Calibration and Validation of SWAT for the Upper Maquoketa River Watershed

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Abstract

A validation study has been performed using the Soil and Water Assessment Tool (SWAT) model with data collected for the Upper Maquoketa River Watershed (UMRW), which drains over 16,000 ha in northeast Iowa. This validation assessment builds on a previous study with nested modeling for the UMRW that required both the Agricultural Policy EXtender (APEX) model and SWAT. In the nested modeling approach, edge-of-field flows and pollutant load estimates were generated for manure application fields with APEX and were then subsequently routed to the watershed outlet in SWAT, along with flows and pollutant loadings estimated for the rest of the watershed routed to the watershed outlet. In the current study, the entire UMRW cropland area was simulated in SWAT, which required translating the APEX subareas into SWAT hydrologic response units (HRUs). Calibration and validation of the SWAT output was performed by comparing predicted flow and NO_3-N loadings with corresponding in-stream measurements at the watershed outlet from 1999 to 2001. Annual stream flows measured at the watershed outlet were greatly under-predicted when precipitation data collected within the watershed during the 1999-2001 period were used to drive SWAT. Selection of alternative climate data resulted in greatly improved average annual stream predictions, and also relatively strong r^2 values of 0.73 and 0.72 for the predicted average monthly flows and NO_3-N loads, respectively. The impact of alternative precipitation data shows that as average annual precipitation increases 19%, the relative change in average annual streamflow is about 55%. In summary, the results of this study show that SWAT can replicate measured trends for this watershed and that climate inputs are very important for validating SWAT and other water quality models.

Keywords: calibration, modeling, nitrate, SWAT, validation, water quality.

CALIBRATION AND VALIDATION OF SWAT FOR THE UPPER MAQUOKETA RIVER WATERSHED

Introduction

Water quality modeling is emerging as a key component of Total Maximum Daily Load (TMDL) assessments and other watershed-based water quality studies. Numerous water quality models have been developed that differ greatly in terms of simulation capabilities, documentation, and technical support. One of the more widely used water quality models is the Soil and Water Assessment Tool (SWAT), which was developed to assess the water quality impacts of agricultural and other land use for a range of watershed scales, including large river basins (Arnold et al. 1998). Detailed documentation on the model inputs is provided in Neitsch et al. 2002a; model theory documentation is presented in Neitsch et al. 2002b and in Arnold et al. 1998. Previous applications of SWAT have compared favorably with measured data for a variety of watershed scales and conditions (Arnold and Allen 1996; Srinivasan, Arnold, and Jones 1998; Kirsch, Kirsch, and Arnold 2002; Arnold et al. 1999; Saleh et al. 2000; Santhi et al. 2001). However, an ongoing need in the use of SWAT is to test it with measured data for different scales, land use, topography, climate, and soil conditions.

The objective of this study was to test SWAT by comparing predicted stream flows and nitrate (NO_3-N) levels with corresponding measured values at the outlet of the Upper Maquoketa River Watershed (UMRW), which is a row-crop dominated watershed typical of much of Iowa. An overview of the data inputs and modeling assumptions is provided first, including a description of how some of the SWAT inputs were derived from a previous UMRW modeling study that used both the Agricultural Policy EXtender (APEX) model (Williams 2002) and SWAT. The sensitivity analysis is performed to provide rough estimated values before adjusting sensitive input parameters during calibration period. The calibration and validation process is then described, including the effect of

selecting alternative climate data inputs to achieve a more accurate replication of measured data at the watershed outlet.

Watershed Description

The UMRW covers an area of about 162 km^2 in portions of Buchanan, Clayton, Fayette, and Delaware counties and lies within the upper reaches of the Maquoketa River Watershed (MRW) that drains a total of 4,867 km^2 of predominantly agricultural land (Figure 1). In 1998, the MRW was listed as a priority watershed within the Iowa Department of Natural Resources Unified Watershed Assessment, with the primary concern being nutrient and sediment losses from agricultural nonpoint sources. Surface monitoring at the UMRW outlet (sampling site 4) located in Backbone State Park showed elevated NO_3-N and phosphate-phosphorus (PO_4-P), depending on the flow conditions (Baker et al. 1999). Tile drains are a key conduit of NO_3-N to the UMRW stream system.

Corn and soybeans are the major crops in the UMRW, accounting for 66% of the total land use (Gassman et al. 2002). Other key land uses included woodland (8.9%), alfalfa (7.5%), Conservation Reserve Program (CRP) land (4.1%), and pasture (4.0%). A total of 90 operations were identified in 1999 (Osei, Gassman, and Saleh 2000) having one or more types of livestock (Figure 1), with production focused primarily on swine, dairy cows, beef cattle, feeder cattle, and/or calves and heifers. The survey also discovered that most of the livestock producers were not taking enough credit for the nutrient content of manure when it was applied to the crop fields.

