SOIL AND WATER ASSESSMENT TOOL HYDROLOGIC AND WATER QUALITY EVALUATION OF POULTRY LITTER APPLICATION TO SMALL-SCALE SUBWATERSHEDS IN TEXAS

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ABSTRACT. *The application of poultry litter to agricultural land has become a topic of interest for policy makers due to public concern about its effects on water quality. The Soil and Water Assessment Tool (SWAT) version 2005 is designed to assess nonpoint and point sources of pollution. In this study, six subwatersheds in Texas (HUC-8; 12070101) are used to evaluate the model's ability to simulate water quality at a small scale. Each of these subwatersheds randomly received poultry litter rates of 0.0 to 13.4 Mg* ha^{-1}. *Monthly and daily data from 2002 were used for calibration purposes, while 2000, 2001, 2003, and 2004 were used for validation. The SCS runoff curve number for moisture condition II (CN2) and the soil evaporation compensation factor (ESCO) parameters were found to be more sensitive than the surface runoff lag time (SURLAG) and initial soil water content expressed as a fraction of field capacity (FFCB). The monthly and daily runoff model simulations for the six subwatersheds resulted in calibration Nash-Sutcliffe efficiency* (N_{SE}) *values of 0.59 and 0.53 and validation* N_{SE} *values 0.82 and 0.80, respectively. The monthly and daily* R^2 *runoff values for the six subwatersheds resulted in calibration values of at least 0.60 and 0.53 and validation* R^2 *values of 0.86 and 0.81, respectively. The observed trends included SWAT's overestimation of runoff in the dry periods and underestimation in the wet periods. The monthly* N_{SE} *and* R^2 *values for sediment and nutrient losses were generally above 0.4 and 0.5, respectively. Paired t-tests for the monthly manually adjusted parameter simulation of sediment, organic N and P,* NO_3*-N, and soluble P for the 2000-2004 period losses showed that their respective SWAT means were not significantly different from the measured values* ($\alpha = 0.05$)*, except for* NO_3*-N losses for the Y10 subwatershed (p-value 0.042). The control subwatershed's measured and simulated water quality results were significantly different* ($\alpha = 0.05$) *from the treated subwatersheds, most likely due to the amount of inorganic N present. Almost all of the subwatersheds that had poultry litter applied resulted in higher sediment, organic N, organic P, and soluble P losses than the control subwatershed upon averaging the monthly validation values. High* NO_3*-N losses may have been a function of poultry litter and commercial fertilizers being applied before a large rainfall event occurred. The subwatersheds that received smaller amounts of commercial fertilizer and/or poultry litter lost more sediment, organic N, and organic P than the subwatersheds that received the higher litter and/or fertilizer treatments. Overall, the SWAT simulated the hydrology and the water quality constituents at the subwatershed scale more adequately when all of the data were used to simulate the model, as evidenced by statistical measures.*

Keywords. *Hydrologic modeling, Nutrients, Poultry litter, Sediment, Subwatershed, SWAT.*

Land application of manure can cause environmental concerns when not properly managed.Public concern regarding the water quality impact of animal wastes has driven policy regulators to scrutinize its application on agricultural land. Duda and Finan (1983) stated that watersheds with intensive animal manure application have the greatest potential to pollute adjacent surface waters. Agricultural practices are commonly regarded as being sources of water and soil contamination (Sharpley, 1995; Abbozzo et al., 1996; Burkholder et al., 1997). The shift in animal production practices toward larger confined animal feeding operations (CAFOs) has resulted in attention directed toward agricultural waste disposal techniques that minimize environmental impairment (Abbozzo et al., 1996; Gburek and Sharpley, 1998; Ribaudo et al., 2003). The poultry industry continues to be challenged with finding an environmentally safe disposal method for large amounts of poultry litter. Land application of manure provides nutrients and organic matter that enhance crop growth and can improve soil physical properties; however, when applied in excess, runoff from manured lands can result in the impairment of nearby water resources. Phosphorus (P) is a recognized contaminant that can cause adverse conditions in surface waters (Sharpley et al., 1994; Grobbelaar and House, 1995; Sims et al., 1998; Daniel et al., 1998). In addition, the incorporation of manure alters soil properties, which can lead to changes in runoff and soil erosion.

Environmental regulation has expedited the necessity of agricultural producers to design and implement more environmentally suitable practices. There is a need to identify

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critical nutrients and their loss/transport potentials. A phosphorus index exists that aids in the assessment of site vulnerability (Lemunyon and Gilbert, 1993), and computer models can simulate multiple watershed management scenarios that can help environmental policy managers make decisions that could ultimately reduce P loss from agricultural lands. Models are an inexpensive tool that can identify optimum watershed management practice scenarios for pollutant transport reduction.

Limited data exist at the small watershed scale for poultry litter application monitoring due to naturally inherent complexities such as rainfall variation, the requirement for a large amount of land, and the equipment and personnel required to collect data and monitor the sampling sites (Harmel et al., 2003; Gilley and Risse, 2000). Wang et al. (2006) used Environmental Policy Integrated Climate version 3060 (EPIC3060) to assess crop yield, runoff, sediment, and nutrient losses from small watersheds with poultry litter applied. The Nash-Sutcliffe efficiency (N_{SE}) values for annual, monthly and daily simulations were above 0.5. EPIC-simulated monthly runoff, sediment, and nutrient losses were not significantly ($\alpha = 0.05$) different from the measured values, except for soluble P losses in one subwatershed.

