HYDROLOGIC EVALUATION OF THE SOIL AND WATER ASSESSMENT TOOL FOR A LARGE TILE-DRAINED WATERSHED IN IOWA

C. H. Green, M. D. Tomer, M. Di Luzio, J. G. Arnold

ABSTRACT. *The presence of subsurface tile drainage systems can facilitate nutrient and pesticide transport, thereby contributing to environmental pollution. The Soil and Water Assessment Tool (SWAT) water quality model is designed to assess nonpoint and point source pollution and was recently modified for tile drainage. Over 25% of the nation's cropland required improved drainage. In this study, the model's ability to validate the tile drainage component is evaluated with nine years of hydrologic monitoring data collected from the South Fork watershed in Iowa, since about 80% of this watershed is tile drained. This watershed is a Conservation Effects Assessment Program benchmark watershed and typifies one of the more intensively managed agricultural areas in the Midwest. Comparison of measured and predicted values demonstrated that inclusion of the tile drainage system is imperative for obtaining a realistic watershed water balance. Two calibration/validation scenarios tested if the results differed in how the data set was divided. The optimum scenario results for the simulated monthly and daily flows had Nash-Sutcliffe efficiency (E_{NS}) values during the calibration/validation (1995-1998/1999-2004) periods of 0.9/0.7 and 0.5/0.4, respectively. The second scenario results for the simulated monthly and daily flows had E_{NS} values during the calibration/validation (1995-2000/2001-2004) periods of 0.8/0.5 and 0.7/0.2, respectively. The optimum scenario reflects the distribution of peak rainfall events represented in both the calibration and validation periods. The year 2000, being extremely dry, negatively impacted both the calibration and validation results. Each water budget component of the model gave reasonable output, which reveals that this model can be used for the assessment of tile drainage with its associated practices. Water yield results were significantly different for the simulations with and without the tile flow component (25.1% and 16.9%, expressed as a percent of precipitation). The results suggest that the SWAT2005 version modified for tile drainage is a promising tool to evaluate streamflow in tile-drained regions when the calibration period contains streamflows representing a wide range of rainfall events.*

Keywords. *AVSWAT-X, CEAP, Hydrologic modeling, SWAT, Tile drains, Watershed.*

In response to interest in environmental impacts of conservation practices implemented by private agricultural landowners, the Natural Resources Conservation Service (NRCS) and Agricultural Research Service (ARS) established the Conservation Effects Assessment Project (CEAP) in 2003. The impacts of conservation practices have been measured at the field level; however, CEAP is designed to measure conservation effects for larger areas, such as watersheds, due to their inclusion of more complex interactions (Mausbach and Dedrick, 2004). The South Fork watershed (SFW) in central Iowa is one of twelve ARS benchmark watersheds; this watershed typifies the more intensively managed agricultural areas of this region, with about 100 swine concentrated animal feeding operations (CAFOs) and 91% of the watershed area dedicated to agricultural production (85% crop, 6% pasture). Agricultural areas of the Midwest have the greatest inputs and processing of nitrogen in the country (Burkart and James, 1999). These watersheds are being monitored to help evaluate and improve performance of national assessment models, such as the Soil and Water Assessment Tool version 2005 (SWAT2005).

The SWAT2005 model is a continuation of modeling efforts by the USDA-ARS (Arnold et al., 1998; Arnold and Fohrer, 2005) and has become an effective means for evaluating nonpoint-source water resource problems (flow, sediment, nutrients) for a large variety of water quality applications nationally and internationally. The model is part of the U.S. Environmental Protection Agency (USEPA) Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) software package (Di Luzio et al., 2002) and is being used by many U.S. federal and state agencies. For example, SWAT is being used to validate flow, sediment, and nutrients in the Bosque River watershed in Texas for total maximum daily load (TMDL) analyses (Srinivasan et al., 1998; Santhi et al., 2001).

Subsurface drainage systems can be a significant source of pollutants (Cambardella et al., 1999; Northcott et al., 2001). Over 25% of U.S. cropland requires drainage enhancements (Pavelis, 1987), with artificial drainage need-

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ed on more than 50% of the agricultural land in some states (Skaggs et al., 1992). The Midwest contains several agricultural watersheds with impaired waters (Du et al., 2005), of which the South Fork watershed is one of many being monitored to identify its pollutant status.

Models that contain a tile drain system include the Agricultural Drainage and Pesticide Transport (ADAPT) model, DRAINMOD, and the Root Zone Water Quality Model (RZWQM), which used DRAINMOD tile flow equations (Singh and Kanwar, 1995). Chung et al. (2002) added a tile flow component to the EPIC (Williams et al., 1984) model using a drawdown time equation. ADAPT, DRAINMOD, and RZWQM use parallel tile systems due to a lack of information about the location and characteristics of the drainage system and are sensitive to the spacing of the drains (Walker et al., 1996; Davis et al., 2000; Northcott et al., 2001). Differences between these models lie in their simulation of flow and water quality.

