration and validation of SWAT typically has been evaluated by comparing the simulated surface runoff, and nutrient concentration in runoff, against measured values at a watershed outlet (Gassman *et al.*, 2007). However, the processes affecting the water and nutrient balance in an agricultural watershed are highly influenced by crop production. The relationships of crop biomass and yield are more relevant to the water balance than the rainfall-runoff processes (Luo *et al.*, 2008), which is also true for the nutrient balance in an agricultural watershed (Hatano *et al.*, 2002; Meisinger *et al.*, 2008). Bypassing crop biomass and yield calibration in SWAT may also result in poor quantification of crop residue remaining after harvest, adversely affecting the simulation of surface run-off and nutrient cycling (Baumgart, 2005). Thus, an accurate representation of watershed hydrology and the nutrient balance requires calibration of crop biomass and yield. Processes that link crop, water, and nutrient balances in SWAT are important, particularly when simulations are used for water quality evaluations.

Despite the influence of crop growth on both hydrology and nutrient cycling, calibration of the crop growth component has rarely been reported (Baumgart, 2005). Additionally, SWAT calibration and validation procedures outlined in the SWAT documentation manuals do not discuss the need for crop yield calibration (Neitsch *et al.*, 2002). A few studies have adjusted crop parameters as a part of their hydrologic or nutrient calibration and indirectly tested the crop submodel. Baumgart (2005) attempted calibration and validation of the SWAT crop submodel using county level crop yield data. Hu *et al.* (2007) calibrated the SWAT crop components while applying the model to assess nitrate movement in an eastern Illinois watershed and reported simulated crop yields within 10% of observed data. Kannan *et al.* (2007) used externally calculated heat units and published crop growth parameters including maximum leaf area index (LAI), canopy height, and root depth for hydrologic calibration of SWAT and reported that the changes made in crop parameters substantially improved the simulation. However, this study did not provide any information about the impact of these changes on crop biomass production and crop yield. Luo *et al.* (2008) used field measured data to test the crop growth and soil water module in SWAT and reported that SWAT performed well in simulating LAI, biomass, and soil water moisture. As crop yield is an essential input for any economic analysis of conservation management, there is a growing interest in simultaneously evaluating the impact of conservation management on both crop yield and water quality to support a proper benefit cost analysis of conservation management.

Thus, the goal of this study was to build upon previous research by further investigating the model's accuracy in simulating crop biomass and yield, surface flow, nutrient loading, and their interaction in a watershed. Our hypothesis is that the inclusion of crop yield in the calibration process will improve the predictive capability of the model. We propose a calibration approach for SWAT by sequentially integrating hydrology, crop, and nutrient components (in the immediate study only nitrogen). A demonstration of the proposed calibration process is given for the UBWC watershed located in central Ohio.

The specific objectives of the study were:

1. To calibrate and evaluate SWAT (version 2005) for simulating streamflow, total nitrogen flux, and crop yield; and
2. To compare predictive efficiency of SWAT following sequential integration of flow, crop, and nitrogen components during calibration.

MATERIALS AND METHODS

Study Area

The UBWC watershed is a 10-digit watershed located in central Ohio (40°06′00″ latitude and 82°42′00″ longitude). It covers 492 square kilometers with 467 km of perennial and intermittent streams that drain into Hoover Reservoir (Figure 1). Soils in the watershed are mostly moderately fine-textured, moderately well drained to very poorly drained, and consist primarily of Cardington (9.6%), Centerburg (20.4%), Bennington (34.6%), and Pewamo (17.2%). Approximately 18% of the watershed is comprised of other minor soils and water. Agriculture is the dominant land use, followed by forest and urban land use. The primary agricultural crops are corn, soybeans, and wheat (USDA-NASS, 2005). Typical agricultural

FIGURE 1. The Upper Big Walnut Creek Watershed, Ohio.

management includes conservation tillage, fertilization, and herbicide application. Normal daily temperatures range from an average minimum of −9.6°C in January to a mean maximum of 33.9°C in July. Normal annual rainfall in the watershed area is approximately 985 mm. Monthly rainfall follows a bimodal distribution with peaks during late spring-early summer and late fall-early winter (King *et al.*, 2008). The UBWC watershed is one of the 12 benchmark watersheds in the United States being evaluated as part of the USDA Agricultural Research Service component of the Conservation Effects Assessment Project (Duriancik *et al.*, 2008). As part of the USDA research program, conservation practices were intensively evaluated in two pairs of experimental watersheds for hydrological, chemical, and ecological responses to conservation practices within the UBWC watershed. Agricultural practices in the selected watersheds are representative of those in the larger UBWC watershed. See King *et al.* (2008) for further details regarding these experimental watersheds.

SWAT Model Description

The SWAT model is a physically based, watershed-scale continuous time simulation model operating on a daily time step (Arnold *et al.*, 1998). Major components of the model include hydrology, weather, erosion, soil temperature, crop growth, nutrients, pesticides, and management activities. The hydrologic processes include evapotranspiration (ET), infiltration, percolation, channel transmission losses, channel routing, surface and lateral flow, shallow aquifer, deep aquifer, and subsurface drainage discharge. SWAT comprehensively links hydrology, nutrient cycling, and crop growth, making it ideal to simulate long-term impacts of climate, land use, and management practices. A thorough description of the theoretical aspects of hydrology, nutrient cycling, and crop growth and their interlinkages in SWAT are provided in Neitsch *et al.* (2005).

As in many crop simulation models, crop growth in SWAT is based on the accumulation of heat units. Once the acquired cumulative heat unit of the crop has surpassed the cumulative heat unit required to reach the maturity, growth of the crop ceases. For each day of simulation, SWAT initially calculates the potential crop growth, i.e., crop growth with plenty of water and nutrients and temperature in the ideal range. If the required potential growing conditions do not exist in a simulation day, SWAT identifies a particular day as a stress day and potential biomass is reduced due to stresses. In addition to biomass, daily LAI is also adjusted for abiotic stress except for the first day of simulation. The daily biomass production in SWAT is simulated by using static radiation use efficiency of the crop, LAI and absorbed photosynthetically active radiation. ET is simulated each day by a user defined ET method and daily LAI. Biomass growth and ET are linked together in the model. The nutrient requirement for each day of biomass growth is calculated by using growth stage specific nutrient factors. SWAT uses three different factors for calculating daily nutrient demand (nutrients at crop emergence, 50% maturity, and at maturity). However, crop nutrient uptake is limited by nutrient supply from the soil. In the case of nitrogen fixing crops, SWAT allows the crop to fix as much nitrogen as needed to meet crop nitrogen demand. The crop yield is computed using harvest index (HI) of the crop, which is defined as the fraction of above ground biomass removal at harvest. The nutrient removed by crop harvest is calculated by using crop yield and nutrient content in the yield.