The ability of water quality models to accurately estimate environmental impacts from manure application needs to be determined. Grayson et al. (1992) provided guidelines for analyzing models, which included testing measured data against simulated data and testing a model's hydrologic processes 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). Small-scale watershed studies have been conducted by Fohrer et al. (2001) and Srinivasan et al. (2005) at 26 ha and 39.5 ha, respectively. Fohrer et al. (2001) successfully analyzed the Soil and Water Assessment Tool (SWAT; Arnold et al., 1998; Arnold and Fohrer, 2005) for sensitivity to crop parameters and land use change. Srinivasan et al. (2005) found that SWAT was able to predict time series streamflow better than the Soil Moisture Distribution and Routing (SMDR) model. However, seasonal variations impacted the watershed behavior, which led to runoff underprediction during the winter and spring and overprediction at the end of summer and fall. These studies are indicated as being small scale due to the relative size of watersheds that have been simulated with SWAT. This study evaluates the ability of SWAT (Arnold et al., 1998; Arnold and Fohrer, 2005) to simulate stream discharge, sediment, organic nitrogen (N) and P, soluble P, and nitrate-N (NO_3-N) loss after poultry litter application to small-scale agricultural land at a research site in central Texas. The purpose of applying the SWAT model to these watersheds was to test if the hydrologic response unit (HRU) output components (soil leaching, evapotranspiration, sediment, and nutrients) are reasonable at this smaller scale.

MODEL BACKGROUND

The SWAT model is a continuation of modeling efforts by the USDA Agricultural Research Service (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, and 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 subwatershed in Texas for Total Maximum Daily Load (TMDL) analyses (Srinivasan et al., 1998; Santhi et al., 2001), and it is one of the models selected by the Conservation Effects Assessment Project (CEAP), which was established in 2003 by the USDA-ARS and the USDA Natural Resources Conservation Service (USDA-NRCS) to measure environmental impacts of conservation efforts at the national level and benchmark subwatershed scale (Mausbach and Dedrick, 2004).

SWAT is a continuous time watershed 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. Detailed descriptions of SWAT model components can be found in Neitsch et al. (2002a, 2002b).

SWAT contains several hydrologic components (surface runoff, ET, recharge, and stream flow) that have been developed and validated at smaller scales within the EPIC, the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS), and the Simulator for Water Resources in Rural Basins (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 nonempirical recharge estimates, accounting of percolation, and applicability to basin-wide management assessments with a multi-component basin water budget. Surface runoff volume and infiltration are computed with the curve number equations or the Green-Ampt equation. The peak rate component uses the Manning formula to determine the (sub) subwatershed 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 schemes 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 HRUs. These HRUs are the product of overlaying soils and land use.

SWAT is a complex model with many parameters that can complicate manual model calibration. A parameter sensitivity analysis method is embedded in SWAT to determine the relative ranking of those parameters that most affect the output variance due to input variability (van Griensven et al., 2002). The SWAT model, version 2005 (SWAT2005), also has an autocalibration procedure embedded that is used to obtain an optimal fit of process parameters. This procedure incorporates the shuffled complex evolution method, which uses a global optimization standard for calibration in which multiple output parameters can be integrated concurrently (van Griensven et al., 2002). A statistical method uses the fit of the observed series to its related simulated series and translates the normalized values of the objective functions (van Griensven and Bauwens, 2003) per variable. These objective functions are then aggregated to a single global criterion determined by optimal fit, which considers all of the participating variables rather than by means of a weighted sum. van Griensven and Bauwens (2003) describe the details of the optimal fit and the weighting dilemma for global optimization measures. Green and van Griensven (2007) describe the use of the parameter sensitivity analysis and autocalibration tools with the data set from this study site.

INPUT DATA

Data used in this study were obtained from an experimental research site located at the USDA-ARS Grassland, Soil, and Water Research Laboratory near Riesel, Texas (31.48° N, 96.89° W) (Harmel et al., 2004) in the Blackland Prairie EPA Level III ecoregion (Griffin et al., 2004). The subwatersheds are denoted Y6, Y8, Y10, Y13, W12, and W13 (fig. 1; HUC-8; 12070101). These subwatersheds are terraced, corn and wheat rotations are planted on the contour, and each has an established grassed waterway. Each subwatershed was simulated as one subbasin and one HRU because of the homogeneous land use and dominant soil combination. The areas and upland slopes range from 4.0 to 8.4 ha and 1.1% to 3.2%, respectively (table 1). Houston Black is the dominant soil series (fine, smectitic, thermic Udic Haplusterts); its physical and chemical properties are listed in table 2. The soil layer properties, including depth, bulk density, texture fractionation, soil pH, and percent organic C, saturated conductivity, and available water capacity, were obtained from the USDA-NRCS Soil Survey Geographic Database (SSURGO). The clays and silty clays present in the Houston Black soil have a shrink-swell potential of 1.3 to 10.2 cm, and cracks can occur to a depth of 30.5 cm or more (USDA-NRCS, 2005). These cracks exist throughout each of the six subwatersheds.

Table 1. Site features of the six subwatersheds near Riesel, Texas.

