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SENSITIVITY ANALYSIS, CALIBRATION, AND VALIDATIONS FOR A MULTISITE AND MULTIVARIABLE SWAT MODEL[1]

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ABSTRACT: The ability of a watershed model to mimic specified watershed processes is assessed through the calibration and validation process. The Soil and Water Assessment Tool (SWAT) watershed model was implemented in the Beaver Reservoir Watershed of Northwest Arkansas. The objectives were to: (1) provide detailed information on calibrating and applying a multisite and multivariable SWAT model; (2) conduct sensitivity analysis; and (3) perform calibration and validation at three different sites for flow, sediment, total phosphorus (TP), and nitrate-nitrogen (NO_3-N) plus nitrite-nitrogen (NO_2-N). Relative sensitivity analysis was conducted to identify parameters that most influenced predicted flow, sediment, and nutrient model outputs. A multiobjective function was defined that consisted of optimizing three statistics: percent relative error (RE), Nash-Sutcliffe Coefficient (R_{NS}^2), and coefficient of determination (R^2). This function was used to successfully calibrate and validate a SWAT model of Beaver Reservoir Watershed at multisites while considering multivariables. Calibration and validation of the model is a key factor in reducing uncertainty and increasing user confidence in its predictive abilities, which makes the application of the model effective. Information on calibration and validation of multisite, multivariable SWAT models has been provided to assist watershed modelers in developing their models to achieve watershed management goals.

(KEY TERMS: modeling; water quality; nonpoint source pollution; nutrients; SWAT model; sensitivity analysis; agriculture.)

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INTRODUCTION

The ability of a watershed model to sufficiently predict constituent yields and streamflow for a specific application is evaluated through sensitivity analysis, model calibration, and model validation. Sensitivity is measured as the response of an output variable to a change in an input parameter, with the greater the change in output response corresponding to a greater sensitivity. Sensitivity analysis evaluates how different parameters influence a predicted output. Parameters identified in sensitivity analysis that influence predicted outputs are often used to calibrate a model. Model calibration entails the modification of parameter values and comparison of predicted output of interest to measured data until a defined objective function is achieved (James and Burges, 1982). The objective function for model calibration generally consists of a statistical test, such as minimization of relative error (RE), minimization of average error (AE), or optimization of the Nash-Sutcliffe Coefficient (R_{NS}^2) (Santhi *et al.,* 2001a; Cotter, 2002; Grizzetti *et al.,* 2003). After achieving the objective function for calibration, validation of the model ensues. Validation procedures are similar to calibration procedures in that predicted and measured values are compared to determine if the objective function is met. However, a dataset of measured watershed response selected for validation preferably should be different than the one used for model calibration, and the model parameters are not adjusted during validation. Validation provides a test of whether the model was calibrated to a particular dataset or the system it is to represent. If the objective function is not achieved for the validation dataset, calibration and/or model assumptions may be revisited.

In assessing statistical results from model calibration and validation, it is important to consider the modeling objectives. Statistical results from two

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different modeling applications may not be appropriately compared if modeling characteristics, such as the number of calibration sites and/or the number of calibration variables being considered, are dissimilar. If only one calibration site is used, the objective function does not consider how well the model predicts watershed response at all other locations within the watershed, and therefore it is simpler to calibrate the model for that one specific site. Whereas, an increase in the number of stream gauges (calibration sites) used for calibrating output variables for a watershed model introduces more constraints on the calibration process.

Watershed models that include multivariables also influence the calibration process. Increasing the number of variables in calibration incorporates additional components of the model into the calibration process that might not otherwise be considered (Haan, 1989). In addition, correlations between one parameter and multiple predicted outputs often complicate the multivariable calibration process. This complication can occur when modification of one parameter causes one predicted variable to more closely coincide with measured values and another predicted variable to less closely coincide with measured values.

Complexity in the calibration and validation process increases with distributed parameter watershed models due to the large number of model parameters needed to achieve calibration, the difficulty associated with calibrating the model at more than one location within the watershed, and the ability to predict multiple watershed response variables. Even with this complexity, publications on developing watershed models are common and applications can be found internationally (e.g., Santhi *et al.,* 2001a; Cotter, 2002; Kirsch *et al.,* 2002; Grizzetti *et al.,* 2003). One watershed model that is often used to evaluate flow, sediment, and nutrients is the Soil and Water Assessment Tool (SWAT). The SWAT model is a physically-based, GIS linked watershed model developed by the U.S. Department of Agriculture-Agriculture Research Service It simulates on a continuous time step with input options for hydrology, nutrients, erosion, land management, main channel processes, water bodies, and climate data and has prediction capabilities for flow, sediment, and nutrient yields (Arnold *et al.,* 1998; Neitsch *et al.,* 2002a).

Publications on SWAT model application rarely include details on the model calibration process. This is particularly true when considering multisite, multivariable SWAT calibration (Santhi *et al.,* 2001b; Kirsch *et al.,* 2002; Grizzetti *et al.,* 2003). Since multisite, multivariable watershed modeling is becoming an important tool for evaluating watershed problems such as reservoir eutrophication, point and nonpoint source impacts, water quantity issues, and land use changes (Santhi *et al.,* 2001b; Eckhardt *et al.,* 2002; Fohrer *et al.,* 2002), it is insightful to review previous multisite and multivariable publications and provide information that has not previously been presented. The objectives were to: (1) provide detailed information on calibrating and applying a multisite, multivariable SWAT model; (2) conduct sensitivity analysis; and (3) perform calibration and validation of a SWAT model at three different sites for flow, sediment, total phosphorus (TP), and nitrate-nitrogen (NO_3-N) plus nitrite-nitrogen (NO_2-N). The results obtained from this research should be applicable to other similar watershed scale, distributed parameter models.