SWAT Model Setup

The watershed boundary was delineated with the ArcGIS-SWAT (ArcSWAT) interface (Olivera *et al.*, 2006) using 30 m resolution digital elevation model (DEM) data from USGS National Elevation Dataset

(USGS, 2007) and a predefined digital stream network from the USGS National Hydrologic Dataset (USGS, 2002). The watershed was divided into eight subwatersheds with a threshold drainage area of 2,500 ha. ArcSWAT divides a subwatershed into smaller discrete hydrological response units (HRUs) with homogeneous biophysical properties using slope, soil, and land-cover maps. Land cover in the UBWC watershed was derived from the National Land Cover Dataset 2001 from USGS (USGS-NLCD, 2001) and slope classes were calculated within SWAT using the DEM. The medium resolution (1:250,000 scale) STATSGO soil map (USDA-NRCS, 2006) was used to characterize soils in the watershed. HRU delineation was completed using the multiple HRU option in ArcSWAT and resulted in 376 HRUs. There were 246 agricultural HRUs, with an average size of 87 ha, which was consistent with the average farm size of 81.1 ha within the watershed. Climatic inputs for the UBWC watershed during the study period (1987-2005) were collected from different sources. The National Climatic Data Center's (NCDC) weather stations at Westerville (gage number 338951) and Centerburg (number 331404) provided daily precipitation, which are available at http://www.ncdc.noaa.gov/oa/ncdc.html. Other climatic inputs, such as daily maximum and minimum temperatures, solar radiation, wind speed, and relative humidity were obtained from the Ohio Agricultural Research and Development Center's weather station at Delaware, Ohio available at http://www.oardc.ohio-state.edu/newweather/.

The SWAT model requires detailed information regarding land use and management practices. Management practices include crop type, crop rotation, planting and harvesting dates, tillage practices, and fertilizer rates. The present study considered 20 agricultural management systems described over 16 years to capture the changes in management options during the simulation period. The cropping rotations considered were corn-soybean, corn-soybean-soybean, and corn-soybean-wheat. Planting and harvesting dates were selected based on cumulative density functions created from county-based agricultural statistics data (NASS, 1990-2005). Nitrogen and phosphorus application rates (N:P) for corn (168 kg/ha:67.2 kg/ha), soybean (16.8 kg/ha:56 kg/ha), and wheat (84 kg/ha:56 kg/ha) were based on tri-state fertilizer recommendations (Vitosh *et al.*, 1995). In addition, split application of nitrogen for corn (112 kg/ha at planting followed by 56 kg/ha as side dressing 1 month after planting) was also included in the 20 management scenarios. Information on tillage practices was taken from the results of surveys conducted by the Conservation Technology Information Center (CTIC).

Calibration and Validation Assessment

Model performance was evaluated using two commonly used error measures in modeling, Nash-Sutcliffe coefficient of efficiency (E) (Nash and Sutcliffe, 1970) and the linear regression coefficient of determination (R^2), which were calculated as follows:

$$E = 1 - \frac{\sum \left(\widehat{X_1} - \overline{X}\right)^2}{\sum \left(X_i - \overline{X}\right)^2}$$

$$R^2 = \frac{\left[\sum \left(\widehat{X_1} - \overline{\widehat{X}}\right)(X_i - \overline{X})\right]^2}{\sum \left(\widehat{X_1} - \overline{\widehat{X}}\right)^2 (X_i - \overline{X})^2}$$

where $\widehat{X_1}$, X_i are individual simulated and individual observed values, respectively, and $\overline{\widehat{X}}$ and $\overline{X}$ are the mean of simulated and the mean of observed values, respectively.

The E values may vary from one to negative infinity. The E is a numeric measure of the relationship between the observed and predicted values and a 1:1 line (a line of slope 1 and intercept 0). Values near 1 indicate that there exists a close agreement with observed and predicted data. Values near zero or less imply that the average value of the observed data is more reliable than the model prediction (Legates and McCabe, 1999). The R^2 value is an indication of the model's ability to explain the variance in the measured data. R^2 values may range from zero to one. The predicted and measured data show no correlation when R^2 equals zero and dispersion of the predicted and measured data become equal when R^2 equals one (Krause *et al.*, 2005).

Moriasi *et al.* (2007) proposed a threshold E value of >0.5 for accepting monthly calibration of SWAT for water quality applications. Considering the Moriasi *et al.* (2007) recommendation, E values of 0.4 (daily), 0.5 (monthly), and 0.7 (annual) were used here as criteria for accepting daily, monthly, and annual time period calibrations. The same threshold values were used to judge the model's performance for R^2 (Gassman, 2008). During calibration, crop yield parameters were calibrated to achieve the highest possible E and R values. For the regression analysis, a t-test was used to determine whether or not the intercept was significantly different from zero and the slope was significantly different from one.

Four-Stage Calibration of SWAT

In agricultural or rural watersheds like UBWC, accurately representing crop water use and nutrient uptake are critical for interpreting the hydrology and nutrient balances. Thus, it is important to consider crop yield in the calibration process. A four-stage calibration approach was designed (Figure 2), and is described below.

Stage 1: Selection of Parameters. An uncalibrated, baseline simulation was performed as part of Stage 1 using SWAT default values for hydrologic, crop, and nutrient parameters. Additionally, a number of sensitive parameters were identified, and a realistic range of parameter values were selected based on the existing body of literature on SWAT (Arnold *et al.*, 1995; Santhi *et al.*, 2001; Neitsch *et al.*, 2002; Baumgart, 2005; Hu *et al.*, 2007; Kannan *et al.*, 2007; Gassman, 2008). Thirty-six hydrology, crop, and nutrient cycling input parameters were adjusted during Stages 2-4 of the calibration (Table 1) and details are reported in the results section.

