Modeling runoff and sediment yields from combined in-field crop practices using the Soil and Water Assessment Tool

D. Maski, K.R. Mankin, K.A. Janssen, P. Tuppad, and G.M. Pierzynski

Abstract: Cropland best management practice recommendations often combine improvements to both tillage and fertilizer application practices to reduce sediment losses with surface runoff. This study evaluated the impact of conventional-till and no-till management practices with surface or deep-banded fertilizer application in sorghum-soybean rotation on runoff and sediment-yield predictions using the Soil and Water Assessment Tool (SWAT) model. The model was calibrated using USDA Natural Resources Conservation Service runoff curve number for antecedent moisture condition II (CN_{II}), saturated hydraulic conductivity, and available water capacity parameters for runoff and USLE cropping factor (C_{min}) for sediment-yield predictions for three field plots (0.39 to 1.46 ha [0.96 to 3.6 ac]) with different combinations of practices and validated for three field plots (0.40 to 0.56 ha [1.0 to 1.4 ac]) over a period of 2000 to 2004. Surface runoff calibration required CN_{II} values greater than the recommended baseline values. No-till treatments required slightly greater curve number values than the till treatment, and this difference was similar to that associated with increasing the soil hydrologic group by one classification. Generally the model underpredicted the sediment yield for all management practices. Baseline C_{min} values were adequate for treatments with soil disturbance, either by tillage or fertilizer deep-banding, but best-fit C_{min} values for field conditions without soil disturbance (no-till with surface-broadcast fertilizer) were 2.5 to 3 times greater than baseline values. These results indicate current model limitations in modeling undisturbed (no-till) field management conditions, and caution that models calibrated for fields or watersheds predominated by tilled soil conditions may not function equally well in testing management scenarios without tillage.

Key words: erosion—fertilizer application—no-till—modeling—Soil and Water Assessment Tool

Combinations of conservation practices can reduce losses of soil and associated pollutants from cropland, though the integrated effects of these practices are not well understood. Sediment is the leading cause of stream and lake impairment in the United States (US Environmental Protection Agency 2003) and in Kansas (Devlin and Powell 1996). Agriculture, including crop production, is the source of pollution for 48% of the impaired river miles reported in the United States (US Environmental Protection Agency 2003). Source control of sediment from cropland requires the use of best-management practices (BMPs) that can reduce sediment detachment and transport in surface runoff. Cropland BMP recommendations to reduce soil erosion often use one or more practices, such as no-till, to reduce soil and surface-cover disturbance, whereas recommendations to reduce runoff generally increase runoff detention time and infiltration capacity.

No-till practices have been shown to reduce runoff volume and sediment loss as compared to tilled cropland (Mickelson et al. 2001b; Seta et al. 1993; Sauer and Daniel 1987), largely due to increased surface residue and soil aggregation, which slows surface runoff and improves infiltration. In contrast, other studies have shown greater runoff volume for no-till due to greater soil moisture content and greater soil compaction than tilled plots (Bundy et al. 2001; Mickelson et al. 2001a; Myers et al. 1995; Zeiman et al. 2006). The most common finding of studies testing the effect of tillage on sediment loss is that increasing tillage intensity increases sediment loss.

Strategic implementation of BMPs, such as no-till, as part of a watershed restoration and protection plan requires an assessment of the impacts of these practices on water quality (Devlin et al. 2005). Watershed models can simulate pollutant loads to receiving water bodies under various BMPs and determine the most effective areas for targeting BMP implementation (Mankin et al. 2005). But realistic estimates of improvements from BMP implementation require realistic model selection and parameterization. The USDA Conservation Effects Assessment Project recognizes the need for model calibration and testing to improve evaluation of the effects of individual and combined conservation practice implementation (USDA Natural Resources Conservation Service [NRCS] 2004). In addition, because water and/or sediments are carriers of other pollutants, accurate runoff and soil-loss predictions are essential for accurate water-quality simulation.

The Universal Soil Loss Equation (USLE) has been widely used to estimate sediment erosion for many cropping systems and management practices in association with soil type, rainfall pattern, and topography (Wischmeier and Smith 1978). USLE computes soil loss for a given site as a product of six major factors: the rainfall and runoff factor (R), the soil erodibility factor (K), the topographic factor (LS), the cover and management factor (C), and the support practice factor (*P*). Wischmeier (1976) suggests that this equation should not be used to estimate soil loss for specific events or time periods, as these short-term records are subject to bias by cyclical effects and random fluctuations in uncontrolled variables whose effects are averaged in the USLE factor values.

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Nonetheless, variations of the USLE have been incorporated into various hydrologic models, like Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998), ADAPT (Chung et al. 1992), and GLEAMS (Leonard et al. 1987), to predict event-based sediment yields. Williams and Berndt (1977) discussed a Modified USLE (MUSLE) used in SWAT. The rainfall energy factor was replaced with a runoff factor, which used predicted daily runoff volume and peak runoff rate to allow its applicability to individual storms.

Several water-quality models, including ANSWERS (Beasley et al. 1980), CREAMS (Knisel 1980), GLEAMS (Leonard et al. 1987), SWRRB (Arnold and Williams 1987), EPIC (Sharpley and Williams 1990), SWAT (Arnold et al. 1998), ADAPT (Chung et al. 1992), WEPP (Flanagan and Nearing 1995), RUSLE (Renard et al. 1997), and AnnAGNPS (Cronshey and Theurer 1998) were developed both at field and watershed scales to simulate the impact of land management on water, sediment, nutrients, and pesticides. Specific testing of these models for simulating the effects of cropland BMPs on runoff and sediment yield from agricultural fields or watersheds exists but is limited, particularly for combinations of in-field BMPs.