Du et al. (2005) assessed the applicability of tile flow in SWAT2000 for nine years for Walnut Creek, a 5100 ha watershed in Iowa. SWAT2000 estimated monthly and daily flow with Nash-Sutcliffe efficiency (E_{NS}) values up to 0.72 and 0.47, respectively. These authors found a lack of statistical significance between measured and SWAT2000-simulated annual data for the Walnut Creek watershed. Singh et al. (2005) found that SWAT simulated observed streamflows (especially low flows) better than the Hydrologic Simulation Program-Fortran (HSPF) model due to its inclusion of subsurface tile drains for the Iroquois River watershed in Illinois and Indiana. Chaplot et al. (2004) simulate the Walnut Creek watershed in Iowa using a version of SWAT2000 with tile drains. The tiles were located at a depth of 2 m for county tiles to 1 m for field tiles. The error associated with the annual stream discharge was less than 10% of the observed loss. These authors found that SWAT was better at predicting high flow events and overestimated low and medium discharge peaks.

Grayson et al. (1992) provided guidelines for analyzing any model. In accordance with these authors' guidelines for testing the usefulness of a model, measured data were tested against SWAT2005 simulated data, and SWAT's hydrologic processes continue to be tested over a wide range of watersheds and conditions, with both positive and negative results reported (Arnold et al., 1999; Chu and Shirmohammadi, 2004; Rosenthal et al., 1995). The objective of this study was to evaluate the model's accuracy in simulating streamflow with the modified tile drain component included, its impact on the SFW hydrologic yield, and the importance of using calibration periods that represent the peak and low precipitation events. The errors associated with the input data were assessed in accordance with CEAP objectives toward quantifying conservation practices.

Model Background

SWAT is a continuous time model that operates on a daily time step. The model is physically based, uses readily available inputs, is computationally efficient for use in large watersheds, and is capable of simulating long-term yields for determining the impact of land management practices (Arnold and Allen, 1996). Components of SWAT include: hydrology, weather, sedimentation/erosion, soil temperature, plant growth, nutrients, pesticides, and agricultural management. The SWAT2000 model includes bacteria transport; urban routines; the Green-Ampt infiltration equation; an improved weather generator; the ability to read in solar radiation, relative humidity, wind speed, and potential ET; Muskingum channel routing; and modified dormancy calculations for tropical areas (Neitsch et al., 2002a, 2002b). The latest version of the model used for this simulation includes bacteria transport, simulated water table and draw down, a subhourly hydrologic routine, and a runoff curve number based on antecedent weather conditions.

SWAT contains several hydrologic components (surface runoff, ET, recharge, and stream flow) that have been developed and validated at smaller scales within the EPIC, GLEAMS, and SWRRB models. Interactions between surface flow and subsurface flow in SWAT are based on a linked surface-subsurface flow model developed by Arnold et al. (1993). Characteristics of this flow model include non-empirical recharge estimates, accounting of percolation, and applicability to basin-wide management assessments with a multi-component basin water budget. The surface runoff hydrologic component uses Manning's formula to determine the watershed time of concentration and considers both overland and channel flow. Lateral subsurface flow can occur in the soil profile from 0 to 2 m, and groundwater flow contribution to total streamflow is generated by simulating shallow aquifer storage (Arnold et al., 1993). Flow from the aquifer to the stream is lagged via a recession constant derived from daily streamflow records (Arnold and Allen, 1996).

The previous SWAT model flow versions have been validated in many river basins throughout the U.S. Current SWAT reach and reservoir routing routines are based on the ROTO (a continuous water and sediment routing model) approach (Arnold et al., 1995), which was developed to estimate flow and sediment yields in large basins using subarea inputs from SWRRB. Configuration of routing schemes in SWAT is based on the approach given by Arnold et al. (1994). Water can be transferred from any reach to another reach within the basin. The model simulates a basin by dividing it into subwatersheds that account for differences in soils and land use. The subbasins are further divided into hydrologic response units (HRUs). These HRUs are the product of overlaying soils and land use.

The SWAT model is continually being enhanced to optimize its accuracy in simulating environmental processes affected by best management practices (BMP). Subsurface tile drainage systems are widely installed within farm fields, making it critical to include them in the development of point and nonpoint source models. This version of SWAT includes a tile drain component (Neitsch, et al., 2004) that can be applied to agricultural watersheds in the Corn Belt and Great Lakes states. This component is important to a watershed's hydrologic balance because tile drains intercept percolating waters and route them, along with chemical pollutants, directly to surface waters (Baker et al., 1975; Logan et al., 1994; Arnold and Allen, 1996).

The SWAT model was set up using AVSWAT-X, an upgrade of AVSWAT (ArcView GIS – SWAT) (Di Luzio et al., 2004a), a software system linking ArcView 3.X Geographic Information System software and the model. AVSWAT is designed to define watershed hydrologic features; store, organize, and manipulate the related spatial and tabular data; and analyze management scenarios. AVSWAT-X provides an extendable environment including optional customized capabilities, such as the SSURGO Extension for AVSWAT (SEA) to allow USDA (1:24,000 scale) soil survey information to be included, an automatic calibration tool, and the Land Use / Land Cover class splitting tool.