Review of SWAT Model Applications

Many publications on SWAT model applications are available; however, few provide detailed information on sensitivity analysis and calibration and validation of the model. For example, parameter selection for sensitivity analysis and results from sensitivity analyses are seldom documented in SWAT model publications. An exception, Spruill *et al.* (2000), included sensitivity analysis results for daily flow on a SWAT model developed for a watershed in Kentucky, USA. Additionally, Cotter (2002) documented sensitivity analysis on the model parameters for a watershed located in Arkansas, USA. While Spruill *et al.* (2000) and Cotter (2002) are part of a small group that has published information from sensitivity analysis of a SWAT model, a larger contingency of SWAT model developers has documented parameters used in calibration.

In reviewing SWAT publications, a list of parameters previously used in model calibration was identified (Table 1). In addition, Tables 2 and 3 show R_{NS}^2 and R^2 statistics from published SWAT calibrations. Details of all the model parameters discussed here are provided in the Appendix. Although a single site calibration is the most often presented application of the SWAT model, multisite calibration is becoming more common (Arnold *et al.,* 1999; Santhi *et al.,* 2001a; Kirsch *et al.,* 2002). The increased frequency of multisite applications is likely due to greater availability of measured data and improved model sophistication and computing abilities.

Streamflow is the single most commonly used watershed response variable in SWAT modeling (Arnold and Allen, 1996; Manguerra and Engel, 1998; Peterson and Hamlett, 1998; Sophocleous *et al.,* 1999). However, multivariable calibrations are conducted when SWAT is implemented to predict more than one variable, such as flow, sediment, nutrients, and pesticides (Santhi *et al.,* 2001a; Cotter, 2002;

TABLE 1. Review of Calibration Parameters by Variable Used by SWAT Modelers.

Output Variable	Calibration Parameters		
Flow	CANMX[4]	Crop Growth Routine[5]	Curve Number[1,2,3,4,5,6,7]
	ESCO[3,5,6]	Revap Coefficients[2,3,4]	Soil Bulk Density[5]
	Soil Properties[1]	AWC[6,7]	EPCO[3]
	Ground Water Parameters[5]		Soil Hydraulic Conductivity[5]
Sediment	AMP[4]	Channel Cover[5]	Channel Erosion[5]
	CH_N2[4]	MUSLE Parameters[5]	PRF[4]
	SLSUBBSN[4]	SPCON[3,4]	SPEXP[3,4]
	USLE_K(1)[4]	SLOPE[4]	CH_N1[4]
TP	ANION_EXCL[4]	ERORGP[4]	Initial Soil Concentration[3]
	PPERCO[3,4]	PSP[4]	SOL_BD[4]
	UBP 4	PHSKD[3,4]	
TN	CMN[5]	Initial Soil Concentration[3]	NPERCO[3,4]

[1] Arnold and Allen (1996)
[2] Srinivasan *et al.* (1998)
[3] Santhi *et al.* (2001b)
[4] Cotter (2002)
[5] Kirsch *et al.* (2002)
[6] Arnold *et al.* (2000)
[7] Arnold *et al.* (1999)

TABLE 2. Summary of Monthly Calibrations Performed on SWAT Models With Their Respective Statistic of Measurement of R^2_{NS} (R^2).

Reference	Base Flow	Runoff Flow	Total Flow	Sediment	P	N
Arnold and Allen (1996)	(0.38 to 0.51)	(0.79 to 0.94)	(0.63 to 0.95)			
Arnold and Allen (1999)	(0.62 to 0.98)					
Arnold *et al.* (2000)*			(0.63)			
Spruill *et al.* (2000)			0.58, 0.89			
Santhi *et al.* (2001b)*			0.79, 0.83 (0.80, 0.89)	0.80, 0.69 (0.81, 0.87)	0.53 to 0.70 (0.60 to 0.71)	-0.08 to 0.59 (0.60 to 0.72)
Cotter (2002)			0.76 (0.77)	0.50 (0.69)	0.66 (0.83)	0.44 (0.54)
Hanratty and Stefan (1998)			0.78	0.59	0.54	0.57, 0.68
Luzio *et al.* (2002)			0.82	0.78	0.58, 0.70	0.60
Tripathi *et al.* (2003)			0.98 (0.97)	0.79 (0.89)		
Srinivasan *et al.* (1998)*			0.77, 0.84 (0.87, 0.84)			
Srinivasan and Arnold (1994)			0.86			

*Multiple calibration sites used in SWAT model calibration

Kirsch *et al.,* 2002; Grizzetti *et al.,* 2003). The increase in the number of variables in the calibration process requires model developers to designate multi-objective functions that consider multiple variables. When evaluating a multivariable objective function, SWAT model users generally calibrate flow first when performing calibration. This is followed by sediment calibration and lastly any nutrient calibrations (Santhi *et al.,* 2001b; Cotter, 2002; Kirsch *et al.,* 2002; Grizzetti *et al.,* 2003). Previous investigations have reported different evaluation priorities for N and P. For example, Santhi *et al.* (2001b) evaluated N and P components by first calibrating organic N and organic P and then calibrating mineral N and mineral P, while Cotter (2002) evaluated NO_3-N first, followed by TP calibration.

TABLE 3. Summary of Annual Calibrations Performed on SWAT Models With Their Respective Statistic of Measurement of R^2_{NS} (R^2).