Bingner et al. (1989) used five models (CREAMS, SWRRB, EPIC, ANSWERS, and AGNPS) to model runoff and sediment yield from three field-sized watersheds in Mississippi, including an upland watershed with 3% to 8% slope planted in soybean, a flat-land watershed planted in continuous cotton under conventional practices, and a terraced watershed planted in corn with some period under no-till practice. They found CREAMS and SWRRB, both precursors to the SWAT model, produced results similar to measured results most often of the models studied. Ewing (1989) found that CREAMS may be fairly accurate in predicting cumulative annual runoff and sediment yield, but no calibration was attempted. Chung et al. (1999) used EPIC to model two field-sized watersheds in southwestern Iowa with an average slope of 8.4% cropped with continuous corn managed with conventional- and ridge-tillage systems. The model was calibrated for water balance. For sediment-yield predictions, a C_{min} value was chosen based on model documentation and USDA NRCS guidelines; however, no actual calibration was performed for sediment yield prediction. The study concluded that EPIC was able to replicate the long-term relative differences between the two tillage systems but called for more model testing and more studies for selecting suitable input parameters to depict different management systems. Yuan et al. (2001) used AnnAGNPS to evaluate alternative BMP scenarios, including reduced-tillage cotton, no-tillage soybean, and winter cover crop for both cotton and soybean, and impoundments, for a small watershed in Mississippi. No calibration was attempted. Predicted total runoff for the three-year period was 89% of the observed, and predicted sediment yield was 104% of the total observed sediment yield. Monthly coefficient of determination (R^2) was 0.5 for runoff and 0.7 for sediment yield. Using the AGNPS model, Mostaghimi et al. (1997) found a relative error of 23.5% for sediment yield for current conditions and assessed several BMP scenarios, including conversion to no-till. However, calibration of parameters for the no-till scenarios was not attempted. Reyes et al. (2004) compared actual runoff and soil loss data using GLEAMS, RUSLE, EPIC, and WEPP model predictions under different BMPs in North Carolina corn plots with conventional tillage, strip tillage, no-tillage controlled traffic, and no-tillage fall traffic. No calibration was done in choosing model parameters (NRCS runoff curve number [CN] for antecedent moisture condition II (CN_{II}) for runoff and USLE cropping factor (C_{min}) for soil loss). The study indicated that none of the models predicted runoff and soil loss satisfactorily.

Calibrated and validated model parameters using field or watershed data are necessary so that field and watershed models can be useful and cost-effective tools for assessing impacts of agricultural BMPs on water quality. SWAT has been calibrated and validated for several BMP scenarios (Vache et al. 2002; Bracmort et al. 2006; Santhi et al. 2006) but not using site-specific field-scale (<5 ha [<12 ac] with mild slopes) experimental runoff and sediment-yield data for integrated crop tillage systems. Anand et al. (2007) evaluated SWAT and ADAPT for runoff, but not sediment losses, on the same site as this study but for only the first three years of the five-year data set.

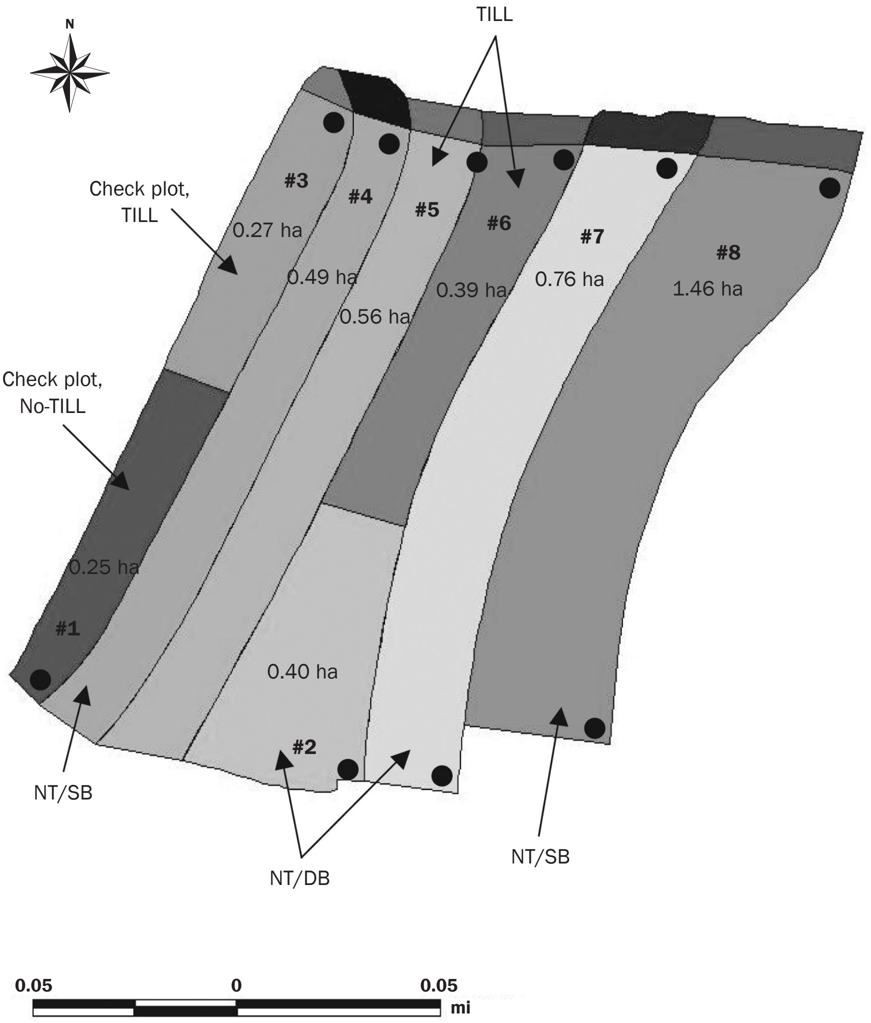
This study tested the capability of the SWAT model to simulate the effects of combinations of management practices on water quality with the following objectives: (1) Calibrate SWAT water quality model using a systematic process to select and verify optimal parameter sets for simulation of runoff and sediment losses for field-scale till and no-till management practices with surface or deep-banded fertilizer application in sorghum-soybean rotation. (2) Validate the model on replicate field using the identified best calibration parameters to evaluate the model runoff and sediment prediction performance.

Methods and Materials

Study Area. The study area was a 4.7-ha (11.6-ac) terraced field in southeastern Franklin County, Kansas, in the Upper Marais des Cygnes basin (HUC 10290101). The Soil Survey Geographic (SSURGO) database (USDA NRCS 2007) identified Summit silty clay loam (fine, montmorillonitic, thermic Vertic Argiudolls) as the major soil in the study area (figure 1). The project site had clayey subsoil, deep water table (>2.3 m [7.5 ft]), and no irrigation or subsurface drainage. A real-time kinematic global-positioning receiver, in conjunction with a local base-station, produced a field survey with horizontal accuracy of 10 to 20 mm (0.4 to 0.8 in) and a vertical accuracy 2 to 3 times the horizontal accuracy (Schmidt et al. 2003) to derive slopes for individual plots (table 1). Plots were imposed on the existing farm field as the drainage areas for individual field terraces.

The site was in a rotation of grain sorghum (*Sorghum bicolor* [L.] *Moench*) and soybean (*Glycine max* [L.] *Merr*), with grain sorghum in 2000, soybean in 2001, grain sorghum in 2002, soybean in 2003, and grain sorghum in 2004. A set of three BMP treatments with two replications each was applied. The TILL treatment had fall chisel tillage and spring field cultivation followed by planting. Fertilizer and herbicides were surface-broadcast with shallow incorporation before planting. The NT/SB treatment was a no-till plot with both fertilizer and herbicides surface-broadcast in the spring without incorporation. The NT/DB treatment was a no-till plot with fertilizer deep-banded in the spring prior to planting and a split (fall/spring) surface application of herbicides. The plots, named by treatment applied and plot numbers, were TILL#6 and TILL#5 for tilled treatments, NT/DB#7 and NT/DB#2 for no-till treatments with deep-banded fertilizer, and NT/SB#8 and NT/SB#4 for no-till treatments with surface-broadcast fertilizer (table 1).