Stage 2: Calibration of Hydrology and Processes Driving the Water Balance. In Stage 2, surface flow was calibrated with hydrology parameters selected in Stage 1 and efficiency criteria were applied to evaluate the simulated and observed surface flow over the calibration period. This was followed by evaluation of predicted ET values over the growing season for corn, soybean, and winter wheat with the reported crop ET values for the study area. In addition, the linkage between ET and LAI for corn, soybean, and winter wheat were also graphically evaluated. Once the crop ET, ET and LAI relation, and efficiency measures for hydrology met the outlined calibration criteria, then calibration moved forward to Stage 3. If not met, Stage 2 was reiterated

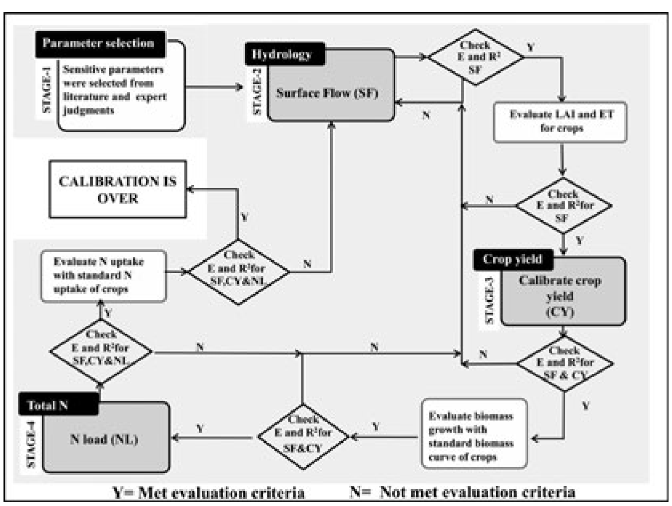

FIGURE 2. Comprehensive Calibration Approach.

by adjusting one or more parameters considered in the hydrology calibration.

Stage 3: Calibration of Crop Yield. Field measurements of corn, soybeans, and winter wheat biomass for the calibration period were not available. Thus, simulated biomass was evaluated against the standard cumulative biomass curves for these crops. However, crop yields for corn, soybeans, and wheat were calibrated and efficiency measures were calculated by using reported crop yields for the area. If the efficiency measures of crop yield and hydrology were satisfactory, then calibration was moved forward to Stage 4, otherwise Stages 2-3 were reiterated to improve the efficiency measures of calibration.

Stage 4: Calibration of Nutrient Loading and Crop Components in Nitrogen Balance. In Stage 4, nutrient loading was calibrated with selected parameters under the nitrogen balance in Stage 1. In addition, crop nitrogen uptake was evaluated over the growing season with standard cumulative nitrogen uptake curves for these crops. Efficiency measures for nutrient loading, crop yield, and hydrology results were calculated and if the results were satisfactory, calibration was complete. Otherwise iteration of Stages 2-4 were carried out to improve the calibration prediction efficiency.

Data Used for Calibration and Validation

Daily streamflow data from the USGS gage station within the UBWC watershed at Sunbury (gage number 03228300) were obtained for the period of 1990-2005. Data from 1990 to 1995 were selected for calibration and data from 1996 to 2005 were used for validation. A 3-year warm-up period was simulated for 1987-1989, prior to the calibration and validation periods.

County level corn, soybean, and wheat yield estimates for 1990-2005 were obtained from USDA-NASS (2005) for the five counties that the watershed spans (Delaware, Morrow, Knox, Licking, and Franklin). County level data for corn, soybean, and wheat yield (bushels per acre) were weighted by the watershed area in each county to determine watershed scale crop yield. Simulated crop yields were converted from tons per hectare of dry weight to bushels per acre of wet weight using relationships outlined by Gassman (2008). The calibration of total nitrogen (TN) load from the watershed was accomplished by using measured TN concentrations from two experimental paired headwater watersheds in the UBWC for the year 2005. TN loading data from one watershed within the pair was used for calibration of the model

TABLE 1. SWAT Parameters Adjusted During Calibration.

Parameter Name	Physical Meaning
PET method	Potential Evapotranspiration method
EPCO	Plant transpiration compensation coefficient
ESCO	Soil evaporation compensation coefficient
FFCB	Initial soil water storage (fraction of field capacity water content)
ICN	Daily CN calculation method (1 = ET based and 0 = soil moisture based)
CNCOEF	Plant ET curve number coefficient
ALPHA_BF	Base flow alpha factor (days)
CN2	Runoff curve number
SURLAG	Surface run-off lag coefficient
SOIL_AWC	Available water capacity of the soil layer (mm H_2O/mm soil)
DDRAIN	Drain tile lag time
TDRAIN	Time required to drain soil from saturation to field capacity (h)
GDRAIN	Drain tile lag time (the amount of time for water to transport through the drain tile) (h)
BIO_E CORN	Plant radiation use efficiency for corn (MJ/m^2)
BIO_E SOYBEAN	Plant radiation use efficiency for soybean (MJ/m^2)
BIO_E WINTER WHEAT	Plant radiation use efficiency for winter wheat (MJ/m^2)
Harvest Index CORN	Harvest index for corn
Harvest Index SOYBEAN	Harvest index for soybean
Harvest Index WINTER WHEAT	Harvest index for winter wheat
LAI CORN	The maximum potential leaf area index for corn
LAI SOYBEAN	The maximum potential leaf area index for soybean
LAI WINTER WHEAT	The maximum potential leaf area index for winter wheat
CNYLD CORN	Nitrogen content in corn yield (kg N/kg yield)
CNYLD SOYBEAN	Nitrogen content in soybean yield (kg N/kg yield)
CNYLD WINTER WHEAT	Nitrogen content in winter wheat yield (kg N/kg yield)
Nitrogen uptake parameter #1 CORN	Nitrogen uptake factor at emergence for corn (kg N/kg biomass)
Nitrogen uptake parameter #1 SOYBEAN	Nitrogen uptake factor at emergence for soybean (kg N/kg biomass)
Nitrogen uptake parameter #1 WINTER WHEAT	Nitrogen uptake factor at emergence for wheat (kg N/kg biomass)
Nitrogen uptake parameter #2 CORN	Nitrogen uptake factor at 50% maturity for corn (kg N/kg biomass)
Nitrogen uptake parameter #2 SOYBEAN	Nitrogen uptake factor at 50% maturity for soybean (kg N/kg biomass)
Nitrogen uptake parameter #2 WINTER WHEAT	Nitrogen uptake factor at 50% maturity for wheat (kg N/kg biomass)
Nitrogen uptake parameter #3 CORN	Nitrogen uptake factor at maturity for corn (kg N/kg biomass)
Nitrogen uptake parameter #3 SOYBEAN	Nitrogen uptake factor at maturity for soybean (kg N/kg biomass)
Nitrogen uptake parameter #3 WINTER WHEAT	Nitrogen uptake factor at maturity for wheat (kg N/kg biomass)
CMN	Humus mineralization factor
NPERCO	Nitrate percolation rate