	Subwatershed					
Feature	Y6	Y8	Y10	Y13	W12	W13
Upland slope (%)	3.2	2.2	1.9	2.3	2.0	1.1
Area (ha)	6.6	8.4	7.5	4.6	4.0	4.6
Channel slope (%)	2.1	2.2	1.4	1.5	1.3	0.8
Channel length km)	0.44	0.46	0.52	0.35	0.32	0.4

Table 2. Houston Black soil series properties.

	Soil Characteristic						
Soil Layer	Depth (m)	Bulk Density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	Soil pH	Organic C (%)
1	0.01	1.25	7.3	35.7	57	8.0	1.50
2	0.18	1.25	7.3	35.7	57	8.0	1.50
3	0.48	1.20	5.4	39.3	55.3	8.3	1.28
4	0.71	1.25	4.9	37.1	58.0	8.2	1.09
5	0.91	1.30	3.8	36.8	59.4	8.0	0.84
6	1.12	1.26	6.0	35.1	58.9	8.0	0.84
7	1.35	1.30	6.4	38.2	55.4	8.1	0.47
8	1.51	1.36	5.7	40.2	54.1	8.3	0.38
9	2.00	1.32	6.6	41.9	51.5	8.2	0.28

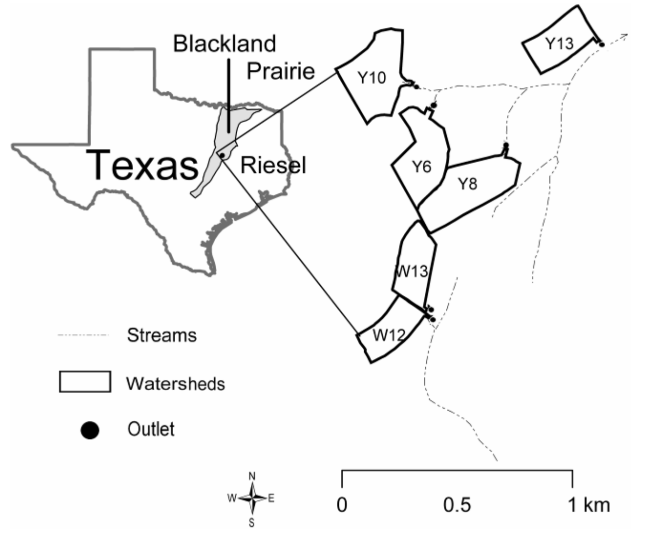

Figure 1. Locations of the six cultivated subwatersheds near Riesel, Texas.

PRECIPITATION AND TEMPERATURE DATA

Daily precipitation totals were obtained from onsite gauges present at each of the six subwatersheds for the five-year (2000-2004) simulation period. The additional climatic inputs of solar radiation, average relative humidity, and average wind velocity were generated in SWAT using historical monthly weather statistics. The mean and standard deviation for the annual precipitation from 2000 to 2004 ranged from 1055 to 1062 mm and 226 to 260 mm, respectively, regarding all six subwatersheds. These ranges reflect the variability inherent in the rainfall that occurs at this site, where there is only a 2 km distance among the subwatersheds. Average rainfall for this area is about 890 mm per year. The Hargreaves potential evapotranspiration method (Hargreaves and Samani, 1985) was used for all model simulations due to its robustness and because it does not require data for relative humidity, wind speed, and solar radiation.

FERTILIZER APPLICATION

The year 2000 is considered the control year in which initial conditions were established; fertilizer was not applied during this year. The initial soil N and P levels ranged from 0.11% to 0.13% and 0.05% to 0.07%, respectively. The poultry litter nutrient analysis is presented in table 3. The range of poultry litter application rates was selected based on those used by agricultural producers. The application rates were determined a priori and were randomly assigned to the subwatersheds (Harmel et al., 2004). Table 4 includes the poultry litter and additional N and P commercial fertilizer inputs.

The control subwatershed, Y6, did not have poultry litter applied and was compared to the five treated subwatersheds, which received varied rates of poultry litter. A target N rate of 170 kg ha^{-1} is common for this Blackland Prairie region and follows corn production recommendations (Gass, 1987).

Table 3. Poultry litter chemical and physical property analysis.

Year	Total N (%)	Total P (%)	Water Extractable ($mg\ kg^{-1}$)			Moisture (%)	Organic C (%)
			NO_3^-	NH_4	Organic P		
2001	2.3	2.1	210	1170	900	50.0	28.4
2002	3.1	3.5	850	3780	1230	9.8	31.2
2003	3.3	1.7	270	4730	780	32.1	na
2004	2.3	2.0	510	2920	800	28.0	na

Table 4. Average poultry litter and inorganic commercial fertilizer rates applied to the six cultivated subwatersheds near Riesel, Texas from 2001-2004.

	Subwatershed					
	Y6	Y8	Y10	Y13	W12	W13
Litter rate ($Mg\ ha^{-1}\ year^{-1}$)	0.0	13.4	6.7	4.5	9.0	11.2
Mean N rate[a] ($kg\ ha^{-1}\ year^{-1}$)	168	370	278	237	296	328
Mean P rate[b] ($kg\ ha^{-1}\ year^{-1}$)	19	358	196	122	229	286

[a] Mean N rate is the mean of N inputs, including poultry litter and inorganic commercial fertilizer, for the 2001-2004 crop years.

[b] Mean P rate is the mean of P inputs, including poultry litter and inorganic commercial fertilizer, for the 2001-2004 crop years.

Table 5. Management operations for the six cultivated subwatersheds near Riesel, Texas.