Figure 1
Layout of study area with eight individual plot watersheds.



Notes: Check plot = till or no-till with no added fertilizer or herbicide. TILL = fall chisel tillage, spring cultivation. NT/DB = no-till, spring deep-banded applications. NT/SB = no-till, spring surface-broadcast applications. ● = sampler locations.

Table 1
Topographic properties of the treatment plots.

Plot	Treatment	Area (ha)	Slope
1	Check plot#1	0.25	6.63%
2	NT/DB#2	0.40	6.05%
3	Check plot#3	0.27	6.63%
4	NT/SB#4	0.49	9.05%
5	TILL#5	0.56	4.89%
6	TILL#6	0.39	6.05%
7	NT/DB#7	0.76	4.90%
8	NT/SB#8	1.46	3.64%

Notes: Check plot = till or no-till with no added fertilizer or herbicide. TILL = fall chisel tillage, spring cultivation. NT/DB = no-till, spring deep-banded applications. NT/SB = no-till, spring surface-broadcast applications.

Data Acquisition. The average annual precipitation (1971 to 2000, Ottawa, Kansas) was 970 mm (38.2 in), with 46% falling between April and July. Annual rainfall for the study period, recorded on-site, was 614 mm (24.2 in) (2000), 940 mm (37.0 in) (2001), 644 mm (25.4 in) (2002), 746 mm (29.4 in) (2003), and 1,075 mm (42.3 in) (2004). April, May, and June generally had the greatest precipitation (figure 2). ISCO 6700 samplers (ISCO, Lincoln, Nebraska) collected one flow-weighted water sample for each runoff event and measured runoff by using 90° V-notch weirs located at the end of each plot terrace channel (Grant and Dawson 2001). Sediment concentration in the runoff was determined in duplicate by filtering 100 mL (3.4 oz) of water with vacuum assist through pre-weighed 0.45-μm (0.0177-mil) pore size filter paper. After filtering, filter papers were dried in an oven at approximately 105°C (221°F) for 24 hours and then weighed to determine sediment mass (Csuros 1987). The sediment yield measured from each plot is summarized in table 2.

SWAT Model Description. The SWAT model is a watershed-scale simulation model developed by the USDA Agricultural Research Service to predict the impact of land-management practices on water, sediment, and agricultural-chemical yields in large, complex watersheds with various soils, topography, and land-use management conditions over long periods of time (Neitsch et al. 1999). The SWAT model components include weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management (Arnold et al. 1998). SWAT has the capability to be used at the watershed/river basin scale, where a watershed is divided into subwatersheds based on the topography. Subwatersheds could be further divided into hydrologic response units, which are unique combination of soil, land-use, and management. In this study, each plot was essentially considered as a single hydrologic response unit with one type of soil, land-use, and management. Management scenarios were specified for each plot, scheduled by dates. All the input files for this hydrologic simulation study were prepared using the Windows interface for SWAT version 99.2. This version allowed more freedom and ease of simulation for individual treatments at field plots as small as 0.40 ha (1.0 ac). No substantive changes in field-scale hydrologic processes have been made from the 99.2 version to the current version (SWAT version 2005) (Neitsch et al. 2004).

SWAT uses the Modified Universal Soil Loss Equation (MUSLE):

$$Y = 11.8\,(Q\,q_p\,a)^{0.56}\,\mathrm{K}\,\mathrm{LS}\,C\,P\,C_f\,, \qquad (1)$$

where Y = sediment yield from an individual storm (Mg), Q = storm runoff volume (m^3), q_p = peak runoff rate ($\mathrm{m}^3\ \mathrm{s}^{-1}$), a = area of the hydrologic response unit (ha), K = soil erodibility factor, LS = slope-length and gradient factor, C = crop management factor, P = erosion control practice factor, and C_f = coarse fragment factor.

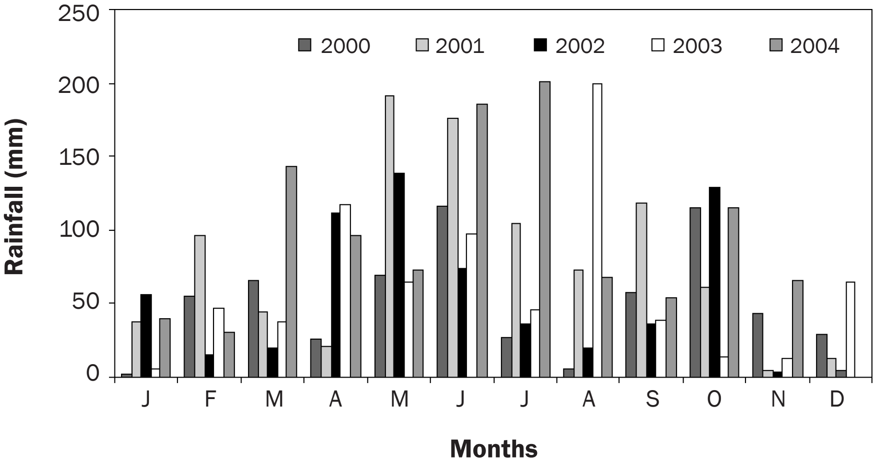
The daily runoff volume (Q) required as an input to equation 1 was derived from the USDA NRCS CN method (USDA Soil Conservation Service 1972) with antecedent moisture condition adjusted daily using a soil-moisture index accounting procedure. The replacement of USLE's rainfall energy factor with a runoff factor increased the model efficiency and also allowed its application to individual storms (Williams and Berndt 1977). The LS and K factors are fixed according to user inputs whereas the C factor is input as an annual minimum C (C_{min}) and adjusted daily according to an exponential function of surface residue.

The USLE C factor has been identified as a critical input for sediment loss predictions (Bingner et al. 1989). Neitsch et al. (2001) suggested USLE C and LS factors for use in SWAT sediment calibration. In this study, both length (L) and slope (S) were field-measured values. Santhi et al. (2001) found the C factor and the linear and exponential factors for channel sediment routing have been used for sediment calibration in SWAT.

The SWAT model (version 99.2) allows the user to designate subbasin information as well as information about routing between successive subbasins. Each treatment plot was simulated as a single subbasin (with no subbasin routing), and output from a plot was simulated by output at the subbasin outlet. Channel input values (for channels within the subbasin) were selected to minimize their influence on flow and sediment transport results. The following channel input values were used: length was 0.05 km (164 ft), average width was 1 m (3.3 ft), slope was 0.005 m m^{-1} (0.005 ft ft^{-1}), effective hydraulic conductivity of alluvium was 0.0 mm h^{-1} (0.0 in hr^{-1}) , and Manning's n value was 0.03.