and TN loading data from the second watershed of the pair was used for validation of the model.

RESULTS AND DISCUSSION

Hydrology

During the second stage of calibration (hydrology), it was determined that the monthly summer streamflow was consistently overpredicted, while ET was underpredicted. Thus, the primary focus of the hydrology calibration was to adjust the hydrology parameters in an effort to reduce the predicted summer streamflow while increasing the summer values for ET. Multiple iterations were completed to identify the optimal calibrated values. The default potential evapotranspiration (PET) calculation method, Penman/Monteith (Monteith, 1965), was replaced by Hargreaves PET method (Hargreaves *et al.*, 1985). Additionally the curve number (CN) was adjusted daily based on plant ET rather than available moisture capacity (Williams and Laseur, 1976; Green *et al.*, 2006; Kannan *et al.*, 2008), by setting the curve number calculation method (ICN) to 1 and the depletion coefficient (CNCOEF) to 0.88 (Table 2). Thus, during the summer months when ET dominates the hydrologic cycle, the CN is automatically adjusted downwardly, permitting greater amounts of infiltration and eventually ET.

Based on previous model applications (Witter, 2006), the initial soil water storage fraction (FFCB) parameter was set to 0.78. To represent extensive subsurface drainage in the southeast part of the watershed, DDRAIN, TDRAIN, and GDRAIN were fixed at 940 mm, 48 h, and 1 h for HRUs located in

TABLE 2. Hydrologic Parameters Adjusted During Four Stage Calibration.

	Original Value	Calibrated Value
PET method	Penman/Monteith	Hargreaves
EPCO	1	0.95
ESCO	0.95	0.98
FFCB	0	0.78
ICN	0	1
CNCOEF	1	0.88
ALPHA_BF	0.048	0.02
CN2	Initial value	Reduced by 10%
SURLAG	4	1
SOIL_AWC	Initial value	Increased by 20%
DDRAIN	0	940
TDRAIN	0	48
GDRAIN	0	1

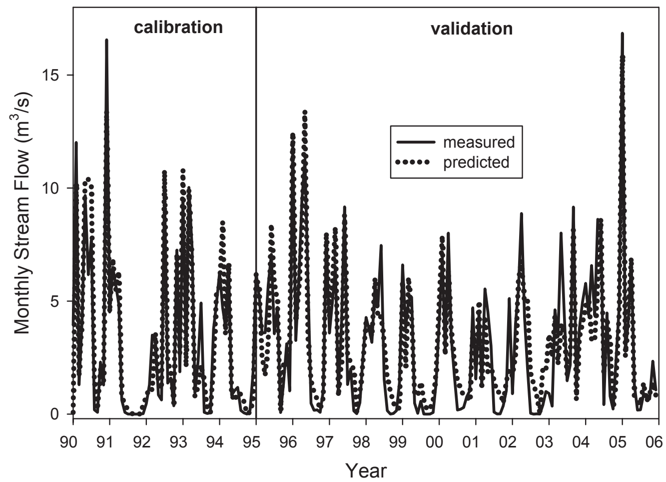

FIGURE 3. Calibration (A) and Validation (B) of Streamflow at USGS Station (gage number 03228300) Located in UBWC Watershed.

the southeastern subwatersheds. Additionally, initial condition curve numbers (CN2) were decreased by 10% for all HRUs. A decrease in CN2 increases water movement into the soil profile. The soil available water capacity (SOL_AWC) was increased by 20% to augment the water storage in the soil profile, permitting the water entering the soil to be available for crop use. Furthermore, the base flow parameter, ALPHA_BF was reduced from 0.048 to 0.02 based on an analysis of USGS stream gage data and an application of a base flow separation program (Arnold *et al.*, 1995). Subsequently, the soil evaporation compensation factor (ESCO) and plant uptake compensation factor (EPCO) parameters were adjusted to better represent crop ET demands. To address event timing, the parameter that controls daily runoff as a fraction of total available water, surface runoff lag coefficient (SURLAG), was changed to 1.

The monthly time series for the calibration and validation periods are presented in Figure 3. In general, the trends in predicted streamflow were consistent with those of observed streamflow. However, discrepancies in peak flow predictions were noted, especially during the validation period. The model efficiency calculations (Table 3) showed that the calibrated model met all the model evaluation criteria. Additionally, intercepts of regression were not significantly different from zero and slopes of regression lines were not significantly different from one for the monthly and annual time steps (Table 3).

Streamflow is only one aspect of the hydrologic balance. ET is as equally important in the hydrologic balance, especially in agricultural watersheds. Following calibration, predicted ET during the validation period was compared with published values for the Ohio crop production region. ET predicted by SWAT using the Hargreaves method was 478 mm for corn and 439 mm for soybeans compared to 464 mm for corn and 432 mm for soybeans reported by Allred *et al.* (2003) for the same region. To ensure crop water usage over the growing season was modeled appropriately, growing season distributions of ET and LAI for corn, soybeans, and wheat for a randomly selected HRU and year were analyzed (Figure 4). Based on visual analysis, the relationship between LAI and ET appears to be simulated correctly; ET increases with increasing LAI and declines following declines in LAI. Thus, the hydrologic simulation results demonstrated that the calibration effectively addressed the crop water usage component of the watershed water balance.