Date	Management Operation
2000	
Aug 1	Research commences
Aug 3-8	Harvest corn, shred stalks (watersheds Y6, Y13, W12, and W13)
Aug 14-Sept 22	Tillage
Oct 2-4	Tillage
Oct 11-13	Terrace work
2001	
Mar 27-Apr 27	Tillage
May 29-Jun 1	Tillage
Jul 11-17	Poultry litter application
Sept 18-21	Tillage (incorporation) and herbicide application
Sept 26-28	Tillage
Oct 29-30	Tillage
Nov 2	Herbicide application
2002	
Feb 20-21	Inorganic commercial fertilizer application and incorporation
Mar 6-7	Plant corn (Pioneer 31R88, 27 in. rows, 64250 seeds ha^{-1})
Mar 11	Herbicide application
Apr 22-24	Tillage
Aug 19-24	Harvest corn
Aug 28-30	Shred stalks
Sept 3-5	Poultry litter application and tillage (incorporation)
Sept 23-27	Tillage
2003	
Jan 30-31	Inorganic commercial fertilizer application and incorporation
Mar 17-19	Tillage
Mar 17-20	Plant corn (Pioneer 31R88, 27 in. rows, 57180 seeds ha^{-1}) and herbicide application
Apr 29	Pesticide application
Aug 20-25	Harvest corn and shred stalks
Sept 9	Tillage (Y6)
Sept 25-27	Poultry litter application
Sept 29-30	Tillage (Y8, Y10, Y13, W12, W13)
Sept 30-Oct 2	Tillage
Oct 1	Inorganic commercial fertilizer application and incorporation
Oct 21-22	Tillage
Oct 22-24	Plant wheat (247 seeds ha^{-1} Coronado hard wheat)
Oct 23-24	Herbicide application
2004	
May 21-Jun 7	Harvest wheat (Y8, Y10, Y13, W12, W13)
Jun 29	Shredded wheat (Y6); yield estimated by plot data
Jul 16	Herbicide application
Aug 4-5	Tillage
Aug 30-Sept 1	Poultry litter application
Aug 30-Sept 2	Tillage (incorporation)

Table 6. Crop type and yield for 2002-2004 for the six subwatersheds near Riesel, Texas.

	Crop Yield ($kg\ ha^{-1}$)					
Year (crop type)	Y6	Y8	Y10	Y13	W12	W13
2002 (corn)	6600	7100	7900	8250	7000	8050
2003 (corn)	5400	6700	6100	5100	7050	6450
2004 (wheat)	1650	2400	2700	2650	2500	2300

This N rate was accomplished via the addition of supplemental N in the form of urea and ammonium nitrate (1:1 liquid urea:ammonium nitrate). Additional N was applied in February 2002 and January 2003. The Y6 subwatershed also received supplemental P (36 $kg\ ha^{-1}$) in January 2003. For the wheat crop, the Y6 control subwatershed had additional inputs of 67 $kg\ N\ ha^{-1}$ and 34 $kg\ P\ ha^{-1}$ in October 2003. Commercial fertilizer additions followed crop production recommendations for the Blackland Houston Black soils and addresses the common practices of local farmers. The management operations are presented in table 5.

From 2002 through 2004, management for each of the six subwatersheds included tillage, planting, harvesting, and nutrient supplementation from poultry litter and/or inorganic N and P inputs (table 5); 2001 was a fallow year. The tillage system included one or two field cultivation operations for seedbed preparation; fertilizer was incorporated using a disc and sweep chisel. Corn was planted in March and harvested in August for the 2002 and 2003 field years. Wheat was planted in October 2003 and harvested in May and June 2004. The potential heat unit (PHU) (growing degree days in °C from planting to maturity) was set to an average of 1800 for corn and wheat. Table 6 presents the crop yields.

HYDROLOGIC DISCHARGE AND WATER QUALITY DATA

Each of the six subwatersheds contained a flow control structure through which the flow rate was recorded in 10 min intervals and water quality samples were obtained (fig. 1). More than 70 water quality samples were taken during each field year, with additional samples taken during the commencement of a rainfall event in order to capture the initial flush of nutrients. Water quality samples were analyzed for NO_3-N, soluble reactive P (SRP), organic N and P, and sediment (Harmel et al., 2004).

SWAT simulates the organic and mineral N and P fractions by separating each nutrient into component pools that can increase or decrease depending on the transformation and/or the additions/losses occurring within each pool. A mass balance is calculated on a daily time scale to capture the series of changes addressed through the respective processes' equations. Neitsch et al. (2002a, 2002b) describe the details of the nutrient process equations.