Figure 2

Monthly rainfall pattern for five years under observation at the study area.



Model Inputs. Weather inputs for SWAT included daily time series of precipitation, maximum and minimum temperature, relative humidity, solar radiation, and wind speed (1999 to 2004). Rainfall was measured on-site, and the remaining data were used from the nearest weather station at Ottawa, Kansas, which was about 20 km (12 mi) from the study site. The soils data used in the model are listed in table 3.

Timing for important operations, such as tillage, fertilizer application, and herbicide application, were plot-specific for each treatment, whereas planting and harvest were carried out on the same date for all treatments (for the period 1999 to 2004). A value of 0.1 was used for P factor to represent a terraced field. Manning's n for overland flow was assumed to be 0.03. Among the three available potential-evapotranspiration methods in SWAT, Penman-Monteith (Monteith 1965) was selected, at the suggestion of the SWAT programmers. This method required the solar radiation, air temperature, relative humidity, and wind speed, and used alfalfa as reference crop. The model calculated crop evapotranspiration from potential evapotranspiration using crop-specific parameters.

In SWAT, individual treatments varied by area, slope, C_{min}, the dates of field operations, and timing, placement, and rate of nutrient and herbicide applications. The SWAT required C_{min} in the crop database file. For the daily runoff and sediment-yield calibration, baseline C_{min} values for grain sorghum and soybeans were set at 0.25 and 0.18 for the TILL treatment and 0.14 and 0.11 for both NT/DB and NT/SB treatments (Wischmeier and Smith 1978). The initial crop residue on the ground surface was 600 kg ha^{-1} (0.25 tn ac^{-1}) for TILL and 800 kg ha^{-1} (0.35 tn ac^{-1}) for NT treatments. Grain sorghum was the crop for 1999, the year prior to project period. Yield data were used to calculate the amount of residue left in the field. The assumption was made that 32 kg (70 lb) of residue (for grain sorghum) was left on the field for every bushel of crop yield (Anand 2004). For validation treatments, the model parameters were kept the same as for the corresponding calibration treatments, other than plot-specific changes in area, residue cover, and slope. Results were compared with measured runoff and sediment yield from the respective treatments.

Model Calibration and Validation. The process of calibrating the model for runoff was adapted from Anand et al. (2007). Observed runoff-event volumes from the field, available for years 2000 to 2004, were used. All runoff events greater than 0.1 mm (0.004 in), either as predicted by the model or measured on site, were compared. This resulted in daily runoff calibration using 60 events for TILL, 63 for NT/DB, and 64 for NT/SB. Similarly, the daily runoff validation used 60 events for TILL, 65 for NT/DB, and 63 for NT/SB. Performance of the model was evaluated by comparing event-based observed and predicted flow volumes. If event runoff was modeled to span more than one day, total runoff for the entire storm (up to three days) was lumped for analysis. This assumption causes two (or three) smaller precipitation (p) values to be used in the CN equation to estimate two (or three) independent daily runoff (r) values. Because the

Table 2
Measured sediment yields.

Date	Sediment yield (Mg ha^{-1})					
	TILL#6	TILL#5	NT/DB#7	NT/DB#2	NT/SB#8	NT/SB#4
2000						
05/27/00	4.644	0.345	0.615	0.078	0.307	0.167
06/14/00	0.126	0.002	0.148	0.046	0.119	0.027
06/20/00	3.266	0.285	0.620	0.150	0.780	0.238
06/26/00	0.209	0.029	0.315	0.027	0.035	0.023
2001						
05/17/01	0.944	0.724	0.204	0.021	0.517	0.582
05/20/01	0.366	0.646	0.103	0.039	0.194	0.344
05/30/01	0.076	0.008	0.115	0.034	0.045	0.031
06/01/01	0.118	0.247	0.040	0.009	0.038	0.061
06/03/01	0.416	0.687	0.141	0.091	0.260	0.192
06/06/01	0.289	0.358	0.112	0.054	0.094	0.081
06/21/01	0.028	0.202	0.026	0.086	0.041	0.015
07/27/01	0.014	0.040	0.008	0.047	0.034	0.004
09/18/01	0.001	0.128	0.003	0.050	0.006	0.001
10/05/01	0.004	0.022	0.004	M	0.009	0.000
2002						
04/21/02	0.002	0.007	0.011	0.000	0.004	0.002
04/27/02	0.025	0.062	0.031	0.008	0.040	0.004
05/08/02	0.002	0.013	0.025	0.011	0.013	0.018
05/12/02	0.171	M	0.100	0.474	0.111	0.060
05/26/02	0.110	0.802	0.029	0.036	0.081	0.035
06/09/02	0.209	0.366	0.109	0.083	0.108	0.048
07/12/02	0.371	0.577	0.213	0.167	0.108	0.082
2003						
04/23/03	0.000	0.001	0.004	0.004	0.003	0.002
04/25/03	0.006	0.013	0.010	0.012	0.003	0.006
05/01/03	0.009	0.015	0.007	0.019	0.013	0.006
06/02/03	0.036	0.037	0.030	0.010	0.046	0.010
07/06/03	0.008	0.009	0.004	0.005	0.007	0.002
08/31/03	0.015	0.029	0.014	0.066	0.055	0.001
2004						
04/20/04	M	0.240	0.030	0.024	0.104	M
04/24/04	0.039	0.016	M	0.007	0.011	0.003
05/14/04	0.002	0.004	M	0.006	0.003	0.001
05/19/04	0.001	0.055	0.001	0.035	0.003	0.000
06/10/04	0.271	1.008	0.241	0.664	0.365	0.173
06/18/04	0.000	0.071	0.006	0.030	0.020	0.007
06/27/04	0.004	0.022	0.002	0.011	0.008	0.004
06/30/04	0.502	0.870	M	0.431	0.385	0.228
07/06/04	0.117	0.261	0.173	0.044	0.070	0.027
07/24/04	0.138	0.319	0.104	0.082	0.118	0.001
09/06/04	0.000	0.001	0.000	0.015	0.014	0.001
10/07/04	0.000	0.000	0.004	0.208	0.006	0.001
11/03/04	0.016	0.041	0.021	0.022	0.014	0.015

Notes: Till #6 = full-width tillage with broadcast and incorporated fertilizer for field plot #6. NT/DB#7 = no-till with deep-banded fertilizer for field plot #7. NT/SB#8 = no-till with surface-broadcast fertilizer for field plot#8. M = missing data for measured sediment yield.