Crop Yield

Stage 3 of the simulation process was to calibrate crop yields. Initial simulated crop yields for all three crops were consistently greater than reported regional yields. However, temporal variability in yield was captured to some extent by the crop submodel. Thus, further calibration was focused on reducing the predicted yield. Following Baumgart (2005), the radiation-use efficiency (BIO_E) was reduced from 35 to 30 for corn, from 25 to 20 for soybean, and from 30 to 25 for wheat. Additionally, the maximum potential LAI was changed to 3.5, 2, and 3 for corn, soybean, and wheat, respectively. The HI was adjusted to 0.45 for corn, 0.27 for soybeans, and 0.35 for wheat (Table 4). Average annual yield for corn, soybean, and wheat following calibration are reported in Table 5. The predicted average annual yields for corn, soybean, and wheat for the calibration and validation periods were not significantly different ($p > 0.01$) from reported yields for the watershed.

TABLE 3. Calibration of Streamflow.

Time Interval		Number of Observations	E	Regression R^2	Intercept	SE	Slope	SE	t-value[1]
Daily	Calibration	2191	0.68	0.68	0.41***	0.11	0.75	0.01	25.00***
	Validation	3653	0.50	0.51	0.52***	0.1	0.58	0.01	42.00***
Monthly	Calibration	72	0.85	0.86	0.36	0.21	0.87	0.09	1.45
	Validation	120	0.86	0.85	0.02	0.16	0.86	0.09	1.56
Annual	Calibration	6	0.98	0.97	−0.05	0.29	0.92	0.09	0.89
	Validation	10	0.87	0.87	0.09	0.42	0.86	0.14	1.00

Notes: Critical values for daily, monthly and yearly time interval for calibration are 2.58, 2.65, and 3.37. Critical values for daily, monthly, and yearly time interval for validations are 2.58, 2.62, and 2.82.
***Significant at 0.01.
[1]Intercept is tested against 0 and slope is tested against 1.

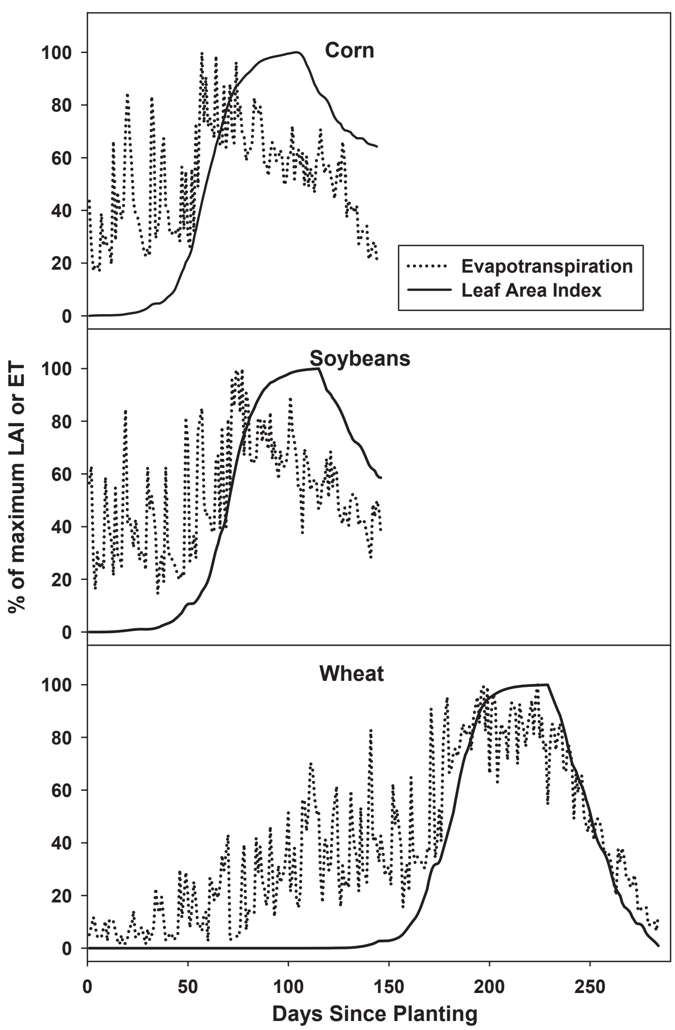

FIGURE 4. Simulated Evaporation/Transpiration (mm) and LAI for Corn, Soybeans, and Winter Wheat.

Considerable variation in all crop yields was noted between the calibration and validation periods. Once calibrated, SWAT was able to accurately predict variation in crop yield (Figure 5). Prediction efficiencies

TABLE 4. Crop Parameters Adjusted During Third Stage Calibration.

	Original Value	Calibrated Value
BIO_E		
• Corn	35	30
• Soybean	25	20
• Winter Wheat	30	25
Harvest Index		
• Corn	0.50	0.44
• Soybean	0.31	0.27
• Winter Wheat	0.40	0.35
LAI		
• Corn	3.0	3.5
• Soybean	3.0	2.0
• Winter Wheat	4.0	3.0

TABLE 5. Average Reported and Simulated Crop Yields.

Crop		Number of Observations	Crop Yield (bushels per acre) Reported	Modeled	t-value[1]
Corn	Calibration	6	118.04	113.95	0.73
	Validation	10	126.93	125.20	0.52
Soybean	Calibration	6	37.37	38.67	0.95
	Validation	10	40.63	43.55	0.91
Winter	Calibration	6	54.95	55.70	0.59
Wheat	Validation	10	62.42	66.11	2.04

[1]Critical "t" value for calibration is 3.37 and validation is 2.82.

(E) for the corn yields were 0.52 during the calibration period and 0.69 during the validation period (Table 6). Similar results were noted for soybean and wheat yields as well. The prediction efficiencies for corn and soybean were consistent with other reported efficiency values (Hu *et al.*, 2007). Evaluation of the measured and predicted regression lines indicated that intercepts were not significantly different from zero and slopes were not significantly different from one except for corn in the validation period (Table 6).