Reference	Base Flow	Total Flow	Sediment	P
Arnold *et al.* (1999)*		-1.11 to 0.87 (0.23 to 0.96)		
Arnold *et al.* (2000)*	(0.62)	(0.89)		
Kirsch and Kirsch (2001)		0.76 (0.78)	0.75 (0.82)	0.07 (0.95)
Kirsch *et al.* (2002)*		0.18 to 0.84 (0.28 to 0.98)		

*Multiple calibration sites used in SWAT model calibration.

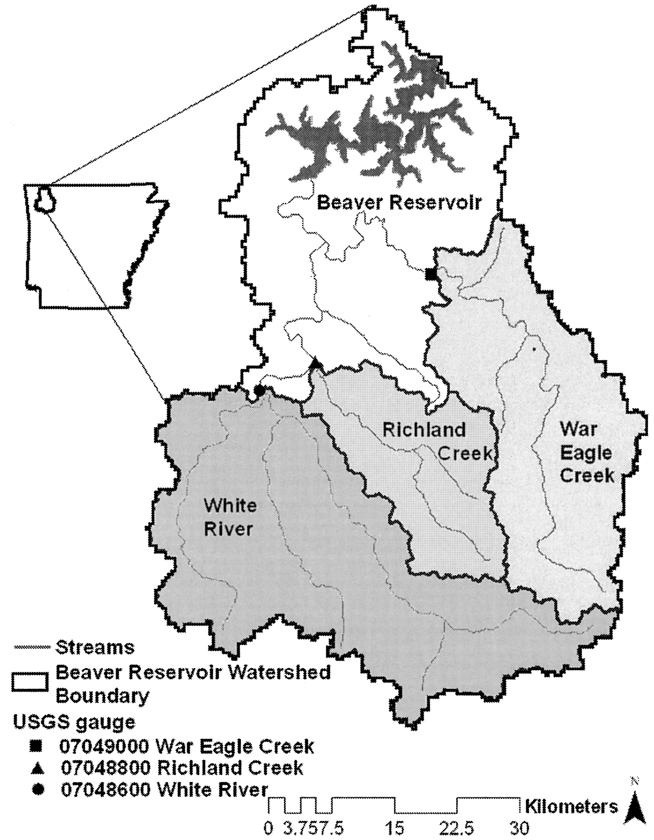

Figure 1. Location of Beaver Reservoir Watershed, Subbasins, and Stream Gauges Used for Model Calibration.

Study Site

This study was conducted in the Beaver Reservoir Watershed (Beaver Watershed) located in northwest Arkansas. Beaver Watershed contains approximately 3,000 km of streams with the main tributaries being Richland Creek, War Eagle Creek, and White River (Figure 1). The watershed encompasses approximately 310,000 ha and is located in the Ozark Plateau. Geographic information system (GIS) analysis of land use land cover data from 1999 for the watershed indicated distributions of 1.1 percent urban, 3.8 percent water, 68.8 percent forest, and 26.0 percent pasture (CAST, 2002). Rapid urbanization is occurring in the watershed. This can be seen in the population increases reported for its largest city, Fayetteville. In 1980, Fayetteville census identified a population of 36,608. This has increased, with a 1990 and 2000 reported population of 42,099 and 58,047, respectively. Beaver Watershed receives wastewater treatment plant (WWTP) effluent from several cities. Although Beaver Watershed is characterized by growing urban areas, it also is home to numerous animal production farms (Table 4). The predominant water quality concern for Beaver Reservoir is increased rates of eutrophication caused by increasing P yields from the watershed (Larson, 1983; USDA-SCS, 1986).

TABLE 4. Animal Production Houses Identified for the Drainage Area of Each Calibration Site for the Beaver Reservoir Watershed SWAT Model (Davis and Cooper, 2002, unpublished report to the Arkansas Water Resources Center).

	Number of Animal Production Houses		
Subwatershed	Chicken	Turkey	Swine
Richland Creek	147	5	25
War Eagle Creek	221	4	15
White River	288	0	50

METHODS

SWAT Model Input

SWAT2000 was used in this application, as it was the current version of the model at the beginning of the project. Mandatory GIS input files needed for the SWAT model include the digital elevation model (DEM), land cover, and soil layers. The following GIS data were used to develop the Beaver Watershed model to simulate watershed response from 1999 to 2002: USGS 30 m DEM (USEPA, 2004), rf3 stream shape file (USEPA, 2004), 28.5 m 1999 land use and land cover image file (CAST, 2002), and STATSGO soils shape file (USEPA, 2004). Based on threshold specifications and the DEM, the SWAT ArcView Interface (Di Luzio *et al.,* 2002) was used to delineate the watershed into subbasins. Subsequently, subbasins were divided into hydrologic response units (HRUs) by the user specified land use and soil percentage (Neitsch *et al.,* 2002a). Subbasin outlets were selected for the Beaver Watershed SWAT model with consideration to point sources, calibration points, and land use.

The primary point sources in the watershed were the cities of Fayetteville, Huntsville, and West Fork. Available data for the modeling period (1999 to 2002) were obtained from each point source facility, including discharge rates and nutrient loads. In addition, sludge application loads were included for the City of Fayetteville. The other utilities did not produce significant amounts of sludge and therefore were not included. Sludge is spread by the facility on pastures as a fertilizer. Therefore, sludge is represented in the model with a unique fertilizer file. The sludge 'fertilizer' is spread on appropriate HRUs annually, as a mass per unit area.