CN equation is nonlinear, splitting a single runoff event (r_1) from a precipitation event (p_1) into two runoff events (r_2 and r_3) from two sequential precipitation events (p_2 and p_3) systematically underestimates runoff if antecedent moisture content (AMC) is constant. That is, if $p_1 = (p_2+p_3)$, then $r_1 < (r_2+r_3)$ if $AMC_1 = AMC_2 = AMC_3$. This is because the initial abstraction is applied to each of the two split events rather than just once to the combined, single event. Even though AMC typically increases due to the rainfall of the second event, this increase is not sufficient to offset the systematic underestimation just described.

Hydrologic calibration used common parameters: CN_{II}, saturated hydraulic conductivity (K_{sat}), and soil available water capacity (AWC). Generally, the baseline values were taken from the common reference manual values for that practice, soil, etc., and each parameter was adjusted within a range that would produce a local maximum for the event-based model efficiency (E_f) (Nash and Sutcliffe 1970) and would allow selection of "best-fit" parameters. Values of 86, 78, and 70 were used for CN_{II}. The baseline K_{sat} values were selected to be 0.4, 0.3, 0.2, and 0.1 mm h^{-1} (0.016, 0.011, 0.008, 0.004 in h^{-1}) as base values (1×) for the four soil layers from the MUUF manual (Baumer et al. 1994). These were varied by factors of 2, 4, 8, and 32, so that the values fall within the range reported in literature (Rawls et al. 1998). The database values of AWC for Summit silty clay loam were 0.18, 0.14, 0.14, and 0.14 mm mm^{-1} (0.18, 0.14, 0.14, and 0.14 in in^{-1}) for the four soil layers. These values were reduced by 50% and 75% during calibration.

The calibration process used a complete factorial analysis of 3 CN_{II}, 5 K_{sat}, and 3 AWC values (45 simulations). Additional simulation runs were performed to determine the parameter set with local-maximum model efficiency. The best-fit parameter set selected for each treatment from the runoff calibration was used for each paired validation plot and for each paired sediment calibration and validation plot.

The calibration process for sediment consisted of comparing event-based model predictions to measured sediment yield values for data from years 2000 to 2004 for all events with either modeled or observed runoff values exceeding 0.1 mm (0.004 in). Simulation was begun in 1999 in order to allow the model to initialize the soil-moisture profile and other conditions. Based on published sensitivity and evaluation studies, C factor (equation 1) was selected as the target model parameter for sediment calibration. The C_{min} input value was adjusted within the range of -50% to +200% from the baseline value until a local maximum event-based E_f was produced.

This study used R^2 of event-based observed versus predicted values and median-based E_f (Coffey et al. 2004; Anand et al. 2007). Coffey et al. (2004) stated that data nonnormality and/or lack of independence of events, particularly for daily data, can violate statistical model assumptions and suggested the use of median-based E_f to account for assumptions of independent and nonnormally distributed datasets. The E_f used the following relation:

$$E_f = 1 - \frac{\Sigma(Q_p - Q_o)^2}{\Sigma(Q_o - Q_{o,m})^2}, \qquad (2)$$

where E_f = median-based Nash-Sutcliffe model efficiency index, Q_p = runoff depth predicted by SWAT, Q_o = runoff depth observed at the field, and $Q_{o,m}$ = median of the observed runoff depths at the field.

Values of R^2 range from 0 to 1.0 and assess the degree of fit of the observed versus predicted linear regression line, with 1.0 indicating a perfect fit. Values of E_f range from $-\infty$ to 1.0 and assess the degree to which predicted data agree with observed data, with 1.0 indicating perfect fit, 0 indicating that the variance between predicted and observed values is of the same magnitude as the variance between the observed and median values (thus the prediction offers no advantage over the use of a median value), and <0 indicating that using the predicted value is worse than using the observed median. A SWAT calibration on runoff using a more-limited data set (three years) at this field site found that E_f provided a sufficient single value to assess model accuracy (Anand et al. 2007). An E_f using an average, instead of median, observed value ($E_{f(a)}$) was also reported to allow comparison with other studies (Moriasi et al. 2007).

The model was tested for event-based predictions. The calibration runs evaluated both four- and five-year periods to account for the excessive sediment measured during the first year, probably due to soil disturbance associated with sampler and weir installation (Anand 2004; Zieman et al. 2006). Similar to calibration runs, the validation phase was further split into four- and five-year periods, and used the appropriate paired calibration parameters for that plot.

Table 3

Summary of soil input variables for Summit silty clay loam (Soil Survey Geographic Database).

	Soil horizon			
Soil properties	**1**	**2**	**3**	**4**
Thickness (mm)	150	200	1090	330
Porosity (mm mm^{-1})	0.47	0.43	0.47	0.47
Wilting point (mm mm^{-1})	0.20	0.20	0.20	0.20
Field capacity (mm mm^{-1})	0.36	0.36	0.36	0.36
Vertical K_{sat} (mm h^{-1})	0.4	0.3	0.2	0.1
Clay	36.00%	38.00%	50.00%	45.50%
Silt	56.35%	54.15%	44.75%	47.63%
Organic matter	2.50%	1.50%	1.50%	0.75%

Results and Discussion

Runoff Calibration and Validation. The best-fit CN_{II} value was 86 for the TILL treatment and slightly greater for NT/SB (88) and NT/DB (89) treatments (table 4). The best-fit K_{sat} values increased in the same order as with CN_{II}. Best-fit AWC values were unchanged from the baseline values.

The SWAT model suggests a range of CN_{II} values for the purpose of calibration. Our CN_{II} values of 86, 88, and 89 were more representative of hydrologic soil group D (CN_{II} range 80 to 91) than its classified soil group C (CN_{II} range 77 to 88). The National Engineering Handbook (USDA Soil Conservation Service 1972) includes soil texture, infiltration rate, and transmission rate, but not tillage, as factors in selecting hydrologic soil group. Whereas most published tables show discrete CNs corresponding to each soil group, the National Engineering Handbook shows that each soil group represents a range of possible CNs. For the examples shown, the CN range was about 5 to 6 units for soil group C and about 3 units for soil group D. This study found a CN increase of about 2 to 3 CN units for NT compared to TILL treatments. This corresponds to an increase of one soil hydrologic group, in this case from soil group C (CN_{II} = 78) to D (CN_{II} = 81).

Daily and monthly summary statistical results (table 4) were similar. The model performed better at a monthly, rather than daily, time step. For example, for TILL#6, SWAT had daily R^2 of 0.52 and E_f of 0.57 ($E_{f(a)}$ = 0.51), which increased to R^2 of 0.63 and E_f of 0.65 ($E_{f(a)}$ = 0.60) for a monthly time scale. In the no-till treatments, the daily E_f values ranged from 0.32 ($E_{f(a)}$ = 0.28) to 0.62 ($E_{f(a)}$ = 0.56) and the monthly values ranged from 0.29 ($E_{f(a)}$ = 0.26) to 0.63 ($E_{f(a)}$ = 0.58).