METHODOLOGY

SWAT MODIFICATION FOR RESTRICTIVE LAYER

To accompany tile drainage systems, soil water routing was modified to predict water table depth by creating a restrictive soil layer at the bottom of the profile for a modified SWAT model (SWAT-M) (Du et al., 2005). In the SWAT2005 model, this restrictive layer (or maximum water table depth) was set by providing a value for a parameter called "depimp" (depth to impermeable layer, in mm). The soil profile above the restrictive layer was then allowed to fill to field capacity, from which the water was transported upward through the profile. The height of the water table was determined from the depth of the impermeable layer through the saturated portion of the profile. Seepage is accounted for at shallow and deeper restrictive layer depths. The lesser the depth of the impermeable layer, the more percolate can move through the lower portions of the soil profile; conversely, the presence of a deep restrictive layer means that less percolate is moved beyond this layer through the soil profile. Du et al. (2005) provides more detail and sample calculations.

Tile flow occurs when the water table height exceeds the height of the tile drains. The flow quantity is calculated with equation 1 (Arnold et al., 1999):

$$tile_{wtr} = (h_{wt} - h_{tile}) * \left(1 - \exp\left[\frac{-24}{t_{drain}}\right]\right) \quad \text{if } h_{wt} > h_{tile} \tag{1}$$

where $tile_{wtr}$ is the amount of water removed from the layer on a given day by tile drainage (mm), h_{wt} is the water table height above the impermeable layer (mm), h_{tile} is the tile height above the impermeable layer (mm), and t_{drain} is the time required to drain the soil to field capacity (h). As the soil profile becomes saturated, aeration stress becomes a concern for plant water uptake. Aeration stress is accounted for by including an estimation of the degree of stress (Williams et al., 1984) and is associated with the drawdown time (t_{drain}).

MODEL EVALUATION METHODS

The performance of SWAT was evaluated using statistical analyses to determine the quality and reliability of the predictions when compared to observed values. Summary statistics included the mean and standard deviation (SD), where the SD is used to assess data variability. The goodness-of-fit measures were the coefficient of determination (r^2) and the Nash-Sutcliffe efficiency (E_{NS}) value (Nash and Sutcliffe, 1970). The r^2 and E_{NS} values are explained in equations 2 and 3, respectively:

$$r^2 = \frac{\left(\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 \sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2} \tag{2}$$

$$E_{NS} = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n}\left(P_i - O_i\right)^2}{\sum\left(O_i - \overline{O}\right)^2} \tag{3}$$

where n is the number of observations during the simulated period, O_i and P_i are the observed and predicted values at each comparison point i, and $\overline{O}$ and $\overline{P}$ are the arithmetic means of the observed and predicted values. The E_{NS} value was used to compare predicted values to the mean of the average annual, monthly, and daily USGS gauged discharge for the watershed, where a value of 1 indicates a perfect fit. The E_{NS} value describes the amount of variance for the observed values over time that is accounted for by the SWAT model. The r^2 value was used to evaluate how accurately the model tracks the variation of the observed values. The difference between E_{NS} and r^2 is that E_{NS} can interpret the model performance in replicating individually observed values, while r^2 does not. For this study, the criteria of $E_{NS} > 0.4$ and $r^2 > 0.5$ were chosen to assess how well the model performed. Chung et al. (1999, 2002) used standards of $E_{NS} > 0.3$ and $r^2 > 0.5$ with EPIC simulations to determine if the model results were satisfactory.

In addition to testing the usefulness of the model, it is important that the model is calibrated using representative precipitation events that include high and low streamflows. Di Luzio and Arnold (2004) used representative storm events to successfully test the hourly streamflow component of SWAT. Wood and Rounds (1998) used only three years of data to simulate reduced P loads on chlorophyll-a and dissolved oxygen. For these authors, the short time period was acceptable because of the range of dry and wet events that occurred. Although findings can be reported for short time periods, longer time spans are desired because they are expected to encompass the range of environmental variability that exists. A longer period of record implies that more of the variability will be captured; however, it is the highs and lows of the rainfall events that must be included in the calibration periods in order to obtain adequate validation results.

INPUT DATA

AVSWAT-X

In AVSWAT-X, the SEA extension (Di Luzio et al., 2004b), has been applied to process and manage SSURGO (Soil Survey Geographic) data sets of varying format and to create the needed digital soil maps. Required soil physical and hydraulic input parameters are generated from pedotransfer functions and are seamlessly included in the modeling framework. Soil survey data sets processed for the South Fork watershed included Hardin, Hamilton, Franklin, and Wright counties (National Cooperative Soil Survey, 1985, 1986).