SWAT Input Data and Management Assumptions

This SWAT validation study builds on the original UMRW simulation study, in which a nested APEX-SWAT modeling approach was used (Saleh et al. 2003; Gassman et al. 2002). APEX was used to simulate the manured cropland and pasture areas because of its enhanced flexibility in simulating different manure application scenarios relative to SWAT. Edge-of-field sediment and nutrient losses simulated in APEX, coupled with losses simulated in SWAT from other land uses, were routed in SWAT through the stream system to the watershed outlet. This approach was also used in two other previous watershed studies that were conducted in Texas, as described in Gassman et al. 2002. In this study the entire watershed was simulated in SWAT for 1997-2001, which provides a
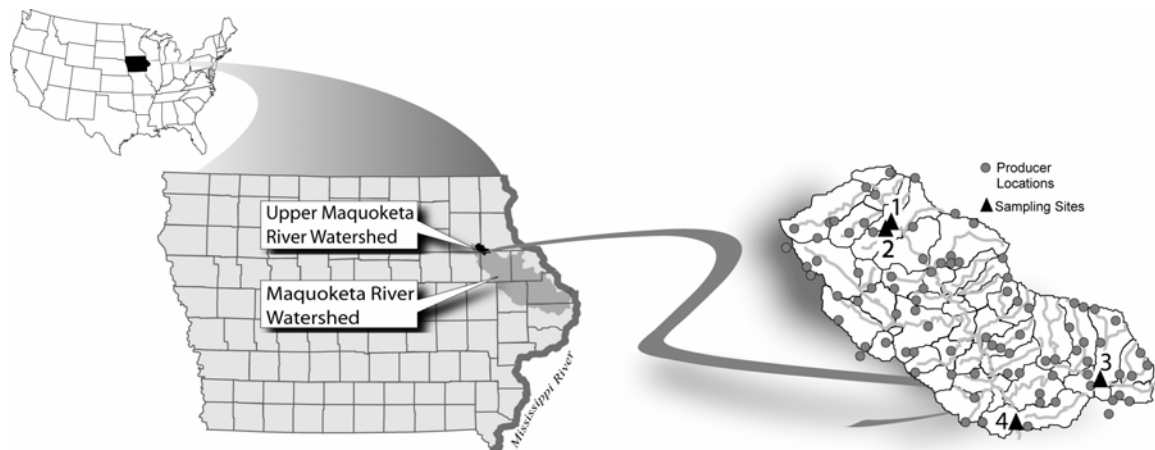
FIGURE 1. Location of the Upper Maquoketa River Watershed with reference to Maquoketa River Watershed and the Mississippi River, the locations of the UMRW livestock operations and sampling sites

two-year "initialization period" and also includes the three years that the monitoring data were collected (1999-2001), which were used for calibrating and validating the model.

The land use/cover, topographic, and soil data required for the SWAT simulations were generated as part of the previous UMRW modeling study, from maps developed within the Geographical Resource Analysis Support System (GRASS) Geographic Information System (GIS) using the GRASS-SWAT Interface Program (Gassman et al. 2002). A total of 52 subwatersheds were created with the GRASS GIS for the UMRW (Figure 1), with the watershed outlet (sampling site 4) located in Backbone State Park. Each subwatershed delineated within SWAT was simulated as a homogeneous area in terms of climatic inputs. However, the subwatersheds were further subdivided into hydrologic response units (HRUs) that were assumed to consist of homogeneous land use and soils. The percentage of the subwatershed that is covered by a specific HRU was input into SWAT; however, the exact spatial location was not accounted for. A land use threshold of 10% was used when the HRUs were created, which limited the land use to categories that covered at least 10% of a given subwatershed. The HRU land use categories generated in SWAT/GRASS included pasture, urban land, continuous corn, corn-soybean, and a five-year rotation of corn and alfalfa. A total of 646 HRUs were used for the UMRW.

As previously noted, the manured cropland and pasture areas were originally simulated in APEX. These APEX areas were translated into SWAT HRUs for this analysis as described in Kanwar, Gassman, and Saleh 2003. Small open lot and buffer strip areas that were simulated in APEX for swine open lot and cattle feeder operations were assumed to be nongrazed pasture areas for the SWAT. The remaining pasture areas simulated within each SWAT subwatershed were split into separate dairy, calf/heifer, and beef cow pasture HRUs to preserve differences in manure deposition rates and grazing periods that were assumed to occur between these different livestock species. The manure was assumed to be applied to cropland that was planted in corn. Manure generated by beef pasture and calf/heifer operations was relatively minor compared to the other types of operations and was assumed to be deposited on pastures and/or corn fields through grazing rather than applied with a manure spreader. It was assumed that the livestock producers applied solid manure at an annual rate of 44.8 t/ha and liquid manure at the rate of 46,745 l/ha, resulting in the N and P application rates shown in Table 1.

The main N fertilizer applications were applied at the same rate for manured fields relative to nonmanured cropland (Table 2). An N fertilizer rate of 159 kg/ha was assumed for continuous corn. Assumed fertilizer rates applied to corn following soybean and alfalfa were 128 and 100 kg/ha, respectively, reflecting some accounting of N credit from the legume crops. Additional "crop-removal" N and phosphate (P_2O_5) fertilizer rates were simulated for both manured and nonmanured fields following corn harvest (Table 2), for continuous corn, corn-soybean, and the second year of corn when rotated with alfalfa for the manured cropland. Smaller starter N and P fertilizer amounts of 10 and 11 kg/ha were assumed to be applied for corn in all rotations, regardless of manure inputs.

Additional details regarding the distribution of livestock in the watershed and the nutrient management assumptions are given in Osei, Gassman, and Saleh 2000 and Gassman et al. 2002.

Soil and Climate Inputs

The soil map and associated soil layer data used for the UMRW SWAT simulation were obtained from the Iowa Department of Natural Resources (http://www.igsb.uiowa.edu/nrgislibx/). The soil slope length and percent slopes were determined from an

TABLE 1. Manure N and P rates (kg/ha) applied to corn by farm type for the UMRW baseline simulations

Nutrient	Tie Stall Dairies	Small Swine (Open Lot)	Large Swine (Confinements)	Cattle, Feeder
Manure N	234	278	293	262
Manure P	49	96	101	71

Note: Baseline manure application rate = 22.4 t/ha; liquid rate of 46,745 l/ha used for swine confinements.

TABLE 2. Expected yields and fertilizer rates based on UMRW survey results

				Fall Crop Removal Fert. Appls. (kg/ha)			
		Expected Yield	Main N Fert. Appl.	Manured Fields		Nonmanured Fields	
Crop	Crop Sequence	(bu/ac)	(kg/ha)[a]	N	P$_2$O$_5$	N	P$_2$O$_5$
Corn	After corn	155	159	18	46	28	68
Corn	After soybeans	160	128	10	26	28	68
Corn	After alfalfa	158	100	10	26	28	68
Soybeans	After corn	55	0	15	39	28	68

[a]The same rate was assumed to be applied to both manured and nonmanured fields.

assessment of mean slope lengths that are given in the 1992 National Resource Inventory (NRI) database (http://www.nrcs.usda.gov/technical/NRI/; Nusser and Goebel 1997). It was assumed that about 80% of the cropped soils were tile drained, based on previous assumptions reported by Keith et al. (2000). A depth of 1.2 m below the soil surface was assumed for all tile drains that were simulated for the UMRW.