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), which were used to assess SWAT's ability to reproduce the distribution of the observed data and to measure the variability between the observed and simulated data. The goodness-of-fit measures used were the coefficient of determination (R^2) (eq. 1) and the Nash-Sutcliffe efficiency (N_{SE}) (eq. 2) (Nash and Sutcliffe, 1970). The percent error (PE) (eq. 3) was used to assess the systematic over- or underprediction and when the absolute value was applied; it showed the magnitude of error:

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

$$N_{SE} = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n}\left(P_i - O_i\right)^2}{\sum\left(O_i - \overline{O}\right)^2} \quad (2)$$

$$PE = \frac{\left|P_i - O_i\right|}{O_i} \times 100 \quad (3)$$

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 N_{SE} value was used to compare predicted values to the mean of the average monthly observed values for the subwatershed, where a value of 1 indicates a perfect fit. The N_{SE} describes the explained variance of the observed values over time that is accounted for by the SWAT model. The R^2 was used to evaluate how accurately the model tracks the variation of the observed values. The difference between the N_{SE} and the R^2 is that the N_{SE} can interpret model performance in replicating individually observed values, while the R^2 does not. For this study, the criteria of $N_{SE} > 0.4$ and $R^2 > 0.5$ were chosen to assess how well the model performed (Green et al., 2006). Results greater than 0.4 for N_{SE} and 0.5 for R^2 meant the model performed satisfactorily, and results below those numbers indicated that the model did not perform well. Santhi et al. (2001a, 2001b) and Ramanarayanan et al. (1997) used criteria of $R^2 > 0.6$ and $N_{SE} > 0.5$ to determine how well the model performed. Chung et al. (1999; 2002) used standards of $N_{SE} > 0.3$ and $R^2 > 0.5$ with EPIC simulations to determine if the model results were satisfactory.

Model performance was also evaluated using a paired t-test. This was used to determine if the difference between observed and simulated monthly means were significantly different from zero ($\alpha = 0.05$) and to determine if the control subwatershed water quality data were significantly different ($\alpha = 0.05$) from the subwatersheds that received poultry litter.

CALIBRATION METHODS

The SWAT hydrologic model requires parameter input for soil bulk density, soil available water capacity, soil texture, soil organic matter content, soil saturated conductivity, land use (crop and rotation), management (tillage, irrigation, nutrient and pesticide applications), weather (daily precipitation, temperature, solar radiation, wind speed), channel geometry (slope, length, bankfull width and depth), and the shallow aquifer (specific yield, recession constant, and revap coefficient) (Arnold, 1992). The soil-related data were based on the USDA-NRCS SSURGO database, which provided the data for available water holding capacity, saturated conductivity, soil depth, bulk density, texture, soil pH, and percent organic carbon. The initial N and P values were extrapolated from the percent organic carbon values, and model defaults were utilized for the nutrient pools. The model was initialized and calibrated with the subwatersheds' 2002 data, and model defaults were used when values were not obtainable. The parameter values were allowed to vary within reasonable uncertainty ranges (table 7) to calibrate for monthly and daily discharge, and annual and monthly sediment and nutrient loss values. All of the sediment and nutrient data available for these subwatersheds were used in this study.

Calibration parameters that impact runoff, and therefore water quality values, include the SCS runoff curve number for moisture condition II (CN2), the soil evaporation compensation factor (ESCO), the surface runoff lag time (SURLAG), and initial soil water content expressed as a fraction of field capacity (FFCB). Using SWAT's parameter sensitiv–

Table 7. Calibrated values of adjusted parameters for discharge, sediment and nutrient calibration of the SWAT2005 model for the six subwatersheds near Riesel, Texas.

Parameter	Description	Range	Calibrated Value Range
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
NPERCO	Nitrogen percolation coefficient (10 m^3 Mg^{-1})	0 to 1	0.2
PPERCO	Phosphorus percolation coefficient (10 m^3 Mg^{-1})	10 to 17.5	17.5
ERORGN	Nitrogen enrichment ratio for sediment loading	0.5 to 3.0	Varies with rainfall event
ERORGP	Phosphorus enrichment ratio for sediment loading	0.5 to 5.0	Varies with rainfall event
CN2	Initial SCS runoff curve number to moisture condition II	30 to 100	74 to 78
PHOSKD	Phosphorus soil partitioning coefficient (m^3 Mg^{-1})	100 to 175	175

ity analysis procedure, which was run on a daily basis, resulted in slight variability among the six subwatersheds, with CN2 and ESCO alternating as the most responsive parameter. The CN2 and ESCO parameters were found to be more sensitive to input variability than the SURLAG and FFCB parameters. Water quality parameters, such as sediment, N, and P fractions, are not yet included in SWAT's parameter sensitivity analysis procedure.

The CN2 parameter was calibrated from the Y6 subwatershed data to a value of 78, which is close to the value (81) recommended by the SCS Handbook (USDA SCS, 1972) for these hydrological soil groups. All of the remaining parameters used SWAT default values except for SURLAG, which required a shorter surface runoff lag time.

RESULTS AND DISCUSSION

RUNOFF

The observed and simulated monthly discharge data from 2000 to 2004 are presented in figure 2, and the related calibration and validation daily and monthly summary statistics are in tables 8 through 11. The model performed well, using the criteria previously stated of $N_{SE} > 0.4$ and $R^2 > 0.5$. The monthly and daily runoff model simulations for the six subwatersheds resulted in calibration N_{SE} values of 0.59 and 0.53 and validation N_{SE} values 0.82 and 0.80, respectively. The monthly and daily R^2 runoff values for the six subwatersheds resulted in calibration values of at least 0.60 and 0.53 and validation R^2 values of 0.86 and 0.81, respectively. The number of years available for simulation and how they are distributed for calibration and validation periods can impact the results. The calibration included parameter initialization, which impacted the statistical results. The validation period used the calibrated parameters and had more time to simulate the watershed runoff, leading to higher statistical values. SWAT's validation of discharge followed the observed values well, as evidenced by the average subwatershed monthly and daily PE values of 9.1% and 11.6%, respectively, which is within an acceptable range of error for those time scales. When only the 2002 calibrated data were used for model runoff simulation, the monthly and daily N_{SE} values were at least 0.59 and 0.53 and had monthly and daily R^2 values of 0.60 and 0.53, respectively.