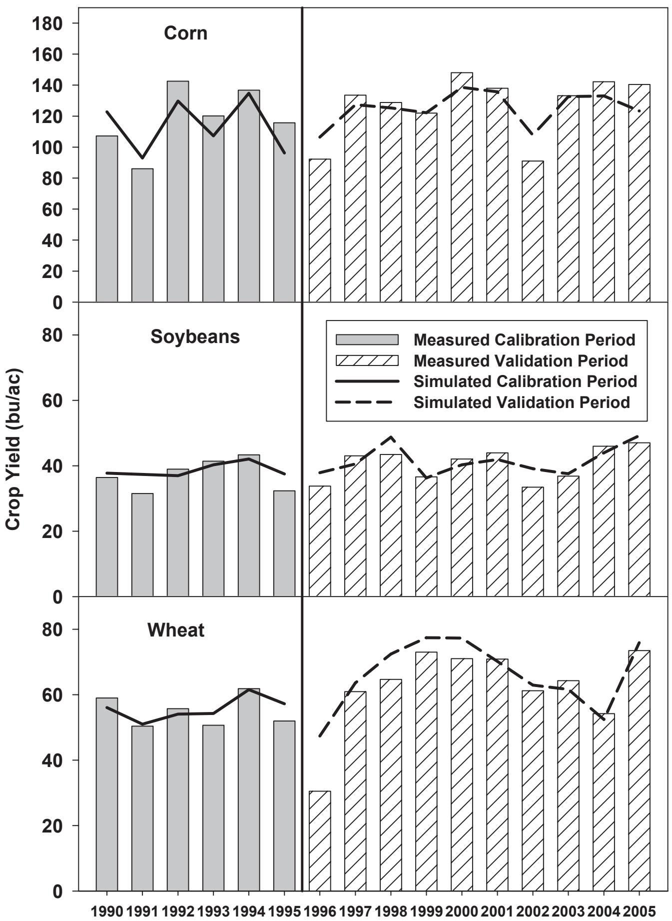

FIGURE 5. Simulated and Reported Crop Yield for Corn, Soybean, and Winter Wheat.

TN Loading

Nitrogen calibration was the fourth and final calibration stage. In an agricultural watershed, calculation of crop yield is important to the overall nitrogen balance. Crops either consume a major portion of applied nitrogen or add nitrogen to the system by biological nitrogen fixation (e.g., soybeans). For the nutrient balance, crops account for two major pools of nitrogen, that removed in the harvested biomass and that returned to the soil through crop residue.

When calibrating TN loading, both input and output sources are required to be considered. Crop yield in SWAT is defined as the fraction of above-ground biomass removed during the harvest as defined by the HI. Plant nitrogen demand and uptake throughout the growing season is accomplished by the nitrogen uptake parameters, PLTNFR-1 (uptake at emergence), PLTNFR-2 (uptake at 50% maturity), and PLTNFR-3 (uptake at full maturity). Calibration of uptake parameters was completed on a crop by crop basis. Initial predicted biological nitrogen fixation by soybeans was greater than reported values but similar to results reported by Hu *et al.* (2007) and Gassman (2008). Thus, PLTNFR-1, PLTNFR-2, and PLTNFR-3 were adjusted in the downward direction to decrease the nitrogen demand by soybeans, which resulted in a lower nitrogen fixation compared to initial simulation results. Following calibration, nitrogen fixation (83.5 kg N/ha) was within the average soybean nitrogen fixation range of 61-122 kg N/ha reported for the state of Ohio (Russelle and Birr, 2004).

Additionally, the amount of nitrogen removed by the crop yield was achieved by calibrating the fraction of nitrogen in the yield parameter (CN_YLD) (Table 7). Figure 6 shows the simulated nitrogen uptake and biomass accumulation over the growing period for corn, soybean, and wheat for a randomly selected HRU in one subwatershed and the standard nitrogen and biomass accumulation graph for the respective crops. The partitioning of biomass and nitrogen uptake predicted by SWAT was similar to the standard biomass and nitrogen accumulation curves for the respective crops. Further examination of nitrogen uptake and biomass accumulation in HRUs across the subwatershed showed that variation among HRUs does not impact the partitioning of biomass and nitrogen uptake predicted by SWAT.

In addition to the crop parameters, two other nitrogen cycling parameters were adjusted. The humus

TABLE 6. Efficiency Criteria for Crop Yield Calibration.

Crops		Number of Observations	*E*	Regression					
				R^2	Intercept	SE	Slope	SE	*t*-value[1]
Corn	Calibration	6	0.52	0.58	17.15	43.23	0.88	0.38	−0.32
	Validation	10	0.69	0.88	−87.53***	27.98	1.71***	0.22	3.22***
Soybean	Calibration	6	0.51	0.62	−33.72	27.95	1.84	0.72	1.16
	Validation	10	0.54	0.61	4.59	10.24	0.87	0.24	0.55
Winter Wheat	Calibration	6	0.53	0.57	−0.99	24.24	1.01	0.44	0.02
	Validation	10	0.61	0.81	−10.55	12.71	1.11	0.19	0.57

***Significant at 0.01.

[1]Intercept is tested against 0, slope is tested against 1, and critical "*t*" value for calibration is 3.37 and validation is 2.82.

mineralization coefficient (CMN) was reduced and the coefficient for percolation (NPERCO) was increased to obtain better predictions. Observed monthly TN loads for both the calibration and validation periods for the two sets of paired watersheds in the UBWC watershed are given in Figure 7.

TABLE 7. Parameters Adjusted During Total Nitrogen Calibration.

	Original Value	Calibrated Value
CNYLD		
• Corn	0.0140	0.0125
• Soybean	0.0650	0.0500
• Winter Wheat	0.0250	0.0150
Nitrogen uptake parameter #1		
• Corn	0.0140	0.0125
• Soybean	0.0650	0.0500
• Winter Wheat	0.0250	0.0200
Nitrogen uptake parameter #2		
• Corn	0.0470	0.0370
• Soybean	0.0524	0.0400
• Winter Wheat	0.0663	0.0463
Nitrogen uptake parameter #3		
• Corn	0.0138	0.0115
• Soybean	0.0258	0.0188
• Winter Wheat	0.0148	0.0108
• CMN	0.0003	0.0002
• NPERCO	0.2000	0.8500

For the calibration and validation periods, monthly E values were 0.73 and 0.65, respectively, for the first set of paired watersheds (A&B), and 0.80 and 0.65, respectively, for the second set of paired watersheds (C&D). In addition, intercepts of regression lines were not significantly different from zero during the calibration or validation periods. Moreover, slopes of the regression lines were not significantly different from one in three cases, except for the calibration period for Pair-1 (Table 8). All values were similar to the reported E value for TN loads in previous SWAT studies (Gassman *et al.*, 2007).