Daily precipitation data were collected at sampling sites 2 and 3 (Figure 2) within the UMRW for the same three-year period (1999-2001) during which the in-stream monitoring data was collected. Two five-year average daily precipitation records for 1997-2001 were then constructed by collating 1997-1998 precipitation data collected at Fayette and Manchester (obtained from the Iowa Environmental Mesonet: http://mesonet.agron.iastate.edu/) onto the site 2 and site 3 data, respectively. Fayette and Manchester were determined to be the two closest climate stations based on a Thiessen Polygon analysis; the locations of both stations are shown in Figure 2. Two other five-year precipitation records were also constructed using only data measured at Fayette and Manchester, to provide an alternative source of climate data inputs for the SWAT
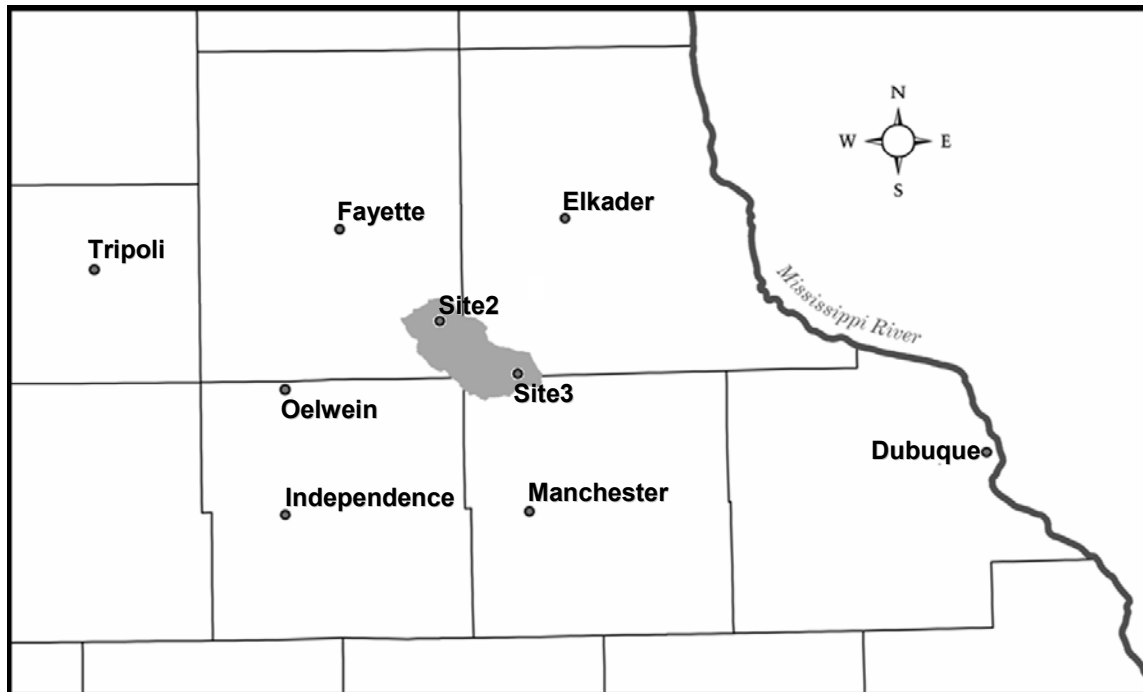
FIGURE 2. Climate stations located near the UMRW (including Fayette and Manchester) and county boundaries

simulation. A comparison of 1999-2001 annual precipitation amounts (Table 3) shows that the precipitation levels measured at sites 2 and 3 were considerably lower than those measured at Fayette and Manchester and those collected at other climate stations in the region. The results from a simple analysis (Table 4) reveal that, in general, the precipitation levels at site 2 and site 3 were lower by 13%-30% and 9%-25%, respectively, than those of other climate stations. Thus, it was of interest to assess the effects of the two different sets of precipitation data on the SWAT hydrologic estimates. The assignment of a specific precipitation record to a given subwatershed was determined based on which rain gage or weather station was closest to the subwatershed.

Maximum and minimum temperature data for 1997-2001 were again obtained from the Iowa Environmental Mesonet for Fayette and Manchester and were used for all of the SWAT simulations. The daily air temperature inputs were used in the SWAT crop growth algorithms and the evapotranspiration computations. The Hargreaves Method (Neitsch et al. 2002b) was used to estimate daily evapotranspiration rates.

TABLE 3. Total annual precipitation (mm) for 1999-2001 (and overall total) for UMRW climate sources

Year	Rain Gauge[a] or Climate Stations[b]								
	Site 2[a]	Site 3[a]	Fayette	Manchester	Elkader	Oelwein	Tripoli	Dubuque	Independence
1999	814.3	807.2	1052.1	943.6	924.0	987.3	1054	910.3	1057.1
2000	750.9	839.4	967	834.9	875.0	955.5	958.1	820.7	840
2001	794.7	795.4	1042.7	893.1	897.0	987.8	811.3	933.7	970.8
Total	2359.9	2442	3061.8	2671.6	2696.0	2930.6	2824	2664.7	2867.9

[a]Measured within the watershed at sampling sites 2 and 3 (Figure 2).
[b]Climate station data was obtained from http://mesonet.agron.iastate.edu/.