These results are in agreement with results reported by other studies. This study found monthly comparison results similar to those in most literature. For example, monthly comparisons for surface runoff prediction showed R^2 values as high as 0.94 and as low as 0.79 (Arnold and Allen 1996). Similar results have been published by using SWAT at other sites, such as Srinivasan and Arnold (1994) with a monthly $E_{f(a)}$ of 0.86; Rosenthal et al. (1995) with a monthly R^2 of 0.75; Bingner et al. (1997) with most individual events having R^2 >0.8; King et al. (1999) with a monthly $E_{f(a)}$ of 0.84; Fohrer et al. (2001) with a daily $E_{f(a)}$ as high as 0.91 for a calibrated watershed and 0.93 for validated watershed; Santhi et al. (2001) with an R^2 >0.6 and an $E_{f(a)}$ >0.5; and Tripathi et al. (2003) with a daily $E_{f(a)}$ of 0.87. Published results (Anand et al. 2007) from SWAT hydrologic analyses from the same site but using only three years of data (instead of five years in this study) found slightly greater daily E_f for the TILL treatment (0.60 vs. 0.57) but lesser daily E_f for NT treatments (0.38 and 0.44 vs. 0.62 and 0.61).

SWAT performed similarly well in simulating tillage and no-till conditions in both calibration and validation phases (table 4). Anand et al. (2007) found poorer results for validation of the NT/DB treatment and suggested SWAT might have limitations in representation of the deep-banding with a field cultivator or timing of rainfall related to these operations. These results, based on a longer climatic period, suggest no such limitation.

Sediment Yield Calibration. The SWAT-predicted daily sediment yield with baseline

Table 4
Daily and monthly runoff calibration and validation parameters and statistical results.

Calibration parameters	Soil horizon	Baseline	Calibration			Validation		
			TILL#6	**NT/DB#7**	**NT/SB#8**	**TILL#5**	**NT/DB#2**	**NT/SB#4**
CN_{II}		78	86	89	88	86	89	88
K_{sat} (mm h^{-1})	1	0.4	0.8	3.2	1.6	0.8	3.2	1.6
	2	0.3	0.6	2.4	1.2	0.6	2.4	1.2
	3	0.2	0.4	1.6	0.8	0.4	1.6	0.8
	4	0.1	0.2	0.8	0.4	0.2	0.8	0.4
AWC (mm mm^{-1})	1	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	2	0.14	0.14	0.14	0.14	0.14	0.14	0.14
	3	0.14	0.14	0.14	0.14	0.14	0.14	0.14
	4	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Daily								
Baseline E_f			0.12	0.37	0.42	0.11	0.32	0.40
Baseline R^2			0.39	0.33	0.32	0.36	0.31	0.30
Best-fit E_f			0.57	0.62	0.61	0.52	0.52	0.59
Best-fit R^2			0.52	0.48	0.51	0.45	0.47	0.49
Monthly								
Baseline E_f			0.39	0.41	0.48	0.32	0.29	0.43
Baseline R^2			0.52	0.40	0.41	0.46	0.44	0.51
Best-fit E_f			0.65	0.56	0.60	0.57	0.48	0.63
Best-fit R^2			0.63	0.47	0.57	0.51	0.51	0.61

Notes: TILL = Fall chisel tillage, spring cultivation. NT/DB = no-till, spring deep-banded applications. NT/SB = no-till, spring surface-broadcast applications.

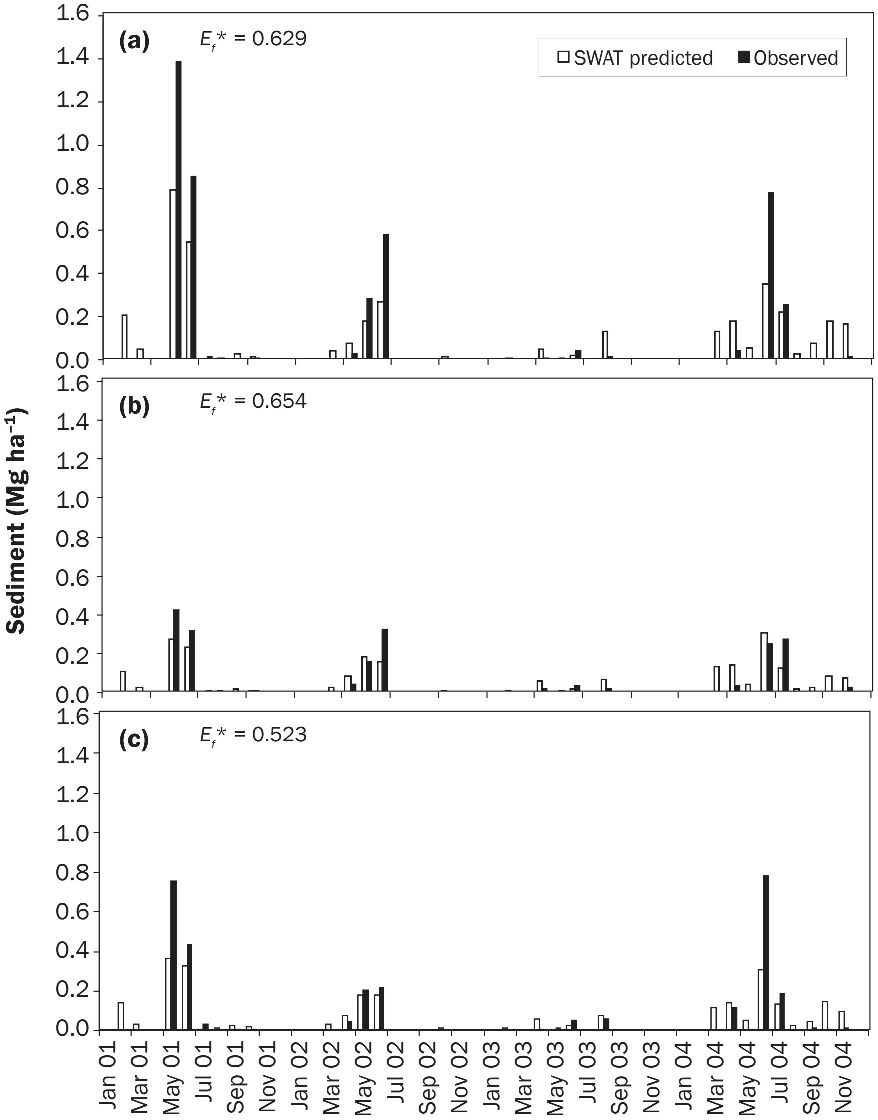
Table 5
Daily and monthly sediment-yield calibration results.