The ability of SWAT to define specific fertilizer types, fertilizer spreading, cattle grazing, and tillage operations adds to SWAT's utility in representing a particular watershed (Neitsch *et al.,* 2002a,b). These nonpoint components were integrated into the model based on best available information. Animal production was simulated in SWAT at the HRU level. Production animals in the watershed included chickens, turkeys, pigs, and cows (beef and dairy). For each animal type, a fertilizer file was created in the SWAT fertilizer database using standard manure compositions (ASAE, 1999). Annual animal production rates for turkeys, pigs, and cows were obtained from Arkansas agricultural statistics (AAS) (USDA-NASS, 2005). Animal production numbers were provided by AAS on 'head per county' basis. To accommodate for the county level animal production data, the animals were partitioned by county into watershed numbers using the following steps: (1) determine the land area within each county that is designated as agriculture (CA); (2) determine the land area of Beaver Reservoir Watershed within each county that is designated as agriculture (WA); (3) calculate a proportion (PR) within each county (WA/CA); and (4) multiply PR by each animal production type to determine the number of animals in the watershed. The animals were then distributed amongst SWAT subbasins using a GIS layer containing the locations of chicken, pig, and turkey houses within the watershed (Davis and Cooper, 2002, unpublished report to the Arkansas Water Resources Center). Based on these calculations, chicken, turkey, and pig waste was simulated annually in the SWAT model at the HRU level as a mass per area. Cattle was simulated within each subbasin so that cattle resided in one HRU in a subbasin at a time and rotated throughout the year between HRUs within a subbasin to represent pasture management conditions in the watershed.

Commercial fertilizer was applied in the management files at the HRU level. Hydrologic response units that were designated as urban or as pasture that contained little to no animal waste received commercial fertilizer. The mass and type (N-P-K) of commercial fertilizer applied was based on a weighted average of all P containing fertilizer combinations identified in the Arkansas State Plant Board (ASPB) annual reports. The data provided by ASPB were at the county level, so a partitioning method was used to determine the proportion applied in the watershed using a similar technique as that for animal numbers.

Weather data from stations within the region were incorporated to provide the most representative precipitation and temperature data available. The weather stations added were Fayetteville Experiment Station, Huntsville, and St. Paul (Figure 2). Other meteorological data required by SWAT (solar radiation, wind speed, and relative humidity) were estimated using the SWAT weather generator.

Initial values that were not available for SWAT model inputs, such as soil chemical composition, were established by simulating the model from 1995 to 2002. The years 1995 to 1998 allow the model to 'stabilize' or calculate values that become initial values for the period of interest. Therefore, beginning the year 1999, the model was considered to represent conditions in the watershed.

Specific datasets were identified to perform calibration and validation of the SWAT model. Measured flow and water quality data were collected from three USGS gauging stations within the watershed during the time period of interest (1999 to 2002): White River near Fayetteville (USGS 07048600), Richland Creek at Goshen (USGS 07048800), and War Eagle Creek near Hindsville (USGS 07049000) (Figure 1). A description of each gauges' drainage area and land cover is provided in Table 5.

Measured data from USGS gauges were compared to specific SWAT outputs during calibration and validation. For flow, predicted total flow for annual and monthly calibration and validation was calculated from the FLOW_OUT model output for the appropriate subbasin in the main channel output file from SWAT (.rch output file). To calibrate and validate base and surface runoff flows, total flow was separated into two components. The measured data were divided into base and surface runoff flows using Base Flow Index (BFI) software (Wahl and Wahl, 2003).

The SWAT model predicted total flow (from SWAT .rch output file) was also partitioned into base and surface runoff flows using the BFI.

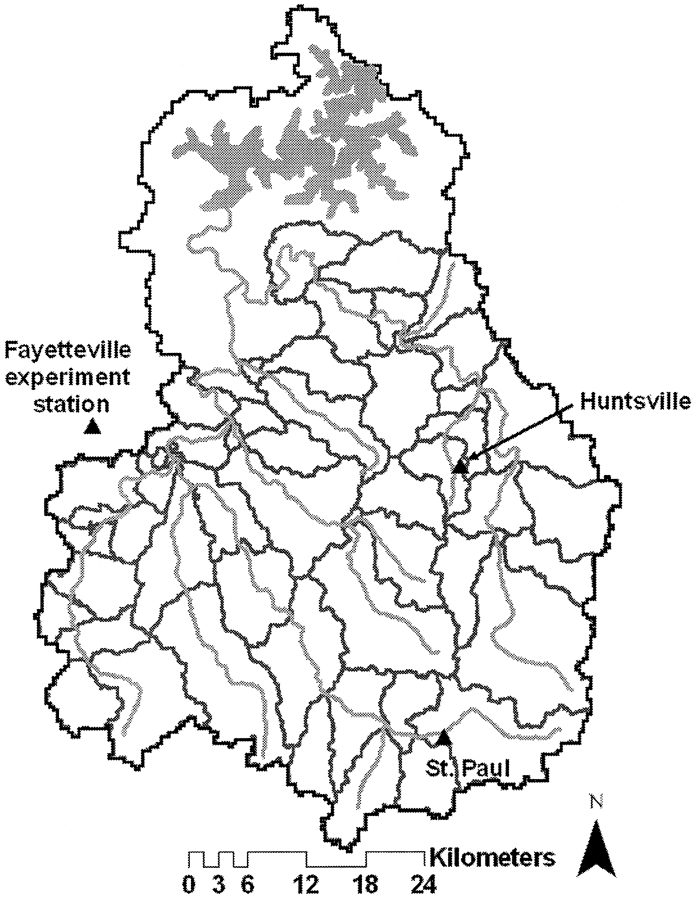

Figure 2. Weather Stations and Subbasin Delineation in the Beaver Watershed SWAT Model.