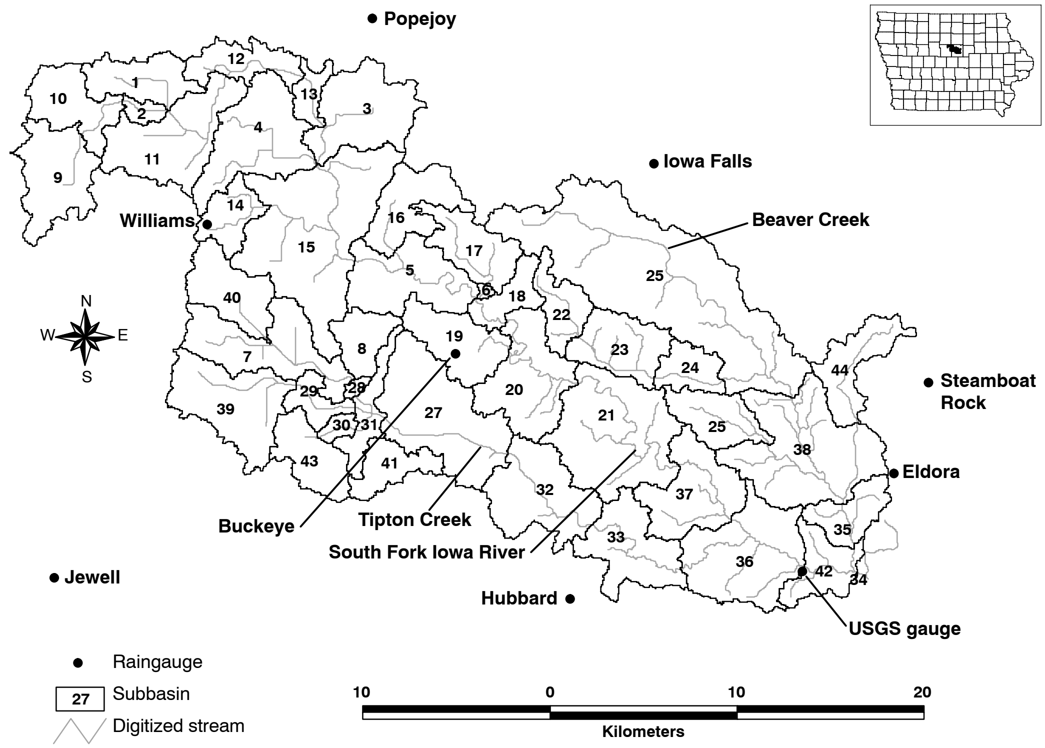

Figure 1. Distribution of rain and temperature gauges, USGS gauge (site 05451210), and subbasins in the SFW.

Watershed Description

The South Fork of the Iowa River covers 775 km^2, including tributaries of Tipton and Beaver Creeks (fig. 1). It is representative of the Des Moines Lobe, the dominant landform region of north-central Iowa. The terrain is young (about 10^4 years since the last glacial retreat), and therefore natural stream incision and development of alluvial valleys has only occurred in the lower parts of the watershed.

The soils are highly productive, with the Clarion-Nicollet-Webster soil association being dominant, forming a sequence (respectively) of well-drained Typic Hapludolls, somewhat poorly drained Aquic Hapludolls, and poorly drained Typic Haplaquolls (National Cooperative Soil Survey, 1986; Soil Survey Staff, 2003).

Topographic Data

The basin was divided into 44 subbasins using the automated delineation tool in AVSWAT-X (Di Luzio et al., 2004a) based on the 30 m grid digital elevation model (DEM) for the watershed (USGS, 2001).

Hydrologic Discharge Data

The USGS established a gauging station (site 05451210) near New Providence in 1995, as part of the Eastern Iowa Basins NAWQA program (Becher et al., 2001) (http://nwis.waterdata.usgs.gov/ia/nwis/dischar ge). This gauge has a watershed area of 58,050 ha. The USGS has made periodic measurements of cross-sectional depths and flow velocities under varying flow conditions, which were used to establish and maintain rating curves defining a relationship between stage height and discharge (http://waterdata.usgs.gov/nwis). These cross-sectional measurements were made during and/or after major events to identify changes in the rating curves that could be affected by changes in the stream bed.

Precipitation and Temperature Data

Daily precipitation totals were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) (www.ncdc.noaa.gov) from eight raingauge stations within and adjacent to the watershed in Iowa (fig. 1). These stations are located in Buckeye, Hubbard, Jewell, Steamboat Rock, Williams, Eldora, Iowa Falls, and Popejoy. Daily maximum and minimum temperatures were also obtained from Eldora, Iowa Falls, and Popejoy from 1998-2004. Solar radiation, wind speed, and humidity values were simulated by the model. The Penman-Monteith potential evapotranspiration option was used for all model simulations.

Land Use Data

Cropping rotations were determined using annual classified satellite data made available by the USDA National Agricultural Statistics Service (NASS) (www.nass.usda.gov/research/Cropland/SARS1a.htm). The classification is carried out by NASS to estimate crop acreages planted in several states each year. About 85% of the watershed is under corn and soybean or continuous corn rotations. Two years of NASS crop-cover data (2002-2003) were overlaid to identify dominant crop rotations occurring on agricultural lands in the watershed (table 1). Rotations were defined based on the sequence of crops observed in each field across the two years of record that were available. Agricultural lands were identified using digitized agricultural field boundaries within the watershed obtained from local Farm Service Agency (USDA-FSA) offices. Non-agricultural land was dominantly pasture and deciduous forest, which were typically located in riparian valleys. Roadways, farmsteads, and towns were classified as urban land. These classes were primarily based on the NASS Crop Data Layer 2002, with spot-checking of

Table 1. Land use classification for the SFW.