Evaluation of the annual data in figure 3 shows that the SWAT trends were to overestimate in dry periods and underestimate in wet periods. These results are good considering that only a five-year period of runoff was available and calibration was performed with one year of data. As illustrated

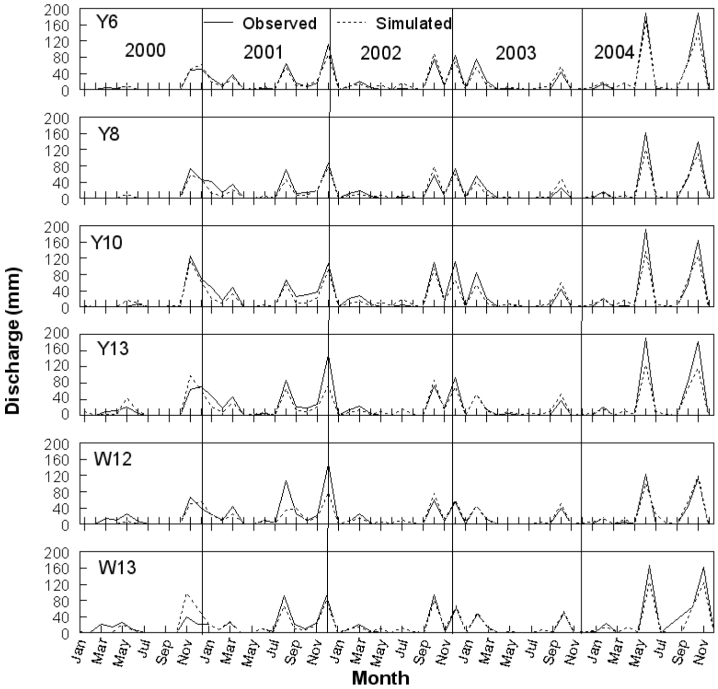

Figure 2. Observed and simulated monthly discharge for the six subwatersheds near Riesel, Texas, during 2000-2004.

Table 8. Daily calibration observed and simulated runoff summary statistics for the six subwatersheds near Riesel, Texas, for 2002.

Sub-watershed	Observed ($mm\ day^{-1}$)		Simulated ($mm\ day^{-1}$)				
	Mean	SD	Mean	SD	N_{SE}	R^2	PE (%)
Y6	0.56	3.3	0.64	2.9	0.69	0.70	14.3
Y8	0.49	2.7	0.50	2.5	0.68	0.69	2.0
Y10	0.81	4.5	0.56	2.9	0.63	0.66	−30.9
Y13	0.63	3.6	0.53	3.1	0.74	0.74	−15.9
W12	0.45	2.9	0.49	2.7	0.61	0.63	8.9
W13	0.53	3.9	0.49	2.7	0.53	0.53	−7.5

Table 9. Monthly calibration observed and simulated runoff summary statistics for the six subwatersheds near Riesel, Texas, for 2002.

Sub-watershed	Observed ($mm\ month^{-1}$)		Simulated ($mm\ month^{-1}$)				
	Mean	SD	Mean	SD	N_{SE}	R^2	PE (%)
Y6	17.2	30.0	16.8	23.2	0.87	0.90	−2.3
Y8	15.0	24.6	14.4	22.7	0.92	0.92	−4.0
Y10	24.7	40.9	17.5	23.5	0.72	0.88	−29.1
Y13	19.1	31.5	16.8	23.3	0.88	0.93	−12.0
W12	13.5	22.1	14.2	21.7	0.76	0.77	5.2
W13	16.2	30.2	14.2	21.5	0.59	0.60	−12.3

Table 10. Daily validation observed and simulated runoff summary statistics for the six subwatersheds near Riesel, Texas, for 2000, 2001, 2003, and 2004.

Sub-water-shed	Observed (mm day^{-1})		Simulated (mm day^{-1})				
	Mean	SD	Mean	SD	N_{SE}	R^2	PE (%)
Y6	0.68	4.6	0.63	3.9	0.81	0.82	-7.4
Y8	0.59	3.6	0.51	3.3	0.85	0.85	-13.6
Y10	0.81	4.6	0.75	4.1	0.84	0.84	-7.4
Y13	0.78	4.9	0.63	3.9	0.81	0.83	-19.2
W12	0.62	4.7	0.55	3.8	0.80	0.81	-11.3
W13	0.64	4.5	0.57	3.9	0.86	0.86	-10.9

Table 11. Monthly validation observed and simulated runoff summary statistics for the six subwatersheds near Riesel, Texas, for 2000, 2001, 2003, and 2004.