Progressive Change in E and R^2 During Each Stage of Calibration

Improvements in E and R^2 with each calibration stage is compared to the baseline model (without calibration) to highlight the need for including crop yield calibration in the calibration process. It is clear that

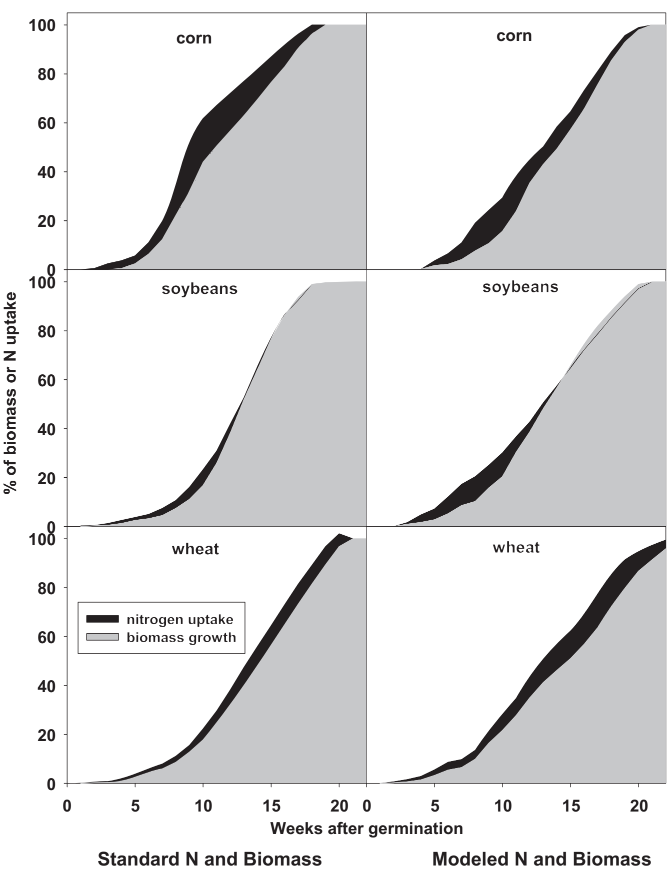

FIGURE 6. Comparison of Modeled nitrogen (N) and Biomass Accumulation for Corn, Soybean, and Wheat With the Standard N and Biomass Accumulation Curves of Corn (Ritchie *et al.*, 1986), Soybean (Ritchie *et al.*, 1982), and Wheat (Hickman *et al.*, 1994).

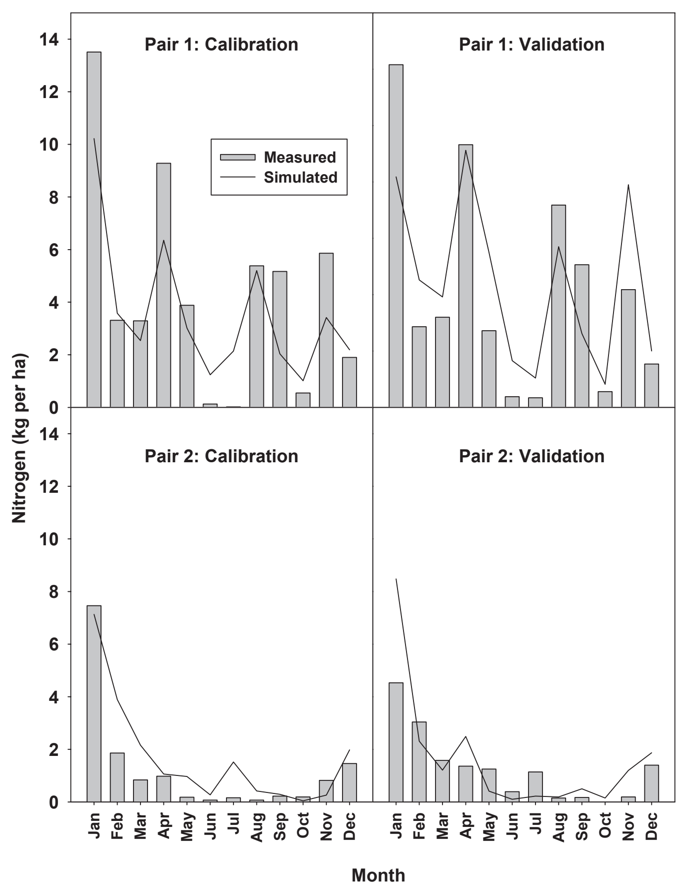

FIGURE 7. Simulated and Observed Total N Loading From Paired Watersheds.

TABLE 8. Efficiency Measures for Total Nitrogen Calibration.

Paired Watershed		Number of Observations	E	Regression					
				R^2	Intercept	SE	Slope	SE	t-value[1]
Pair – 3	Calibration	12	0.73	0.87	−0.58	0.74	1.64***	0.18	3.56
	Validation	12	0.65	0.66	−0.39	0.64	1.09	0.25	0.36
Pair – 2	Calibration	12	0.82	0.86	−0.31	0.31	0.91	0.11	0.82
	Validation	12	0.66	0.75	−0.01	0.01	1.41	0.29	1.41

***Significant at 0.01.
[1]Intercept is tested against 0, slope is tested against 1, and critical "t" value for calibration and validation is 2.72.

with sequential integration of flow, crop, and nitrogen components during calibration, prediction efficiency showed progressive improvement from Stage 2 to Stage 4 for discharge, crop yield, and nitrogen loading (Table 9 shaded area represents the noncalibrated steps). Improvement in E could be observed in all output time steps for discharge during the calibration period. The greatest E values for daily, monthly and annual output time steps were observed following Stage 4 calibration. However, maximum improvement in the E value occurred for the daily output time step in the calibration period, from −0.2 to 0.67. Additionally, R^2 was also found to be greatest in Stage 4 or equal to Stage 3 for discharge except for the annual output time step (Table 10 shaded area illustrates the noncalibrated steps).