Land Use	Percent of Watershed
Soybean/corn, manure	23.6
Soybean/corn, no manure	18.1
Corn/soybean, manure	17.7
Corn/soybean, no manure	14.0
Continuous corn, manure	8.3
Urban	7.8
Pasture	4.1
Continuous corn, no manure	4.1
Forest	1.9
Wetland	0.24
Water	0.23

non-agricultural areas using 2002 aerial photography and land use maps available from the Iowa Department of Natural Resources. The combination of land use and soil type resulted in 727 HRUs.

Tile Drains

Artificial drainage was installed to allow agricultural production, beginning more than 100 years ago. Approximately 35% of the watershed's soils are classified as well drained, but most are present on steeper slopes that are not farmed or are surrounded by poorly drained soils. Subsurface tile drainage and constructed ditches have significantly decreased surface water storage and hastened the routing of water from the watershed. The tile mains were digitized from county records. The drainage districts tend to coincide with the watershed subbasins where poorly drained soils are common. Approximately 80% of the agricultural watershed is tile drained. This estimated value includes all of the soils that are not well drained and a few that are well drained but are surrounded by poorly drained soil. Although the depth of the impermeable layer can be altered, a 2.5 m depth to impermeable layer (depimp) and a standard tile drain depth of 1.0 m were used for the entire basin in this study to account for tile flow. The tile drains were used to reduce the water content to field capacity within 24 h; therefore, the time to drain (t_{drain}) soil to field capacity was set at 24 h. The drain tile lag time (g_{drain}) and depth to drainage (d_{drain}) were set to 96 h and 1 m, respectively. The best available information for the values of t_{drain}, g_{drain}, and d_{drain} was obtained from a representative of the South Fork Watershed Alliance (M. Tomer, personal communication, January 2005).

Calibration Methods

The SWAT hydrologic model requires soil parameter input for bulk density, available water capacity, texture, organic matter, saturated conductivity, land use (crop and rotation), management (tillage, irrigation, nutrient and pesticide applications), weather (daily precipitation, temperature, solar radiation, wind speed), channels (slope, length, bankfull width and depth), and the shallow aquifer (specific yield, recession constant, and revap coefficient) (Arnold, 1992).

Table 2 lists the ranges of adjusted parameters suggested by the SWAT model and the calibrated values of the adjusted parameters used for discharge calibration of the SWAT2005 model for the SFW. All other parameters were kept at the SWAT default values.

Two model calibration and validation scenarios of the USGS gauge station discharge data were used to discern if a difference exists in the results using different calibration and validation periods from the same data set. The calibration and validation timeframes selected were from 1995-2000 and 2001-2004, respectively, and from 1995-1998 and 1999-2004, respectively. Both of the calibration periods used the same calibrated parameter values, which include the simulations that include or do not include the tile drainage component. The first calibration and validation scenario was selected because it included peak and low-flow streamflow events. The second scenario split the nine-year data set, giving the first five complete years to calibration and the last four years to validation. The comparison of SWAT2005 water yield simulations with and without tile flow used the same calibration parameters that have been used throughout this study.

Results and Discussion

Water Balance

In accordance with Grayson et al. (1992), SWAT2005's runoff simulation data were tested against measured runoff data. The annually averaged simulated stream discharge (190.5 mm) is 94% of the measured average value (201.7 mm) (table 3).

Seasonal trends can be depicted by plotting measured and predicted monthly streamflow values against time (fig. 2). The largest measured and simulated monthly discharge event (June 1998) had values of 148.4 mm and 168.5 mm, respectively, indicating a difference of only 12%. The second largest event (May 1999) had less than a 4% flow difference. For the 19 measured events with greater than 40 mm runoff, SWAT2005 overestimated discharge five times and underestimated discharge 14 times. This indicates that no clear trend existed for over- or underestimation. The error associated with the measured monthly discharge is estimated to average between 5% and 10%, with the peaks of the largest events

Table 2. Calibrated values of adjusted parameters for discharge calibration of the SWAT2005 model for the SFW.

Parameter	Description	Range	Calibrated Value
ESCO	Soil evaporation compensation factor	0.01 to 1.0	0.95
FFCB	Initial soil water storage expressed as a fraction of field capacity water content	0 to 1.0	0.8
Surlag	Surface runoff lag coefficient (days)	0 to 4	0.2
ICN	Based on the SCS runoff curve number procedure and a soil moisture accounting technique	0 or 1	1
CNcoeff[a]	Curve number coefficient	0.5 to 2.0	0.2
CN2	Initial SCS runoff curve number to moisture condition II	30 to 100	66-78
PHU	Potential heat unit (used for corn and soybeans)	1000 to 2000	1800

[a] Williams and LaSeuer, 1976.

Table 3. Comparison of measured and simulated annual stream discharge for the SFW (1995-2004).