TABLE 4. The difference of precipitation (%) for site 2 and site 3 relative to the other climate stations

	Fayette	Manchester	Elkader	Oelwein	Tripoli	Dubuque	Independence
Site 2	-29.74	-13.21	-14.24	-24.18	-19.65	-12.92	-21.53
Site 3	-25.38	-9.40	-10.40	-20.01	-15.62	-9.12	-17.44

Sensitivity Analysis

Hydrologic conditions vary greatly between different watersheds. For example, Arnold et al. (2000) found that three different basins within the Upper Mississippi River Basin exhibited clear differences in hydrologic sensitivity. Thus, a sensitivity analysis was performed for 1999-2001 for the UMRW to reduce uncertainty and provide parameter estimation guidance for the calibration step of the study. Three of the four input parameters that were evaluated in the sensitivity analysis performed for this study were the curve number, soil available water capacity, and soil evaporation coefficient, which are the three parameters evaluated by Arnold et al. (2000) in their sensitivity analysis of SWAT, and these were also found to be very sensitive in SWAT studies performed by Spruill, Workman, and Taraba (2000), Santhi et al. (2001), and Jha et al. (2003). The curve number determines the partitioning of precipitation between surface runoff and infiltration as a function of soil hydrologic group, land use, and antecedent moisture condition (Mishra and Singh 2003). The available water capacity is a key soil parameter that has been found to affect groundwater recharge estimates in simple water balance models (Finch 1998). The soil evaporation coefficient values adjust the depth distribution for evaporation from soil to account for the effect of capillary action, crusting, and cracking (Neitsch et al. 2002b).

The fourth input parameter evaluated for the sensitivity analysis was precipitation. Van Liew and Garbrecht (2001) found that simulated surface runoff volume varied from 0% to 27% in response to variations in precipitation that ranged from -60% to +60%, relative to the baseline precipitation volume. Thus, further sensitivity analysis was also performed for the site 2 and site 3 precipitation inputs, to ascertain how much shifts in precipitation affect flow volumes predicted by SWAT at the UMRW outlet.

Several simulations were executed for each input parameter and were performed within the allowable range of values for the specific parameter while holding all other input values constant. The sensitivity of each input parameter was calculated separately for surface runoff and base-flow, as a function of average annual values. The range of annual precipitation was varied from -40% to 40% for both site 2 and site 3, to reflect the range of precipitation difference of these two sites relative to other climate stations in the region (Table 4). The curve numbers were allowed to vary between -6 to +6 to account

for uncertainty in the soil and land use conditions of the watershed. The soil available water capacities were obtained from a soils database (USDA 1992) and were adjusted within a range of -0.04 to +0.04. The soil evaporation coefficient, which has a range between 0.0 and 1.0, was varied in this study from 0.5 to 1.0.

Figure 3 shows the sensitivity of surface runoff and base-flow to precipitation, curve number, soil evaporation coefficient, and soil available water capacity. As expected, increased precipitation resulted in greater surface runoff and base-flow (Figure 3a). An increase in precipitation of 30% resulted in surface runoff and base-flow increases of roughly 200%. However, surface runoff and base-flow declined by only 25% in response to a precipitation decrease of 30%. The sensitivity of surface runoff and base-flow to curve number change is shown in Figure 3b. The resulting relationship confirms that base-flow is inversely correlated to curve number, because infiltration decreases with increased surface runoff and vice versa. Figure 3c shows that decreasing the soil evaporation coefficient allows lower soil layers to compensate for water deficits in the upper layers, resulting in higher soil evaporation. Consequently, with higher soil evaporation, there is less water available for surface runoff and base-flow. Both surface runoff and base-flow increased in response to decreasing soil water capacity (Figure 3d). This occurs because less pore space is available to hold water when the soil water capacity decreases, resulting in higher runoff and percolation.

Calibration and Validation

To calibrate and validate the model, an automated base-flow method developed by Arnold and Allen (1999) was first used to estimate the relative contributions of surface runoff and base-flow at the outlet of the watershed from 1999 through 2001. The base-flow separation analysis yielded a subsurface contribution of about 57%, based on values of 0.025 and 40 days for the base-flow alpha factor and groundwater delay time parameters, respectively. The base-flow alpha factor and groundwater delay time were two of the parameters selected for calibrating SWAT (Table 5); these parameters were chosen on the basis of the results of previous SWAT calibration studies (Spruill, Workman, and Taraba 2000; Santhi et al. 2001; Jha et al. 2003). Table 5 lists the initial and final values of the selected calibration parameters, as well as possible ranges for each parameter (where
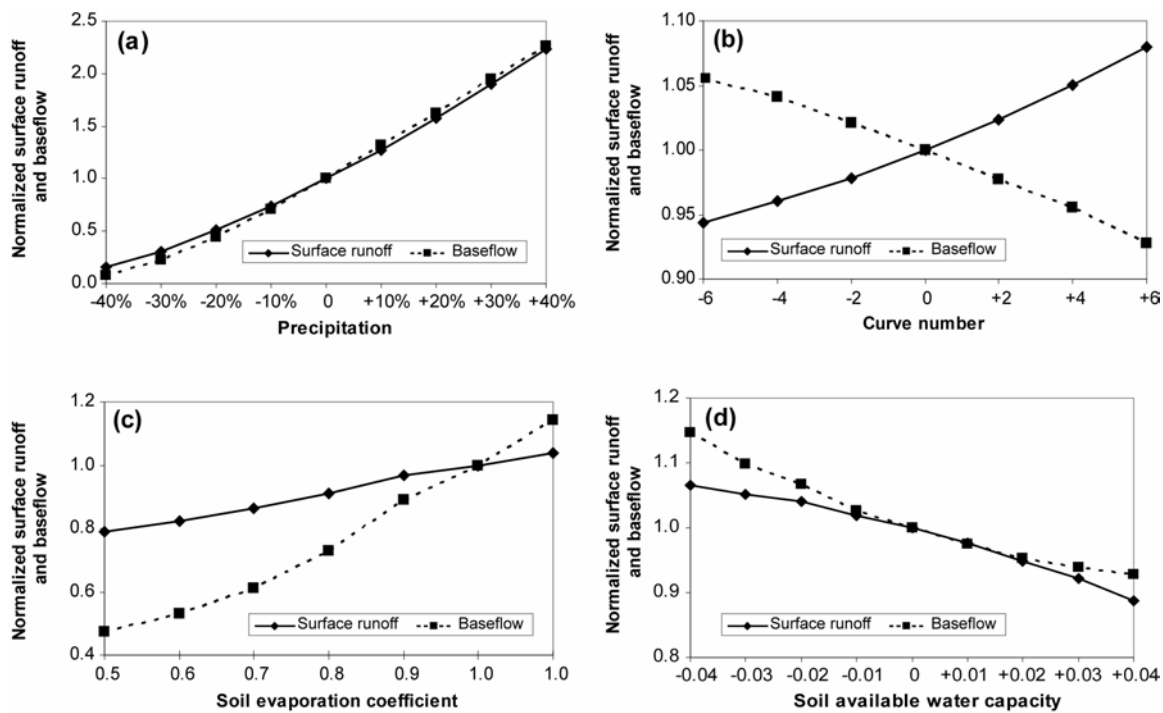
FIGURE 3. Sensitivity of surface runoff and base-flow to (a) precipitation, (b) curve number, (c) soil evaporation coefficient, and (d) soil available water capacity