Sub-water-shed	Observed (mm month^{-1})		Simulated (mm month^{-1})				
	Mean	SD	Mean	SD	N_{SE}	R^2	PE (%)
Y6	21	40	20	34	0.94	0.96	-3.9
Y8	18	33	16	27	0.90	0.93	-13.1
Y10	25	43	21	33	0.89	0.94	-15.1
Y13	24	43	21	31	0.82	0.86	-12.7
W12	20	36	17	27	0.82	0.86	-9.4
W13	20	36	20	31	0.86	0.87	-0.6

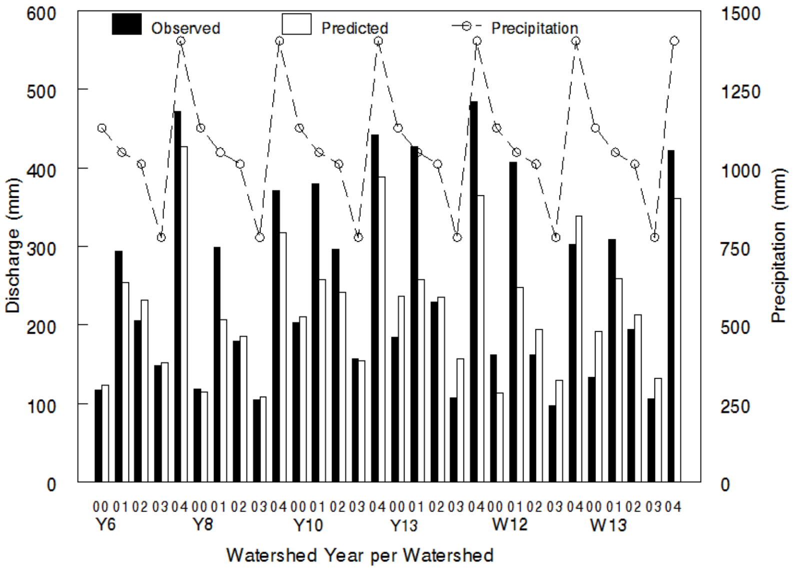

Figure 3. Annual observed and predicted discharge and annual precipitation.

by figure 2, 2001 and 2004 are considered the wet years as compared to 2000 and 2003; 2002's runoff amount is in the middle of the range for the five-year period, which contributed to it being selected as the calibration year. If runoff was evaluated each year: in 2000, runoff was overestimated in four subwatersheds; in 2001, runoff was consistently underestimated in all of the subwatersheds; runoff was overestimated in five of the six subwatersheds during 2002 and 2003; and during the wettest year (2004), five of the six subwatersheds underestimated runoff. Although the annual results are more general, the detail, as presented in table 8, shows that the monthly and daily PE remained below 20%.

A comparison between the observed and predicted discharge indicated that SWAT followed the observed data well for all the subwatersheds, with a trend toward underestimation (tables 8 through 11, fig. 3). The predicted annual runoff vs. annual precipitation ratios ranged from 10% to 30%, while the observed annual discharge vs. precipitation ranged from 10% to 40%, with the largest variation during the drought in 2001. A paired t-test of the entire five-year period indicates no significant difference ($\alpha = 0.05$) between the observed and simulated annual discharge data for all of the subwatersheds. The exclusion of the calibration year (2002) also shows no significant difference ($\alpha = 0.05$) between the observed and simulated annual discharge data.

WATER QUALITY CONSTITUENTS

Figure 4 illustrates the average annual runoff, sediment, and nutrient losses for 2000-2004. The solid line is the 1:1 line, and the dashed line is the linear regression line. Most of the regression lines are close to the 1:1 line, indicating that the averaged annual measured data closely matches the simulated data.

Although SWAT's monthly simulation of NO_3-N with manually adjusted parameters only yielded one subwatershed p-value indicating a significant difference in means (table 12), the N_{SE} and R^2 values are lower than 0.5, indicating that SWAT did not adequately simulate the measured data (fig. 4). Two N_{SE} values for the W13 and Y8 subwatersheds are slightly above 0.4, and all of the R^2 values are below 0.5, which according to the criteria established for this study means that the model did not perform acceptably. Corn was planted in March and wheat was planted in October for these subwatersheds. Fertilizer was applied while the plants were not growing (July 2001, February and September 2002, January and September 2003, and August 2004), leaving the nutrients exposed to movement with sediment (P) or by water (nitrate). The subwatershed with the highest crop yield was W13, which received the second highest fertilizer/poultry litter inputs (Y8 had the highest fertilizer/poultry litter inputs). The subwatersheds that received the highest total N rates (Y8 > W13 > W12 > Y10 > Y13 > Y6) were not the ones with the most NO_3-N measured (tables 12 and 13). The three subwatersheds with the lowest amount of N or poultry litter ap-