Year	Precipitation (mm)	Measured Streamflow (mm)	Simulated Streamflow (mm)
1996	814.5	150.8	109.8
1997	710.7	249.1	216.9
1998	992.3	357.6	349.2
1999	799.1	279.4	255.6
2000	747.0	56.9	135.4
2001	827.0	231.2	236.3
2002	793.0	186.5	139.3
2003	696.0	143.1	143.6
2004	651.3	160.8	128.6
Total	7086.3	1819.4	1716.6
Average	781.2	201.7	190.5

having a slightly higher error (15%), having followed USGS stream discharge protocol. This study's simulated error is approximately 6%. This simulated error is within the same order of magnitude as that found by Arnold and Allen (1996) and Gerhart (1984), who each reported a 5% error.

Tile Flow

The SFW data were simulated with and without the inclusion of the tile drainage system. Table 4 includes the hydrologic budget for the simulation without the tile flow component from 1995 to 2004. The presence of tile drains significantly impacts the SFW water yield. The water yield components (groundwater flow, tile flow, lateral flow, and surface runoff) listed in table 4 clearly indicate that simulating the tile drainage system is critical to accurately represent the hydrologic balance of the watershed. The mean annual water yield with and without tile flow, expressed as a percentage of precipitation, are significantly (α = 0.05) different (25.1% and 16.9%, respectively), indicating the importance of including tile flow in water yield calculations for affected watersheds. Without the tile drains present, the soil remains wetter; therefore, more water is available for surface runoff. This reapportionment of water could impact management decisions regarding the reduction of pollutants, such as excess nutrients and pesticides in the environment.

Calibration and Validation Scenarios

Long-term averages are known to have less simulated error than short-term values (Winter, 1981). However, the division of hydrologic data may impact the calibration and validation results. Two calibration/validation scenarios were

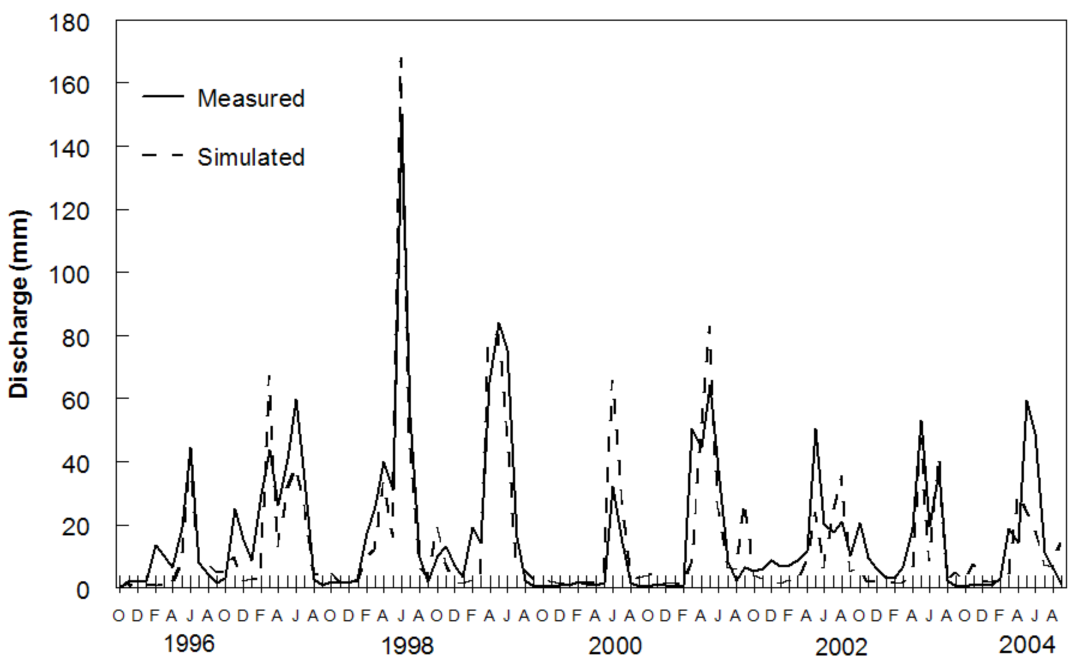

Figure 2. Observed and simulated monthly discharge for the SFW at the USGS gauge site from October 1995 through September 2004.

Table 4. Predicted hydrologic budget for the SFW from 1995 through 2004, including two calibration/validation scenarios and SWAT2005 simulations with and without the tile flow component.

Hydrologic Component	With Tile Flow (mm) 1995-2004	Without Tile Flow (mm) 1995-2004	Calibration (mm) 1995-1998	Validation (mm) 1999-2004	Calibration (mm) 1995-2000	Validation (mm) 2001-2004
Precipitation	768.0	768.0	786.3	757.4	770.0	748.4
Surface runoff	38.1	117.4	39.0	37.4	38.0	37.5
Lateral flow	7.1	0.40	6.3	6.6	6.7	6.0
Tile flow	136.4	0.0	157.5	118.0	151.2	110.9
Groundwater flow	10.8	11.7	10.0	10.3	10.3	9.4
Evapotranspiration	569.2	638.6	559.5	577.2	550.2	585.5
Potential ET	1190.6	1191.6	1113.7	1233.2	1150.4	1261.4

Table 5. Scenario 1: Annual, monthly, and daily streamflow calibration (1995-1998) and validation (1999-2004) statistics of the measured and simulated data for the SFW at the USGS gauge (site 05451210).