In the case of crop yield, generally an improvement in E and R^2 was observed (Tables 9 and 10). As our focus was to improve overall efficiency of the model by meeting prefixed criteria for discharge, crop yield, and TN rather than individual improvement, improvement in discharge or TN would outweigh a corresponding reduction in E or R^2 value of crop yield.

Comparison of Four-Stage Calibration With Traditional Calibration

Crop biomass growth and crop yield influence the amount of nitrogen removed by the crop harvest and the amount of nitrogen added by nitrogen fixation (for soybean only). In addition, crop growth also influences ET, an important component in the watershed water balance. Thus, a comparison of these factors under four-stage calibration and traditional calibration was completed to understand the direct impact of crop calibration on the watershed nitrogen budget. Hence, another SWAT model for UBWC was developed and calibrated with a traditional approach. As the focus was to compare the crop nitrogen uptake, crop nitrogen fixation and crop nitrogen removal, details of traditional calibration (parameters adjusted for calibration) are not reported here. During streamflow calibration for the traditional method, CN2, EPCO, SOIL_AWC, ESCO, SURLAG, and CNCOEF were adjusted. TN calibration using the traditional approach was accomplished by adjusting NPERCO, N_UPDIS, CMN, and RSDCO. The streamflow efficiency measures indicated that both E and R^2 for the traditional approach were 3-5% better than the four-stage calibration approach. However, the efficiency measures for TN calibration showed that the E and R^2 values for the traditional calibration method were 10-20% lower than the corresponding four-stage calibration E and R^2 statistics. The area weighted ET for the model calibrated with the traditional approach (only corn and soybean were considered because the reported ET for the study area was available only for corn and soybean) was 494 mm and for the four-stage approach was 449 mm, which was consistent with the 452 mm area weighted average for corn and soybean calculated from reported ET for the region. In addition, the area

TABLE 9. Improvement in E Measures in Each Stage of Calibration.

		Flow			Crop			Nitrogen	
	Stages	Day	Month	Annual	Soybean	Corn	Wheat	Pair-3	Pair-2
Baseline	Stage-1	−0.2	0.62	0.66	−8.87	−5.22	−3.28	−1.64	−6.67
Calibration	Stage-2	0.54	0.56	0.61	−6.42	−7.03	−22.05	−4.35	−51.55
	Stage-2 & 3	0.67	0.85	0.98	0.52	0.52	0.58	−0.95	−4.99
	Stage-2, 3 & 4	0.68	0.85	0.98	0.51	0.52	0.53	0.73	0.82
Baseline	Stage-1	−0.31	0.52	0.65	−1.38	−7.32	0.29	−8.36	−14.8
Validation	Stage-2, 3 & 4	0.50	0.86	0.87	0.54	0.69	0.61	0.65	0.66

TABLE 10. Improvement in R^2 Measures in Each Stage of Calibration.

		Flow			Crop			Nitrogen	
	Stages	**Day**	**Month**	**Annual**	**Soybean**	**Corn**	**Wheat**	**Pair-3**	**Pair-2**
Baseline	Stage-1	0.44	0.75	0.86	0.24	0.23	0.27	0.00	0.14
Calibration	Stage-2	0.60	0.73	0.48	0.42	0.49	0.28	0.00	0.14
	Stage-2 & 3	0.68	0.50	0.99	0.60	0.59	0.76	0.02	0.04
	Stage-2, 3 & 4	0.68	0.86	0.97	0.62	0.58	0.57	0.87	0.86
Baseline	Stage-1	0.33	0.70	0.58	0.56	0.65	0.53	0.02	0.00
Validation	Stage-2, 3 & 4	0.51	0.85	0.87	0.61	0.88	0.81	0.66	0.75

weighted nitrogen removed by crops (corn and soybean), using the traditionally calibrated model was 195 kg/ha compared to 145 kg/ha using the four-stage calibration. The 145 kg/ha value was consistent with that reported by Hu *et al.* (2007). Thus, from this study it is clear that the four-stage approach for calibration would result in better efficiency values, better simulation of crop growth, and correct partitioning of the crop components of water and nitrogen balance in the watershed compared to the traditional approach.

CONCLUSIONS

The importance of a thorough calibration procedure that accounts for not only the major discharge and water quality (nitrogen here) components but also crop yield is emphasized. A four-stage calibration approach integrating hydrology, crop yield, and nitrogen cycling is presented for SWAT using the case of UBWC watershed in central Ohio. The four stages and the sequence of their application were: (1) parameter selection, (2) hydrology calibration, (3) crop yield calibration, and (4) nutrient loading calibration. Each stage was linked backward and forward to achieve the highest combined calibration prediction efficiency for streamflow, crop yield, and TN loading. A 6-year period of data was used for calibration followed by 10 years for validation. The interrelationships between various hydrology, crop growth, and nitrogen cycling processes in the SWAT model were also explored. Two major components of the hydrologic balance were evaluated: crop ET and streamflow. Simulated ET was comparable to that reported for the Ohio crop production region. The link between LAI and crop ET was also captured by the four-stage approach. Following each stage of calibration, the computed streamflow E and R^2 values improved. The yield calibration for corn, soybeans, and wheat was accomplished through evaluations of total biomass with standard biomass curves of the respective crop. The predicted crop yields were not statistically different from reported yield values. The important components in watershed nitrogen balance, uptake of nitrogen by crop and TN load from the watershed were considered for calibration of nitrogen. The link between crop uptake and biomass growth was compared with standard crop nitrogen and biomass growth curves which in turn resulted in higher E and R^2 values for TN loading simulation. The comprehensive calibration approach demonstrates the importance of exploring partitioning of water balance and nitrogen balance by SWAT simulation instead of the traditional calibration of streamflow and TN load at the watershed outlet. A comparison of traditional (without crop calibration) and four-stage calibration (including crop yield calibration) showed that four-stage calibration provided greater efficiency as well as correct partitioning of the crop components of water and nitrogen balance in the watershed.

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