About twice a month sediment and nutrient sampling occurred at the three USGS gauges, therefore, daily measured sediment and nutrient concentrations were not available. Daily concentrations were estimated from collected samples using LOADEST2 software. The LOADEST2 daily concentrations were multiplied by daily flow rates to estimate monthly and annual sediment, TP, and NO_3-N plus NO_2-N yields. Nitrate-nitrogen plus NO_2-N was used in calibration and validation instead of total nitrogen (TN) because more samples were available with measured NO_3-N plus NO_2-N than with measured TN. Measured sediment yields were compared with SWAT predicted SED_OUT from the main channel output file (.rch). Measured TP yields were compared to the sum of ORGP_OUT and MINP_OUT from the SWAT main channel output file (.rch). Measured NO_3-N plus NO_2-N yields were compared to the sum of NO3_OUT and NO2_OUT from the SWAT main channel output file (.rch).

SWAT Model Sensitivity Analysis, Calibration, and Validation

Sensitivity analysis was conducted to determine the influence a set of parameters had on predicting total flow, sediment, TP, and NO_3-N plus NO_2-N. Sensitivity was approximated using the relative sensitivity (S_r)

$$S_r = \left(\frac{x}{y}\right)\left(\frac{y_2 - y_1}{x_2 - x_1}\right) \tag{1}$$

where x is the parameter and y is the predicted output. x_1, x_2 and y_1, y_2 correspond to ±10 percent of the initial parameter and corresponding output values, respectively (James and Burges, 1982). The greater the S_r, the more sensitive a model output variable was to that particular parameter. However, there are some limitations to using the S_r to assess parameters within a model. Primarily, these limitations are related to the assumption of linearity, the lack of consideration to correlations between parameters, and the lack of consideration to the different degrees of uncertainty associated with each parameter. Parameters were selected for sensitivity analysis by reviewing previously used calibration parameters and documentation from the SWAT manuals.

TABLE 5. Land Cover and Drainage Area for 1999 for Each Calibration Point in the Beaver Reservoir Watershed (CAST, 2002).

	Land Cover ha (percent)					Area
Subwatershed	Forest	Pasture	Urban	Water	Other	(ha)
Richland Creek	23,840 (65.9)	12,240 (33.8)	30 (0.1)	50 (0.1)	30 (0.1)	36,200
War Eagle Creek	43,380 (63.7)	24,240 (35.6)	320 (0.5)	100 (0.2)	50 (0.1)	68,100
White River	80,020 (78.5)	19,160 (18.8)	2,290 (2.3)	360 (0.3)	100 (0.1)	102,040

Following sensitivity analysis, a multiobjective function was evaluated for calibration. The multiobjective function was derived to incorporate multivariables (Yan and Haan, 1991; Yapo *et al.,* 1998; Madsen, 2003). Watershed response variables included in the multiobjective function were annual and monthly flow volume, sediment yield, TP yield, and NO_3-N plus NO_2-N yield. For the calibration of the Beaver Watershed SWAT model, three statistical measurements were included. The multiobjective function was defined as the optimization of the following three goodness-of-fit statistics for each of the previously identified variables.

SWAT model annual calibration was performed by minimizing the Relative Error (RE in percent) at the gauge locations

$$RE(\%) = \left|\frac{(O-P)}{O}\right| * 100 \tag{2}$$

where O is the measured value and P is the predicted output. The SWAT model was further calibrated monthly using the R_{NS}^2, which is defined as

$$R_{NS}^2 = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2} \tag{3}$$

where O is measured values, P is predicted outputs and i equals the number of values (Nash and Sutcliffe, 1970). Monthly coefficient of determination (R^2) was also calculated since R_{NS}^2 is sensitive to outliers (Kirsch *et al.,* 2002). A significance test can be performed when conducting a linear regression analysis with a null hypothesis that the coefficient of determination is equal to 0. The R^2 statistic is calculated as

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - O_{avg})(P_i - P_{avg})}{\left[\sum_{i=1}^{n}(O_i - O_{avg})^2 \sum_{i=1}^{n}(P_i - P_{avg})^2\right]^{0.5}}\right)^2 \tag{4}$$

Combining the three test statistics, output variables of interest, three calibration sites, and temporal components, the multi-objective function (F) was described by

$$F(O,P) = \begin{cases} minimize \sum_{i=1}^{y}\left(\sum_{j=1}^{c}\left(\sum_{k=1}^{v} RE(O,P)\right)\right) \\ optimize \sum_{l=1}^{m}\left(\sum_{j=1}^{c}\left(\sum_{n=1}^{w} R^2(O,P), R_{NS}{}^2(O,P\right)\right) \end{cases} \tag{5}$$

where y is the number of years, c is the number of calibration sites, v is the number of variables evaluated annually, m is the number of months, and w is the number of variables evaluated monthly. For this evaluation y is 4, c is 3, v is 6, m is 48, and w is 4. The multiobjective function was evaluated so that no particular variable, calibration site, or time was given precedence over another. However, this optimization required balancing among the different variables, calibration sites, and time steps. Balancing amongst combinations of variables, sites, and time steps is necessary since improvement in optimizing one combination might result in a lower optimization for another combination. Balancing amongst combinations was achieved by targeting equal levels of optimization amongst the combinations.

Due to correlations between parameters and predicted outputs and measurement uncertainty (Madsen, 2003), a logical order was followed in modifying parameters to achieve the objective function. The order used to optimize the objective function was: (1) total flow, (2) surface runoff and base flow, (3) sediment, (4) TP, and (5) NO_3-N plus NO_2-N. Santhi *et al.* (2001b), Cotter (2002), Kirsch *et al.* (2002), and Grizzetti *et al.* (2003) developed multivariable SWAT models using similar prioritization of the model output variables.