	Annual (mm)		Monthly (mm)		Daily (mm)	
	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
Calibration (1995-1998)						
Mean	250	210	20.6	16.7	0.7	0.6
SD	100	120	27.8	28.1	1.3	1.3
r^2	1.0		0.9		0.7	
E_{NS}	0.7		0.9		0.7	
Validation (1999-2004)						
Mean	180	200	13.9	13.4	0.5	0.5
SD	80	70	17.3	19.0	0.9	1.0
r^2	0.7		0.6		0.5	
E_{NS}	0.6		0.5		0.4	

used to determine if results differed based on how the nine-year data set was divided. The first scenario ensured that the calibration and validation periods contained streamflows that represented a wide range of flow events. The second scenario split the data set almost in half, with the first five complete years used for calibration and the remaining years for validation. Table 4 lists the predicted hydrologic budget for each of the calibration/validation scenarios. A lack of significance was found for the hydrologic components in the comparison of the calibration periods and also applies in the comparison of the validation periods.

In the first scenario (table 5), the data were divided so that the calibration and validation periods each contained one of the two largest and lowest discharge events. The annual/monthly/daily calibration and validation r^2 values were 1.0/0.9/0.7 and 0.7/0.6/0.5, and the E_{NS} values became 0.7/0.9/0.7 and 0.6/0.5/0.4, respectively. The calibration period contained one dry year and one large discharge event. The inclusion of a wide range of streamflow conditions resulted in a high E_{NS} value because overall SWAT2005 seems to simulate wet years better than dry years and the validation had more dry years than wet years.

The statistical results are better with the first scenario than with the second scenario (table 6). The second calibration scenario included the drought year (2000), which resulted in a streamflow overprediction by 238% (56.9 mm measured, 135.4 mm predicted) (table 3); any attempt to reduce this overestimation resulted in the underestimation of discharge for the other calibration years. The validation period of January 2001 through September 2004 resulted in the simulated average discharge (161.9 mm) accounting for 90% of the measured average discharge (180.4 mm).

Table 6. Scenario 2: Annual, monthly, and daily streamflow calibration (1995-2000) and validation (2001-2004) statistics of the measured and simulated data for the SFW at the USGS gauge (site 05451210).

	Annual (mm)		Monthly (mm)		Daily (mm)	
	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
Calibration (1995-2000)						
Mean	190	170	17.6	17.0	0.6	0.6
SD	140	120	26.1	29.4	1.2	1.3
r^2	0.9		0.9		0.7	
E_{NS}	0.9		0.8		0.7	
Validation (2001-2004)						
Mean	180	150	16.4	14.4	0.5	0.5
SD	40	50	18.2	18.8	0.9	0.9
r^2	0.7		0.6		0.3	
E_{NS}	−0.8		0.5		0.2	

The importance of including representative discharge events in both calibration and validation periods is evidenced by the change in E_{NS} and r^2 statistics for both scenarios. In the second scenario, the validation period (2001-2004) did not contain discharge events as large as the ones in 1998 and 1999. The placement of the driest year's discharge data (2000) impacts both the calibration and validation results, with the underprediction of discharge in the validation since the validation does not contain either of the two largest discharge events and contains multiple dry years. Additional effort to calibrate for the low measured discharge in 2000 resulted in a pervasive underprediction for the other calibrated years.

The r^2 values reflect SWAT's overall ability to predict the validation period's discharge well. However, what occurs is the averaging effect of the under- and overestimations balancing each other to give the impression that SWAT predicted each year well. In reality, SWAT was unable to predict the low flow in the drought year of 2000 and, when incorporated into the calibration period, this results in streamflow underprediction for the following years. SWAT was able to predict the trend of discharge events even when the amount was underpredicted (fig. 2). That is why the E_{NS} values are given more weight as a reflection of the model's streamflow prediction capability.

The E_{NS} value disparity between the two calibration/validation scenarios reveals that distributing the peak rainfall events resulted in a better match of simulated and measured data. The inclusion of a wide range of flow conditions allows for better parameter initialization and ultimately better streamflow validation results. The ability of SWAT to predict discharge better during wetter years results in the improvement of the goodness-of-fit statistics due to the inclusion of large values. E_{NS} proves to be a good quantitative measure of the usefulness of carefully selecting calibration timing.

It is important for simulation models to have close agreement with the measured means and standard deviations because the agreement indicates that the frequency distributions are similar. The measured and predicted means and standard deviations compare well for almost the entire range of flows (tables 5 and 6). The summary statistics and goodness-of-fit values are presented in table 4, which shows no significant difference ($\alpha \geq 0.05$) between measured and simulated means, calculated on annual, monthly, and daily bases.

With the exception of 2000 and 2004, the average relative percent difference between measured and simulated monthly values was 14.6%, ranging from 1.1% (1999) to 27.6% (1996). The yearly r^2 values are acceptable, while the validation E_{NS} values raise concern regarding SWAT2005's ability to accurately simulate discharge through 2003 and September 2004. The E_{NS} values for the annual/monthly/daily calibration and validation periods were 0.9/0.8/0.7 and −0.8/0.5/0.2, respectively, indicating that SWAT2005 varied in its ability to simulate streamflow. An alternative to this conclusion is that SWAT would satisfactorily predict discharge if a representative calibration period was used. For example, the inclusion of the drought year in the calibration period led to the underprediction of streamflow during the validation period.