relevant) based primarily on ranges given by Neitsch et al. (2002a). The following steps were then taken to complete the calibration and validation process for this study, based on comparisons between the simulated and measured data at the watershed outlet: (1) calibrate the long-term average annual stream flow; (2) calibrate the monthly stream flows; (3) calibrate the monthly NO_3-N load; (4) validate the monthly stream flow; and (5) validate the monthly NO_3-N loads. For the first step, the annual stream flow was calibrated against measured stream flow at the outlet of the watershed for 1999. This step was performed to ensure that the local water balance was realistic. Once the simulated annual stream flow was within 10% of the measured stream flow, the monthly stream flows and NO_3-N levels were then calibrated for 1999. For the validation step, the stream flows and NO_3-N levels were estimated for 2000 and 2001 using input parameter values determined during the calibration step.

TABLE 5. Initial and final values of the calibration parameters, plus possible ranges where applicable

Parameter	Range[a]	Initial Value	Final Calibrated Value
Curve number	±6	-	-6
Soil available water capacity (SOIL_AWC)	±0.04	-	-0.04
Soil evaporation coefficient (ESCO)	0.01-1.0	0.95	0.85
Base-flow alpha factor, days (ALPHA_BF)	0.1-1.0	0.025	0.9
Groundwater revap. coefficient, (GW_REVAP)	0.02-0.2	0.02	0.04
Groundwater delay time, days (GW_DELAY)	0-100	40	50
Time to drain soil to field capacity, hours (TDRAIN)	-	24	48
Drain tile lag time, hours (GDRAIN)	-	96	96
Depth to subsurface drain, mm (DDRAIN)	-	1200	1200

[a]The ranges are based primarily on recommendations given in the *SWAT User's Manual* (Neitsch et al. 2002a); the curve number range was selected arbitrarily.

Results and Discussion

Each SWAT simulation was executed for the 1997-2001 period to encompass a complete cycle of the five-year corn and alfalfa rotations and to provide a two-year "initialization period." Calibration of SWAT was performed for year 1999 while 2000 and 2001 were used as the validation years. The 1999-2001 annual average stream flow was greatly under-predicted using the five-year precipitation records that included the 1999-2001 site 2 and site 3 rain gauge data (Figure 4). Even though further adjustments were made to the curve number, soil water available capacity, and soil evaporation coefficient parameters, the annual average stream flow was still under-predicted by 23% to 59%. The annual average stream flow was more accurately predicted when the precipitation records based solely on the Fayette and Manchester climate station measurements were used (Figure 5). A slight under-prediction of 0.74% was estimated for the three-year average when using the alternative precipitation data. The annual average results shown in
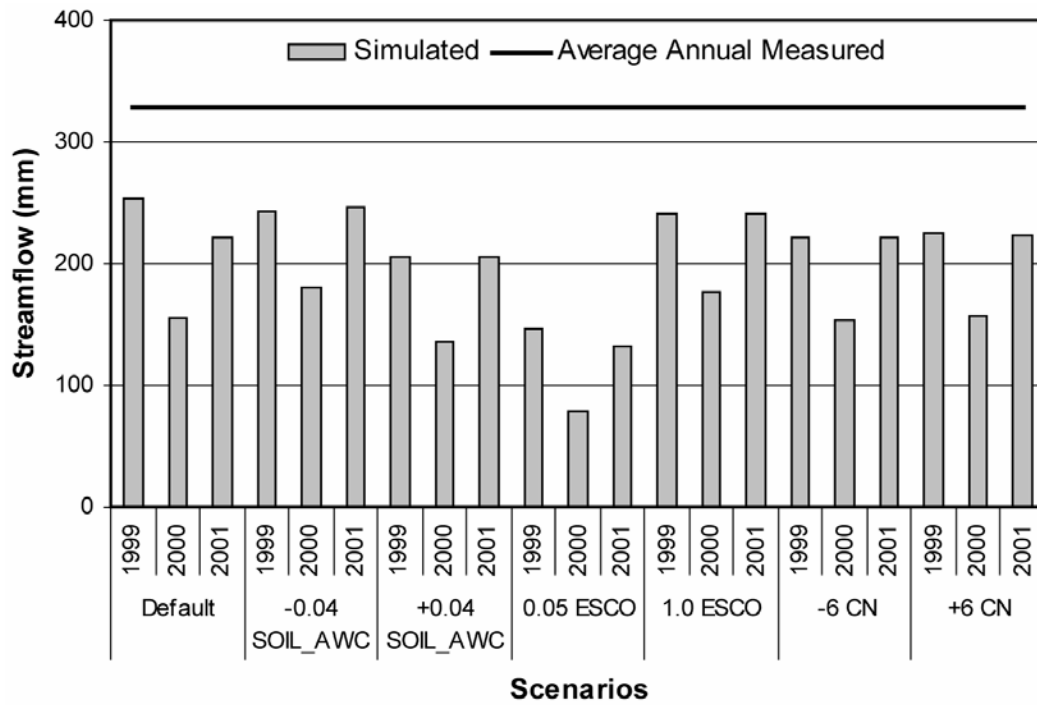
FIGURE 4. Simulated versus measured UMRW annual stream flows with various scenarios in response to the five-year precipitation records from the site 2 and site 3 rain gauge data
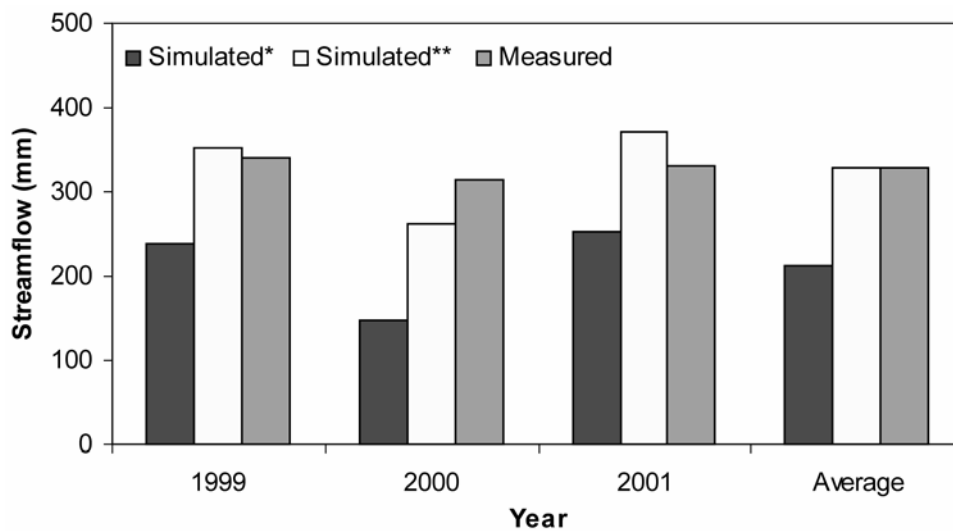