Hydrologic outputs (total flow, surface runoff, and base flow) were calibrated first because of their influence on other output variables. In addition, measurement uncertainty was assumed to be less with hydrologic data since estimated flow was developed from daily gauge readings, whereas sediment and nutrient yields were estimated from twice a month samples using the LOADEST2 program. Hydrologic calibrations were followed by sediment calibration because of the influence sediment can have on P transport in a watershed (Nearing *et al.,* 2001; Cambell and Edwards, 2001). Phosphorus predictions were minimized before NO_3-N plus NO_2-N since there was greater certainty in P predictions by the model, due to the detailed P inputs from nonpoint and point sources. After optimizing the objective function for annual output variables (base flow, surface runoff flow, total flow, sediment, TP, and NO_3-N plus NO_2-N) and monthly output variables (total flow, sediment, TP, and NO_3-N plus NO_2-N), the process was repeated to ensure that in optimizing one variable, other variables were not substantially influenced.

Model calibration resulted in a set of parameters that achieved the objective function as described by Equation (5). Like other distributed parameter models, SWAT also suffers from the equifinality of parameters [i.e., there exists more than one combination of parameter values that may result in the same model output (Beven, 1993)]. To test if a calibrated parameter set was appropriately selected for the watershed, model validation was performed. Validation required that the same goodness-of-fit statistics be calculated similar to calibration, the only difference being that the validation dataset was different from the calibration dataset.

Flow calibration was conducted at the White River and War Eagle Creek for years 1999 to 2000 and the Richland Creek for year 1999. Likewise, flow validation followed at the White River and War Eagle Creek Stations for years 2001 and 2002 and the Richland Creek for year 2000. The White River Station was used for calibration and validation of sediment, TP, and NO_3-N plus NO_2-N yields using 2000 to 2001 data for calibration and 2002 data for validation. Sediment, TP, and NO_3-N plus NO_2-N sampling for Richland Creek and War Eagle Creek was less comprehensive beginning in April 2001. Measured outputs for these streams could be compared to predicted yields; however, a comprehensive calibration and validation was not possible at these two stations.

RESULTS AND DISCUSSION

Model Calibration and Validation

Sensitivity analysis was performed on 51 different SWAT parameters using Equation (1) for annual flow, sediment, N, and P export from the watershed. The parameters resulting in the greatest S_r values for each variable are provided in Table 6.

The parameters identified in sensitivity analysis and through SWAT documentation review were investigated to optimize the multiobjective function defined by Equation (5). The multiobjection function was achieved by modifying the parameters listed in Table 7. Hence, Table 7 contains the calibration parameters for the Beaver Watershed SWAT model.

Not all of the parameters identified by sensitivity analysis were modified during calibration, and some parameters were modified during calibration that were not identified during sensitivity analysis. Parameters other than those identified during sensitivity analysis were used during calibration primarily due to the goal of matching the model as closely as possible to processes naturally occurring in the watershed. Therefore, sometimes it was necessary to change parameters other than those identified during sensitivity analysis because of the type of error observed in predicted variables. Parameters chosen other than those identified in sensitivity analysis were not randomly selected, but rather based on calibration parameters identified in other published results (Table 1). Although error observed between

TABLE 6. List of Parameters and Their Ranking That Produced the Five Highest Relative Sensitivity for Each Model Output.

Variables	**Ranking[1]**				
	1	**2**	**3**	**4**	**5**
Surface Runoff	CN2[2,3]	ESCO[3]	CNOP[2,3]	SOL_AWC[1,2,3]	SLSUBBSN
Total Flow	ESCO[3]	CN2[2,3]	SOL_AWC[1,2,3]	SOL_BD[1,3]	CNOP[2]
Sediment	CNOP	SLOPE[3]	ESCO	EPCO	USLE_P[3]
Organic N	USLE_P	SLOPE	CNOP[2]	USLE_K	SOL_BD1
NO_3	CNOP[2]	CN2[2]	ESCO	USLE_P	EPCO
Organic P	SPEXP	EVRCH	EPCO	USLE_P	FERT_LY1[2]
Soluble P	USLE_P	CNOP[2]	EPCO	SPEXP	EVRCH

[1] Ranking of 1 is equal to the highest calculated S_r.

[2] Parameters that were identified in previously published SWAT sensitivity analyses as influencing the respective variable (Spruill *et al.,* 200; Cotter, 2002).

[3] Parameters that were identified as calibration parameters in previously published SWAT models (Arnold and Allan, 1996; Srinivasan *et al.,* 1998; Santhi *et al.,* 2001b; Cotter, 2002; Kirsch *et al.,* 2002).

TABLE 7. List of Calibration Parameters With Input File Extension for Each Output of Interest for the Beaver Watershed SWAT Model.

Flow	Sediment	TP	NO_3-N Plus NO_2-N
ALPHA BF.gw	AMP.bsn[2]	AI2.wwq	BC3.swq
CN2.mgt[1,2]	CH_N1.sub[2]	BC4.swq	NPERCO.bsn[2]
ESCO.hru[1,2]	OVN.hru	CMN.bsn	RS3.swq
SURLAG.bsn	PRF.bsn[2]	ERORGP.hru[2]	RS4.swq
	ROCK.sol	FRT_LY1.mgt[1]	
	SLOPE.hru[1,2]	PHOSKD.bsn[2]	
	SLSUBBSN.hru[2]	PPERCO.bsn[2]	
	SPCON.bsn[2]	RS2.swq	
	USLE_K.sol[2]	RS5.swq	
	USLE_P.mgt[1,2]	UBP.bsn[2]	

[1] The parameter was identified in the Beaver Watershed SWAT model sensitivity analysis of the respective variable.
[2] The parameter was identified in SWAT publications as a calibration parameter (Table1).

measured values and predicted output may sometimes be resolved using any of a multiple of parameters, it is important to select the parameter that best describes the process with which the error is associated. Models that are developed without regard to the processes described by different parameters will likely result in a calibration that represent a particular dataset rather than a calibration that represents the system being modeled.