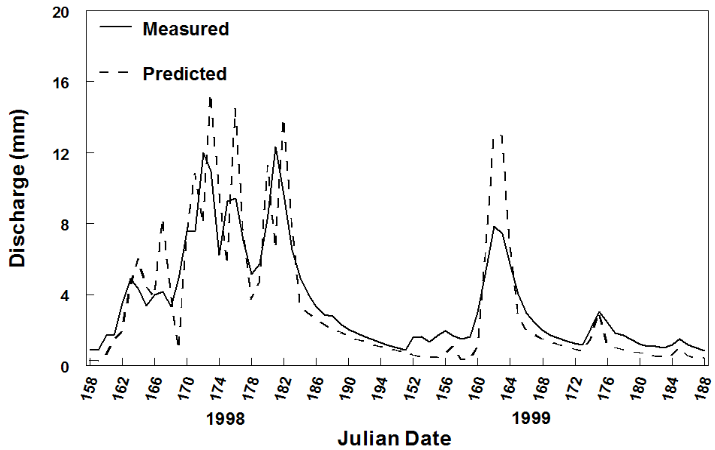

Figure 3. Measured and predicted daily streamflow for June 1998 and June and July 1999 in the SFW at the USGS gauge site.

Du et al. (2005) found a lack of statistical significance between measured and SWAT-M simulated annual data for the Walnut Creek watershed. These authors also found that SWAT-M's simulated discharge values were closer to measured values than were those of SWAT2000. In this study, a lack of significance was found between the annual measured and simulated data using SWAT2005, which has the updated tile drainage component.

Although SWAT operates on a daily time step, the model was originally intended to accurately predict monthly or annual hydrologic parameters. There can be considerable uncertainty within a day, as one value represents the range of rainfall intensities and temperature variation that can occur within a day. With these inherent uncertainties, the daily peak and hydrograph recession characteristics are critical model predictions of watershed streamflow. Figure 3 shows the daily measured and predicted flows from the two largest runoff events during the monitoring period considered. The graph demonstrates the effect of the drought year (2000) for the calibration. In the attempt to minimize the overestimation of the dry year, most other peaks are underestimated. The model closely simulates the daily hydrograph recessions.

Tables 5 and 6 and figures 2 and 3 both show the positive and negative aspects of the model results and the importance of including a wide range of data in model calibration in order to adequately validate data.

Although inputs to the model are physically based, the amount of uncertainty is unknown due to several sources of error potentially introduced by model and field data. Model error can result if physical processes within the basin are not well represented by model algorithms and if parameters included in the simulation are not realistic (Arnold and Allen, 1996). Discharge data must be representative, and error can readily be introduced if the data do not represent the variability that occurs in the basin. Monitoring network design, gauge station characteristics, and accurate rating curve determinations are critical in this regard. In addition, the precipitation network must represent the variation of precipitation that occurs in the basin. Each of these components can vary considerably in its contribution to uncertainty. While the model's processes need to be as accurate as possible, errors in the measured data will continue to be reflected in the simulation's over- or underpredictions. Future work will focus on nitrates, soluble phosphorus, manure management, crop rotations, and quantifying uncertainty.

Conclusion

The SWAT2005 model with a modified tile drain component was evaluated for nine years of measured flow in the South Fork watershed (SFW) in central Iowa because 80% of the watershed is tile drained. A downstream USGS gauging station was used as the outlet site of the SFW and was selected to investigate the overall hydrologic simulation ability of SWAT2005. In this article, tile drainage was investigated for its impact on water balance; without its inclusion, the surface flow would be overestimated, resulting in a non-representative water balance with erroneous management implications. Two calibration/validation scenarios tested if the results differed in how the data set was divided. The optimum scenario results for the simulated monthly and daily flows had Nash-Sutcliffe efficiency (E_{NS}) values during the calibration/validation (1995-1998/1999-2004) periods of 0.9/0.7 and 0.5/0.4, respectively. The second scenario results for the simulated monthly and daily flows had E_{NS} values during the calibration/validation (1995-2000/2001-2004) periods of 0.8/0.5 and 0.7/0.2, respectively. The optimum scenario reflects the distribution of peak rainfall events represented in both the calibration and validation periods.

The calibration/validation scenarios indicate the importance of including a wide range of data to effectively calibrate the model. From this study, SWAT2005 appears to simulate wet years better than dry years. Water yield results were significantly different for the simulations with and without the tile flow component (25.1% and 16.9%, expressed as a percent of precipitation). Each water budget component of the model gave reasonable output, which reveals that this model can be used for the assessment of tile drainage with its associated practices. SWAT appraisals of land use management practices can be more accurate when the hydrologic balance has been calibrated effectively by using a wide range of discharge events. SWAT2005 is able to accurately simulate subsurface flow and stream discharge when applied to a watershed-scale basin.

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