FIGURE 5. Simulated versus measured UMRW annual stream flows in response to the five-year precipitation records (*=site 2 and site 3, **=Fayette and Manchester)

Figure 5 could indicate that measurement error occurred for the rain gage data collected at sites 2 and 3. The impact of the alternative precipitation data shows that as average annual precipitation increases 19%, the relative change in average annual streamflow is about 55% (Table 6). Further analysis was performed with only the five-year records that consisted entirely of precipitation data collected at Fayette and Manchester.

Simulated daily flows are shown relative to corresponding measured flows for 1999-2001 at the UMRW outlet (Figure 6). The model accurately tracked most of the peak flow events that occurred during the year, although the peaks were usually over-predicted. In contrast, the majority of the low-flow periods were under-predicted by SWAT. Figure 7 shows the predicted and measured average monthly flows for 1999-2001. Some of the high-flow periods were over-predicted while other high-flow periods were under-predicted. The regression of the measured and simulated average monthly flow resulted in a r^2 value of 0.73, indicating that the model accurately tracked the average monthly flow trends during the simulation period.
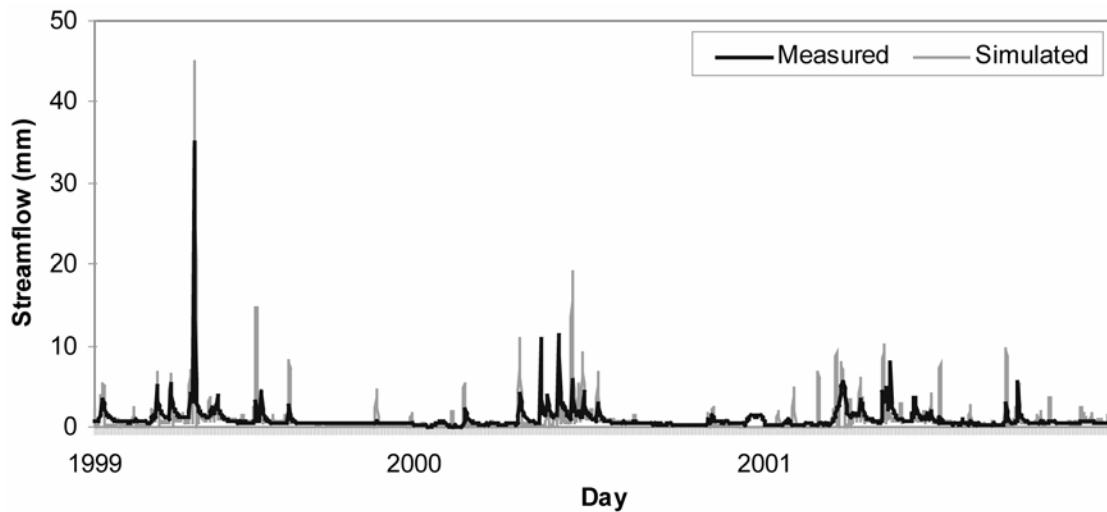
The simulated versus measured average monthly NO_3-N levels are plotted in Figure 8. The NO_3-N trend was again accurately tracked by SWAT, as reflected in the r^2 value of 0.72. However, the majority of the months with observed high NO_3-N levels were over-predicted by the model. The cumulative three-year NO_3-N load was under-predicted by SWAT by 7.3%.