Although the primary interest in Beaver Watershed was P export from the watershed, other variables were incorporated in the calibration process (sediment and NO_3-N plus NO_2-N). These additional variables provided a more holistic SWAT model that considered other processes that influence the watershed system. In addition, a more comprehensive model validation was possible because of inclusion of sediment and NO_3-N plus NO_2-N data in the analyses.

Results of annual and monthly calibration for outputs of interest are shown in Tables 8 and 9, respectively. For monthly flow predictions, R_{NS}^2 ranged from 0.50 to 0.89 and R^2 ranged from 0.41 to 0.91, respectively, and were similar to the ranges previously published for multisite, multivariable model calibrations (Table 2). The lower R_{NS}^2 and R^2 values for monthly flow calibration were from Richland Creek for 1999 and White River for 1999 and could be attributed to many factors including uncertainty in measured rainfall data. The effects of spatial and temporal variability in rainfall on model output uncertainty has been documented in the past (Haan, 1989; Chaubey *et al.,* 1999). Another potential source of uncertainty is increased urbanization in the watershed. The area is experiencing rapid growth, which has resulted in intense road and building construction that increases flow rates and erosion. Since the latest landuse and landcover GIS input was based on 1999 data, all construction activities occurring after 1999 are not included in the analyses. In addition, a large highway project (Interstate 540) has recently been finished in the area that may have altered hydrology and erosion in parts of the watershed.

Based on observations from this study, multisite SWAT models developed with similar land cover calibration subwatersheds will more closely predict measured values, which is due to the spatial properties of SWAT parameters. In the SWAT model, parameters are assigned at different spatial levels: HRU, subbasin, and watershed. Therefore, substantial differences in land cover amongst calibration subwatersheds within one SWAT model may limit model users' ability to calibrate. This limitation may occur due to the inability to vary some parameters that are designated on a watershed level basis. Hence, it might be more appropriate to build separate SWAT models for calibration areas that possess substantial physical differences that would benefit from greater spatial variability in parameterization.

Generally, TP and sediment monthly statistics indicated a better calibration than NO_3-N plus NO_2-N (Table 9). A better fit between predicted and measured values for P and sediment than NO_3-N plus NO_2-N is likely associated with the quality of input data used for this particular model. Because of the interest in P yields exiting the watershed, input collection focused on all potential sources of P. Sources of N were included in the model; however, less emphasis was placed on obtaining all possible N sources.

TABLE 8. Annual RE (percent) Results for the Three SWAT Calibration Sites by Variable and Year.

	Richland Creek			**War Eagle Creek**			**White River**		
	1999	**2000**	**2001**	**1999**	**2000**	**2001**	**1999**	**2000**	**2001**
Total Flow	6.6	-6.2		17.0	-6.3		-8.5	5.9	
Base Flow	3.5	0.3		-8.2	-26.1		-2.3	6.6	
Surface Runoff	4.4	-2.2		33.4	1.1		-6.0	5.8	
Sediment Yield			12.4			14.4		76.7	27.6
TP Yield			-10.1			-2.1		55.8	-46.7
NO_3-N Plus NO_2-N Yield			52.7			28.2		-125	-33.0

TABLE 9. Monthly R_{NS}^2 (R^2) Results From the Three Beaver Reservoir Watershed SWAT Model Calibration Sites.

	Richland Creek			**War Eagle Creek**			**White River**		
	1999	**2000**	**2001**	**1999**	**2000**	**2001**	**1999**	**2000**	**2001**
Total Flow	0.50 (0.52)	0.89 (0.89)		0.81 (0.65)	0.89 (0.91)		0.77 (0.41)	0.86 (0.90)	
Sediment Yield			0.60 (0.61)			0.43 (0.45)		0.23 (0.85)	0.76 (0.80)
TP Yield			0.49 (0.50)			0.51 (0.58)		0.40 (0.78)	0.67 (0.82)
NO_3-N Plus NO_2-N Yield			-0.04 (0.01)*			0.29 (0.47)		-2.36 (0.84)	0.25 (0.25)*

*Regression not significant ($p < 0.05$).

The model validation results (Tables 10 and 11) indicated generally a similar relationship between measured output and predicted output to calibration results. A close agreement between measured values and predicted outputs on an annual scale as indicated by RE (Table 10) and on a monthly scale as indicated by R_{NS}^2 and R^2 (Table 11) shows that the model parameters represent the processes occurring in the Beaver Watershed to the best of their ability given available data and may be used to predict watershed response for various outputs.

While the calibrated and validated SWAT model can be used to assess current conditions in the watershed, the completed SWAT model may also be used to evaluate alternative management scenarios. Santhi *et al*. (2001a), King and Balogh (2001), and Kirsch *et al*. (2002) have all used the SWAT model to evaluate potential management changes in a watershed and how the changes influenced predicted constituent yields from the watershed. By using the completed SWAT model to investigate management scenarios, the user should be able to provide watershed managers with information that could be used in developing watershed management plans.

SUMMARY AND CONCLUSIONS

The SWAT model is a very useful tool for investigating alternative watershed management strategies on watershed hydrologic and water quality response. However, calibration and validation of the model is a key factor in reducing uncertainty and increasing user confidence in its predicative abilities, which makes the application of the model effective. Information on sensitivity analysis, calibration, and validation of multisite, multivariable SWAT models was provided to assist watershed modelers in developing their models to achieve watershed management goals.