	C_{min} value			Daily statistic		Monthly statistic		Avg. sediment yield (Mg ha^{-1} y^{-1})	
Parameters: Period Treatment	**Percent change from baseline C_{min}**	**Grain sorghum**	**Soybean**	E_f	R^2	E_f	R^2	**Measured**	**Predicted**
Baseline: 2001 to 2004									
TILL#6	0%	0.25	0.18	0.62	0.66	0.76	0.74	1.08	0.70
NT/DB#7	0%	0.14	0.11	0.65	0.58	0.71	0.63	0.48	0.42
NT/SB#8	0%	0.14	0.11	0.40	0.49	0.65	0.63	0.74	0.39
Best-fit: 2001 to 2004									
TILL#6	+25%	0.31	0.23	0.66	0.70	0.80	0.87	1.08	0.96
NT/DB#7	–3%	0.13	0.10	0.69	0.60	0.77	0.70	0.48	0.44
NT/SB#8	+175%	0.39	0.30	0.60	0.51	0.72	0.77	0.74	0.69
Baseline: 2000 to 2004									
TILL#6	0%	0.25	0.18	0.03	–0.06	0.38	0.36	2.51	0.57
NT/DB#7	0%	0.14	0.11	0.07	–0.11	0.33	0.31	0.72	0.34
NT/SB#8	0%	0.14	0.11	0.12	0.09	0.25	0.24	0.84	0.32
Best-fit: 2000 to 2004									
TILL#6	+150%	0.63	0.45	0.04	–0.06	0.49	0.43	2.51	0.86
NT/DB#7	–3%	0.13	0.10	0.07	–0.11	0.41	0.38	0.72	0.38
NT/SB#8	+175%	0.39	0.30	0.23	0.13	0.54	0.46	0.84	0.56

Notes: TILL = fall chisel tillage, spring cultivation. NT/DB = no-till, spring deep-banded applications. NT/SB = no-till, spring surface-broadcast applications. E_f = median-based Nash-Sutcliffe efficiency. R^2 = coefficient of determination.

Figure 3

Monthly observations and calibrated sediment yield results for (a) TILL#6, (b) NT/DB#7, and (c) NT/SB#8 treatments.



Notes: TILL = fall chisel tillage, spring cultivation. NT/DB = no-till, spring deep-banded applications. NT/SB = no-till, spring surface-broadcast applications.

and best-fit values of C_{min} were compared with measured sediment yield (table 5). Model efficiency results for baseline as well as best-fit parameter sets were lower for the five-year (2000 to 2004) compared to the four-year (2001 to 2004) calibration periods. This was suspected to be due to the influence of soil disturbance during sampler and weir installation on measured sediment yields in 2000. Results from both periods are presented, although discussion focuses on the four-year period to minimize the potential effect of initial soil disturbance on model results.

The model under-predicted the average sediment yield compared to measured sediment yield for the baseline as well as best-fit C_{min} (table 5). Calibrated results produced daily E_f >0.6 ($E_{f(a)}$ = 0.55) and daily R^2 >0.5 for all treatments. Generally, the best-fit calibration statistics were greater than the baseline. This supported the need for site-specific calibration of C_{min} to provide optimal results.

The best-fit calibration required greater C_{min} for TILL#6 (+25%) and NT/SB#8 (+175%) relative to baseline values. The best-fit and baseline C_{min} values (0.14 for grain sorghum and 0.11 for soybeans) for the NT/DB#7 treatment differed by <0.01 C_{min} units. This difference is considered negligible since C_{min} values typically are specified to 0.01 unit resolution.

Monthly statistics were greater than daily statistics in all cases. Monthly modeling efficiency was highest for TILL#6 (E_f = 0.80 or $E_{f(a)}$ = 0.75), followed by NT/DB#7 (E_f = 0.77 or $E_{f(a)}$ = 0.70) and NT/SB#8 (E_f = 0.72 or $E_{f(a)}$ = 0.66), which was not the same ranking as for daily modeling efficiency. Based on the general performance ratings for the $E_{f(a)}$ statistics, the monthly modeling efficiencies for all the treatments were good ($0.65 < E_{f(a)} \leq 0.75$) (Moriasi et al. 2007).

The SWAT-predicted daily sediment yield for best-fit calibration was pooled for the monthly time step for all the months and compared with measured data (figure 3, table 5). Sediment yield was under-predicted by SWAT in all the treatments (figure 3). For all four years, the observed sediment yields, especially during May and June (high rainfall months, figure 2), were generally greater.

Graphical presentation of E_f with respect to C_{min} demonstrates the existence of a best-fit C_{min} value (with local-maximum E_f) and the model sensitivity to changes in C_{min} (figure 4). This figure also demonstrates the range of C_{min} values that produced a small variation in model efficiency (here, ±1% E_f). These ranges of C_{min} values for grain sorghum and soybeans for the treatments at ±1% E_f variations are shown in table 6. For TILL#6 and NT/DB#7, the range of C_{min} within ±1% E_f included the baseline parameter value. The C_{min} values within ±1% E_f range for NT/SB#8, however, were 2.5 to 3 times greater than the baseline C_{min}. This result appears to indicate that the baseline values provide a reasonable estimate of management practices with greater levels of soils disturbance, either by chisel tillage and cultivation (TILL) or by deep-banded fertilizer application (NT/DB), but not for no-till with surface broadcast fertilizer application (NT/SB). Whereas surface conditions of crop fields with tilled soils are largely influenced by crop and mechanical tillage effects, soil properties and erosivity characteristics of crop fields managed under no-till conditions are highly dependent on site-specific soil macrofauna, climate, and other influences on soil surface condition (Mankin et al. 1996).

Table 6

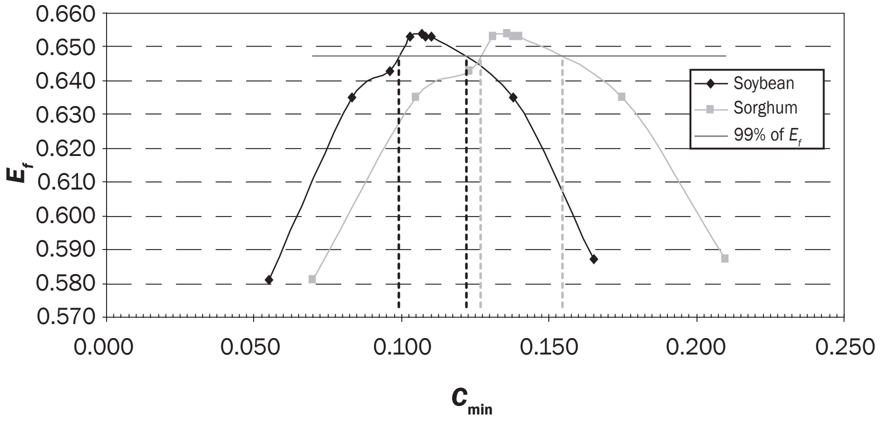
Range of C_{min} corresponding to ±1% E_f variation from the best-fit value for sediment calibration.