Conclusions

Sensitivity analyses performed with SWAT showed that the simulated base-flow and runoff was sensitive to variations in precipitation, curve number, soil available water capacity, and the soil evaporation coefficient. Clearly, the choice of values of these inputs

TABLE 6. Amount of average annual precipitation and streamflow data for 1999 through 2001

Climate Stations	Fayette and Machester	Site 2 and Site 3	% difference
Average annual precipitation (mm)	944.8	797.2	19
Average annual streamflow (mm)	328.8	212.4	55

FIGURE 6. Simulated versus measured daily stream flows at the UMRW outlet (1999-2001)
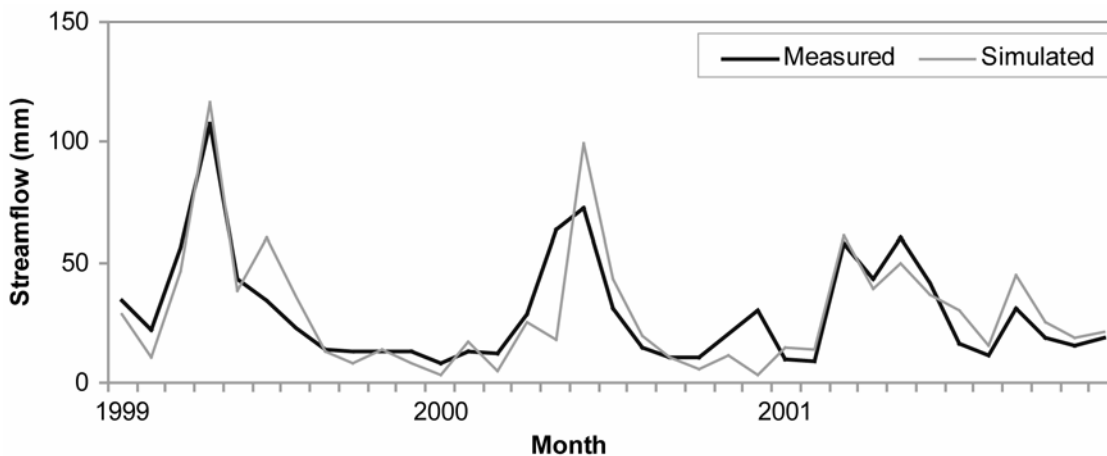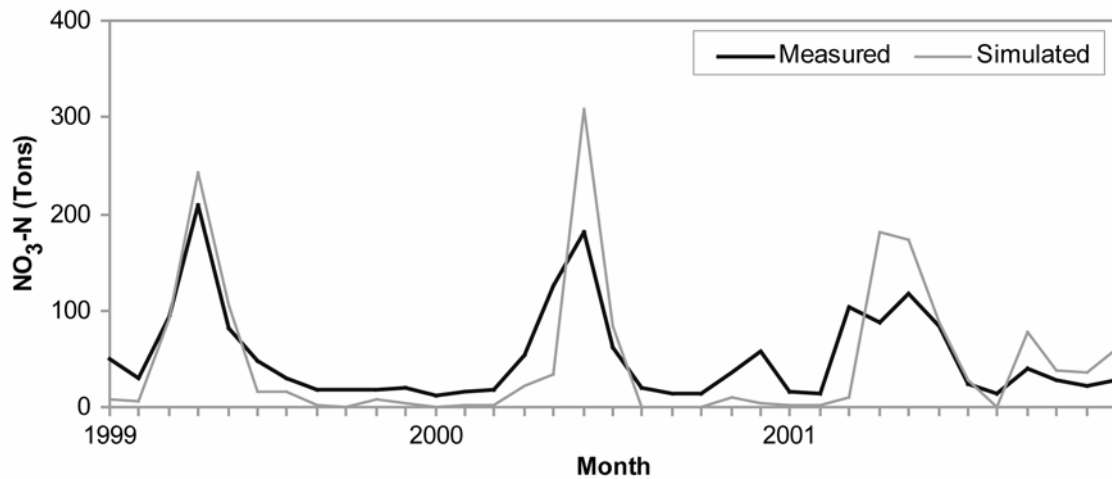

FIGURE 7. Simulated versus measured monthly stream flows at the UMRW outlet (1999-2001)

can greatly affect the predicted stream flow results, underscoring that care must be taken in selecting the most accurate input values possible.

Annual stream flows measured at the UMRW outlet for the 1999-2001 period were greatly under-predicted when precipitation data collected within the watershed during that period were used as input to SWAT. The predicted annual stream flows improved greatly when precipitation data were used that were measured at climate stations outside

FIGURE 8. Simulated versus measured monthly NO₃-N loads at the watershed outlet during 1999-2001

the watershed. These results do not follow expectations and leave us to wonder whether measurement error may have occurred regarding the precipitation data collected at UMRW sampling sites 2 and 3. Further investigation may be warranted to verify why the large discrepancies exist between the precipitation data at sites 2 and 3 and the corresponding data collected at other climate stations in the region. Further simulations with SWAT using only the climate data collected at the Fayette and Manchester climate stations showed that the model was able to accurately track monthly measured stream flows and nitrate losses at the watershed outlet. The r^2 statistics found for the monthly stream flows and NO₃-N losses were equal to 0.73 and 0.72, respectively. These results compare favorably with previous r^2 values reported by Saleh et al. (2003) of 0.79 for stream flows and 0.74 for the NO₃-N loads, using the APEX-SWAT approach. However, the annual stream flows and three-year average annual stream flow were more accurately simulated in this study. It can be concluded that both the APEX-SWAT and SWAT-only methods are viable simulation approaches for the UMRW.

References

Arnold, J.G., and P.M. Allen. 1996. "Estimating Hydrologic Budgets for Three Illinois Watersheds." *J. Hydrol.* 176: 57-77.

———. 1999. "Automated Method for Estimating Baseflow and Groundwater Recharge from Stream Flow Records." *J. Am. Water Resour. Assoc.* 35(2): 411-24.