Objective 1

Information provided in previous publications regarding calibrating a SWAT model is presented in this paper. Methods for collecting input and calibrating and validating a SWAT model using multiple sites and multiple variables were described in detail. Specifically, information not presented in detail in previous publications was included.

TABLE 10. Annual RE (percent) Validation Results for the Three Sites by Variable and Year.

	Richland Creek		**War Eagle Creek**		**White River**	
	2001	**2002**	**2001**	**2002**	**2001**	**2002**
Total Flow	-29.2		-8.5	-5.6	0.5	-23.1
Base Flow	9.2		-10.0	-11.2	5.8	13.8
Surface Runoff	-10.6		-7.9	-0.9	-1.0	-21.7
Sediment Yield					12.4	-10.6
TP Yield					10.6	-51.2
NO_3-N Plus NO_2-N Yield					-6.5	-0.7

TABLE 11. Monthly R_{NS}^2 (R^2) Validation Results for the Three Sites by Variable and Year.

	Richland Creek	**War Eagle Creek**		**White River**	
	2001	**2001**	**2002**	**2001**	**2002**
Total Flow	0.85 (0.82)	0.72 (0.77)	0.73 (0.81)	0.87 (0.91)	0.78 (0.83)
Sediment Yield	0.85 (0.82)		0.32 (0.77)		0.45 (0.69)
TP Yield			0.67 (0.76)		-0.29 (0.58)
NO_3-N Plus NO_2-N Yield			0.49 (0.71)		0.13 (0.59)

Note: All regressions were significant ($p < 0.05$).

Objective 2

Sensitivity analysis was completed using the S_r. The SWAT parameters with the highest S_r for surface flow, total flow, sediment, organic N, NO_3, organic P, and soluble P were CN2, ESCO, CNOP, USLE_P, CNOP, SPEXP, and USLE_P, respectively.

Objective 3

Annual and monthly calibration and validation at three sites for flow, sediment, TP, and NO_3-N plus NO_2-N was completed and evaluated using the RE, R_{NS}^2, and R^2 statistics. The R_{NS}^2 and R^2 for each variable were generally within ranges reported in previous SWAT publications.

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APPENDIX

SWAT parameters referred to in this paper.

Parameter Abbreviation	Input File	Description
AI2	.wwq	Fraction of algal biomass that is N
ALPHA_BF	.gw	Base flow alpha factor
ANION_EXCL	.sol	Fraction of porosity (void space) from which anions are excluded
APM	.bsn	Peak rate adjustment factor for sediment routing in the subbasin
BC3	.swq	Rate constant for hydrolysis of organic N to NH4
BC4	.swq	Rate constant for mineralization of organic P
CANMX	.hru	Maximum canopy storage
CH_COV	.rte	Channel cover factor
CH_EROD	.rte	Channel erodibility factor
CH_K(1)	.sub	Effective hydraulic conductivity in tributary channel alluvium
CH_L(1)	.sub	Longest tributary channel length in subbasin
CH_N(1)	.sub	Manning's n value for the tributaries
CH_N(2)	.rte	Manning's n value for the main channel
CH_W(1)	.sub	Average width of tributary channels
CMN	.bsn	Rate factor for humus mineralization of active organic nutrients (N and P)
CN2	.mgt	Initial SCS runoff curve number for moisture condition II
CNOP	.mgt	SCS runoff curve number for moisture condition II
EPCO	.hru	Plant uptake compensation factor
ERORGP	.hru	Phosphorus enrichment ratio for loading with sediment
ESCO	.hru	Soil evaporation compensation factor
EVRCH	.bsn	Reach evaporation adjustment factor
FRT_LY1	.mgt	Fraction of fertilizer applied to top 10 mm of soil
GW_DELAY	.gw	Ground water delay time
GW_REVAP	.gw	Ground water "revap" coefficient
GWQMN	.gw	Threshold depth of water in the shallow aquifer required for return flow to occur
NPERCO	.bsn	Nitrate percolation coefficient
OVN	.hru	Manning's n value for overland flow
PHOSKD	.bsn	Phosphorus soil partitioning coefficient
PPERCO	.bsn	Phosphorus percolation coefficient
PRF	.bsn	Peak rate adjustment factor for sediment routing in the main channel
PSP	.bsn	Phosphorus availability index
REVAPMN	.gw	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur
ROCK	.sol	Rock fragment content
RS2	.swq	Benthic P source rate coefficient
RS3	.swq	Benthic NH4 source rate coefficient
RS4	.swq	Organic N settling rate coefficient
RS5	.swq	Organic P settling rate coefficient
RSDIN	.hru	Initial residue cover
SLOPE	.hru	Average slope steepness
SLSUBBSN	.hru	Average slope length
SOL_AWC	.sol	Available water capacity of the soil layer
SOL_BD	.sol	Moist bulk density
SOL_K	.sol	Saturated hydraulic conductivity
SOL_ORGN	.chm	Initial organic N concentration in the soil layer
SOL_ORGP	.chm	Initial organic P concentration in soil layer
SOL_ZMX	.sol	Maximum rooting depth of soil profile
SPCON	.bsn	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing
SPEXP	.bsn	Exponent parameter for calculating sediment re-entrained in channel sediment routing
SURLAG	.bsn	Surface runoff lag coefficient
UBP	.bsn	Phosphorus uptake distribution parameter
USLE_K	.sol	USLE equation soil erodibility K factor
USLE_P	.mgt	USLE support practice factor