Period		Treatment		
Crop type	C_{min} procedure	TILL#6	NT/DB#7	NT/SB#8
2001 to 2004				
Grain sorghum	Range ±1% E_f (baseline)	0.243 to 0.400 (0.25)	0.128 to 0.155 (0.14)	0.320 to 0.440 (0.14)
Soybeans	Range ±1% E_f (baseline)	0.175 to 0.290 (0.18)	0.100 to 0.123 (0.11)	0.250 to 0.350 (0.11)
2000 to 2004				
Grain sorghum	Range ±1% E_f	0.505 to 0.665	0.130 to 0.185	0.365 to 0.445
Soybeans	Range ±1% E_f	0.365 to 0.485	0.103 to 0.145	0.285 to 0.350

Notes: TILL = fall chisel tillage, spring cultivation. NT/DB = no-till, spring deep-banded applications. NT/SB = no-till, spring surface-broadcast applications.

Figure 4

Example of model calibration results for NT/DB#7 treatment (2001 to 2004) showing C_{min} for grain sorghum and soybean corresponding to ±1% E_f variation.



Note: NT/DB = no-till, spring deep-banded applications.

These influences are not easily captured by baseline parameters tied to soil, crop, and management characteristics that are more consistent and transferable across climatic and soil morphologic regions.

Sediment Yield Validation. SWAT performed well in simulating the validation plots, though the performance statistics decreased from those on the calibration plots. On a daily basis, TILL#5 plot showed little improvement to calibrated C_{min}. Considering the baseline C_{min} value, TILL#5 showed the maximum difference in simulated results in terms of monthly statistic (both E_f and R^2) as well as average sediment yield (table 7). Of the three treatments modeled, NT/DB#2 gave the best (daily and monthly) simulation statistics. Similarly, for the best-fit calibrated C_{min}, NT/DB#2 gave the best model performance statistics compared to NT/SB#4 and TILL#5 treatments. Using the calibrated C_{min} value, NT/SB#4 gave similar results in terms of R^2, but E_f (or $E_{f(a)}$) was negative (-0.81 or -0.86) compared to E_f of 0.24 ($E_{f(a)}$ of 0.21) when baseline C_{min} value was used.

For the baseline C_{min}, model performance statistics on validation plots for the five-year period (table 7) were better than those obtained on calibration plots (table 5). In addition, model efficiency for four-year and five-year simulation periods was almost same (table 7). Both observations are likely due to a lesser influence of soil disturbance from sampler and weir installation on the measured sediment yields in validation plots in contrast to calibration plots. For example, the magnitude of measured sediment on validation plot TILL#5 (1.71 Mg ha^{-1} y^{-1} [0.76 tn ac^{-1} yr^{-1}]) was two-thirds of the measured sediment-yield on the corresponding calibration plot TILL#6 (2.51 Mg ha^{-1} y^{-1} [1.12 tn ac^{-1} yr^{-1}]). This result reinforces the need for great care in instrumenting field sites for runoff and erosion measurement, and for understanding errors inherent in measured data used to calibrate and validate model results so that measured values are not over-interpreted as "actual" values.

Summary and Conclusions

Surface runoff calibration required CN_{II} values greater than the recommended baseline values, although the values were well within the calibration range suggested for SWAT. No-till treatments required slightly greater CN values than the till treatment, and this difference was similar to that associated with increasing the soil hydrologic group by one classification. The associated K_{sat} values were also greater for no-till treatments than the till treatment. The baseline database AWC values were appropriate for all treatments.

The SWAT model under-predicted the average annual sediment yield compared to measured yield with baseline as well as calibrated C_{min} values for till and no-till treatments. Similarly, the model performed well in validation plots. For all four years, measured sediment yields, especially during May and June (months with greater rainfall), were generally greater than simulated sediment yields.

Baseline C_{min} values provided reasonable results for management systems that included some soil-surface disturbance but not for systems without soil disturbance. Baseline C_{min} values were within 1% of the best-fit calibrated values for treatments with soil disturbance, either by tillage or fertilizer deep-banding. But best-fit C_{min} values for field conditions without soil disturbance (no-till with surface-broadcast fertilizer) were 2.5 to 3 times greater than baseline values. These results are consistent with surface soil erosivity characteristics being dominated by mechanical tillage in disturbed soils compared to site-specific biological and climatic effects in no-till soils. Study results also caution that models calibrated for fields or watersheds predominated by tilled (or otherwise disturbed) soil conditions may not necessarily function equally well in similar fields or watersheds managed without tillage (or other soil-surface disturbance).

Table 7

Daily and monthly sediment-yield validation results.

Parameters: Period	Daily statistic		Monthly statistic		Avg. sediment yield ($Mg\ ha^{-1}\ y^{-1}$)	
Treatment	E_f	R^2	E_f	R^2	Measured	Predicted
Baseline: 2001 to 2004						
TILL#5	0.24	0.35	0.38	0.48	1.98	0.53
NT/DB#2	0.49	0.44	0.61	0.62	0.73	0.63
NT/SB#4	0.24	0.29	0.42	0.50	0.51	0.78
Best-fit: 2001 to 2004						
TILL#5	0.25	0.35	0.48	0.53	1.98	0.58
NT/DB#2	0.49	0.44	0.67	0.66	0.73	0.62
NT/SB#4	−0.81	0.28	0.33	0.41	0.51	1.41
Baseline: 2000 to 2004						
TILL#5	0.22	0.32	0.30	0.36	1.71	0.43
NT/DB#2	0.46	0.42	0.52	0.50	0.64	0.51
NT/SB#4	0.22	0.21	0.29	0.41	0.50	0.63
Best-fit: 2000 to 2004						
TILL#5	0.30	0.25	0.50	0.38	1.71	0.65
NT/DB#2	0.46	0.42	0.58	0.53	0.64	0.51
NT/SB#4	−0.69	0.21	0.36	0.49	0.50	1.15

Notes: TILL = fall chisel tillage, spring cultivation. NT/DB = no-till, spring deep-banded applications. NT/SB = no-till, spring surface-broadcast applications. E_f = median-based Nash-Sutcliffe efficiency. R^2 = coefficient of determination.

Acknowledgements

This material is based upon work supported by the USDA Cooperative State Research, Education, and Extension Service under Agreement No. 2001-51130-11377, the Kansas Sorghum Commission, the Kansas Corn Commission, the Kansas Wheat Commission, and the Kansas Fertilizer Research Fund. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the USDA. The authors would like to thank operators at the Experiment Station in Ottawa, Kansas, Mary Knapp for providing weather data, and Yasumaru Hirai for helping in computer program. Contribution No. 08-28-J from the Kansas Agricultural Experiment Station, Manhattan, Kansas.

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