Arnold, J.G., R.S. Muttiah, R. Srinivasan, and P.M. Allen. 2000. "Regional Estimating of Baseflow and Groundwater Recharge in the Mississippi River Basin." *J. Hydrol.* 227: 21-40.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and P.M. Allen. 1999. "Continental Scale Simulation of the Hydrologic Balance." *J. Am. Water Resour. Assoc.* 35(5): 1037-51.

Arnold, J G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. "Large Area Hydrologic Modeling and Assessment." Part 1, "Model Development." *J. Am. Water Resour. Assoc.* 34: 73-89.

Baker, J.L., S.W. Melvin, M.M. Agua, J. Rodecap, A. Saleh, and T. Jones. 1999. "Collection of Water Quality Data for Modeling the Upper Maquoketa River Watershed." ASAE Paper No. 992222. American Society of Agricultural Engineers, St. Joseph, MI.

Finch, J.W. 1998. "Estimating Direct Groundwater Recharge Using a Simple Water Balance Model—Sensitivity to Land Surface Parameters." *J. Hydrol.* 211: 112-25.

Gassman, P.W., E. Osei, A. Saleh, and L.M. Hauck. 2002. "Application of an Environmental and Economic Modeling System for Watershed Assessments." *J. Am. Water Resour. Assoc.* 38(2): 423-38.

Jha, M., P.W. Gassman, S. Secchi, R. Gu, and J. Arnold. 2003. "Hydrologic Simulations of the Maquoketa River Watershed with SWAT." In *AWRA'S 2003 Spring Specialty Conference Proceedings.* TPS-03-1 [CD-ROM]. Edited by D. Kolpin and J.D. Williams. Middleburg, VA: American Water Resources Association.

Kanwar, R., P.W. Gassman, and A. Saleh. 2003. "Completion Report for the Component #3 on the 'Use of the SWAT Model' of the Iowa Water Quality Protection Project." Des Moines, IA: Iowa Department of Natural Resources.

Keith, G., S. Norvell, R. Jones, C. Maquire, E. Osei, A. Saleh, P. Gassman, and J. Rodecap. 2000. "Livestock and the Environment: A National Pilot Project: CEEOT-LP Modeling for the Upper Maquoketa River Watershed, Iowa: Final report." Report No. PR0003. Texas Institute for Applied Environmental Research, Tarleton State University Stephenville, TX.

Kirsch, K., A. Kirsch, and J.G. Arnold. 2002. "Predicting Sediment and Phosphorus Loads in the Rock River Basin using SWAT." *Trans. ASAE* 45(6): 1757-69.

Mishra, S.K., and V.P. Singh. 2003. *Soil Conservation Service Curve Number (SCS-CN) Methodology.* Dordrecht, The Netherlands: Kluwer Academic Publishers.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2002a. *Soil and Water Assessment Tool User's Manual,* Version 2000. Temple, TX: Blackland Research Center, Texas Agricultural Experiment Station. http://www.brc.tamus.edu/swat/swat2000doc.html (accessed May 17, 2005).

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, J.R. Williams, and K.W. King. 2002b. *Soil and Water Assessment Tool Theoretical Documentation,* version 2000. Temple, TX: Blackland Research Center, Texas Agricultural Experiment Station. http://www.brc.tamus.edu/swat /swat2000doc.html (accessed May 17, 2005).

Nusser, S.M., and J.J. Goebel. 1997. "The National Resources Inventory: A Long-Term Multi-Resource Monitoring Programme." *Environ. Ecol. Stat.* 4: 181-204.

Osei, E., P. Gassman, and A. Saleh. 2000. "Livestock and the Environment: A National Pilot Project: CEEOT-LP Modeling for the Upper Maquoketa River Watershed, Iowa: Technical Report." Report No. RR0001. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, TX.

Saleh, A., J. G. Arnold, P. W. Gassman, L.M. Hauck, W.D. Rosenthal, J.R. Williams, and A.M.S. McFarland, 2000. "Application of SWAT for Upper North Bosque River Watershed." *Trans. ASAE* 45(3): 1077-87.

Saleh, A., P.W. Gassman, J. Abraham, and J. Rodecap. 2003. "Application of SWAT and APEX Model for Upper Maquoketa River Watershed." ASAE Paper No. 032063. American Society of Agricultural Engineers, St. Joseph, MI.

Santhi, C., J.G. Arnold, J.R. Williams, W.A. Dugas, and L. Hauck. 2001. "Validation of the SWAT Model on a Large River Basin with Point and Nonpoint Sources." *J. Am. Water Resour. Assoc.* 37(5): 1169-88.

Spruill, C.A., S.R. Workman, and J.L. Taraba. 2000. "Simulation of Daily and Monthly Stream Discharge from Small Watersheds using the SWAT Model." *Trans. ASAE* 43(6): 1431-39.

Srinivasan, R.S., J.G. Arnold, and C.A. Jones. 1998. "Hydrologic Modeling of the United States with the Soil and Water Assessment Tool." *Water Resour. Develop.* 14(3): 315-25.

U.S. Department of Agriculture, Soil Conservation Service (USDA). 1992. *STATSGO Data User Guide.* Pub. No. 1492. Washington, DC: U.S. Government Printing Office. http://www.ncgc.nrcs.usda.gov/ products/datasets/statsgo/.

Van Liew, M.W., and J. Garbrecht. 2001. "Sensitivity of Hydrologic Response of an Experimental Watershed to Changes in Annual Precipitation Amounts." ASAE Paper No. 012001. American Society of Agricultural Engineers, St. Joseph, MI.

Williams, J.R. 2002. "The APEX Manure Management Component." In *Proceedings of the Total Maximum Daily Load (TMDL) Environmental Regulations Conference*, pp. 44-51. ASAE Publication No. 701P0102. Edited by A. Saleh. St. Joseph, MI: American Society of Agricultural Engineers.