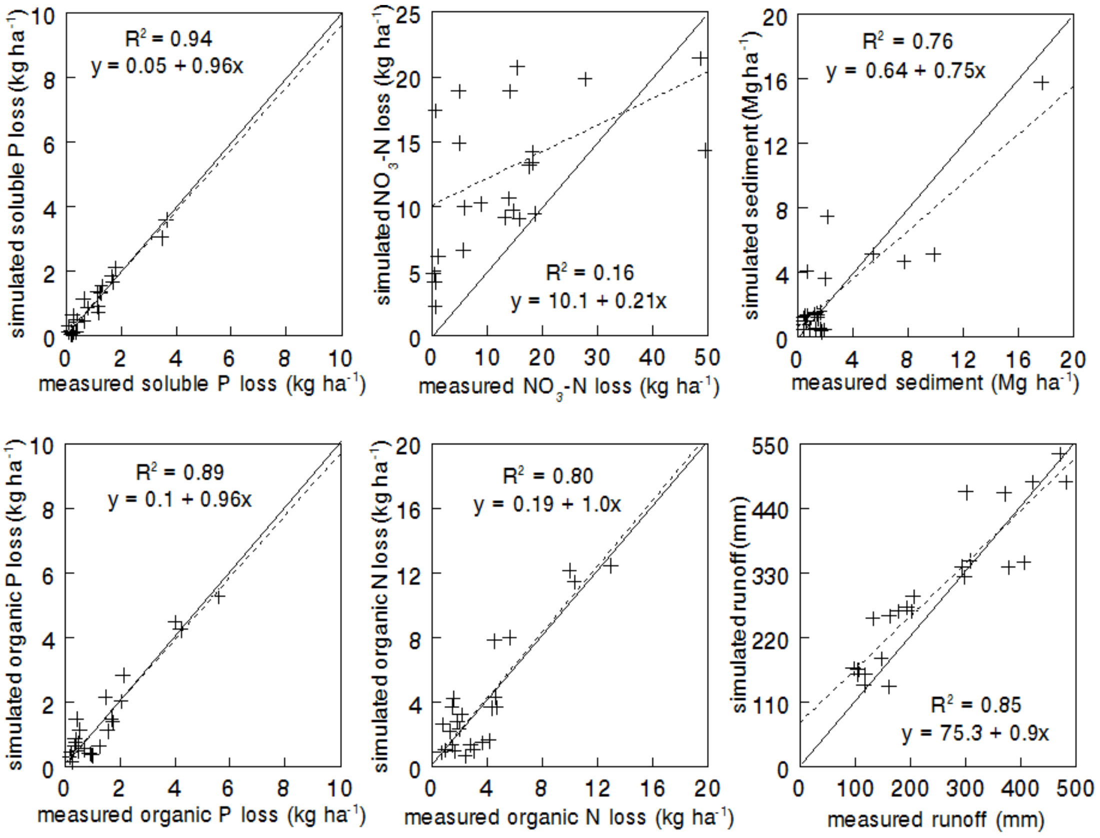

Figure 4. Measured and simulated annual runoff, sediment, and nutrient losses for the six subwatersheds for the period 2000-2004.

plied (Y6, Y10, and Y13) had the highest NO_3-N concentrations measured in runoff (Y10 > Y13 > Y6 > W13 > Y8 > W12).

A possible explanation for these results is the amount of inorganic N present. In addition, Y10, Y13, and Y6 had the highest runoff amounts, which may have attributed to the increased amounts of NO_3-N available for transport, especially due to application near a large rainfall event. The disparity between the measured and simulated values may be attributable to the proximity of large rainfall events that occurred soon after poultry litter had been applied. Rainfall events that resulted in greater than 50 mm runoff followed fertilizer/poultry litter applications in August 2001, October 2002, February 2003, and September and October 2003. The W13 subwatershed had the highest yields of all the subwatersheds (table 6), received the second highest fertilizer inputs (table 4), and has the lowest slope (table 1).

Sediment loss was most likely due to land management practices rather than slope, since the control watershed has the steepest gradient and four of the subwatersheds had higher monthly sediment loss means. The N_{SE} and R^2 sediment values were affected by SWAT's overestimation of sediment in 2000 and 2001. None of the sediment-related p-values were significant (table 13). The N and P simulated organic loads were not significantly ($\alpha = 0.05$) different from the measured loads. Organic N and organic P followed the trend of sediment loss (Y13 > W12 > W13 > Y8 > Y6 > Y10) in both the measured and simulated data. The subwatersheds with the highest soluble P applied via poultry litter and commercial fertilizer also had the highest soluble P measured in runoff (W13 and Y8, respectively). The control watershed had the lowest soluble P runoff concentration. The model was able to track measured soluble P concentrations due to its predominant transport in surface runoff rather than leaching.

Comparing the simulated data for the control subwatershed (Y6) with the five treated subwatersheds resulted in a significant difference ($\alpha = 0.05$) in the average water quality parameters (organic N, organic P, soluble NO_3-N, soluble P, and sediment). The SWAT model does not differentiate between manure particles and soil particles, so the term sediment refers to all soil and/or soil amendment particles from land processes. When commercial fertilizer was applied and followed by large rainfall events, high measured soluble N losses were not accounted for by the model due to the increased amount of NO_3-N leached. Soluble P was simulated well due to its predominant transport in surface runoff rather than leaching. The Y10 subwatershed had poor statistical results (table 10; N_{SE} and R^2) due to SWAT's overestimation of sediment in 2000 and 2001. While none of the sediment-related p-values were significant, W12 is close to being significant (p-value 0.051), which may be related to the inability of SWAT to account for the channel being cleared of sediment in 2002. Organic N and P loss accompanied sediment transport in both the measured and simulated data. The N and P simulated organic concentrations were not significantly (α = 0.05) different from the measured concentrations.

Almost all of the subwatersheds that had poultry litter applied resulted in higher sediment, organic N, organic P, and soluble P losses than the control subwatershed upon averaging the monthly validation values. High NO_3-N losses may have been a function of poultry litter and commercial fertilizers being applied before a large rainfall event occurred. The

Table 12. Monthly measured and validation simulation from manually adjusted parameters of water quality constituent summary statistics per subwatershed in Riesel, Texas for the years 2000-2004.

Statistical Measure		Subwatershed					
		Y6	Y8	Y10	Y13	W12	W13
Sediment							
Measured (Mg ha^{-1})	Mean	0.14	0.16	0.11	0.29	0.26	0.22
	SD	0.34	0.59	0.25	0.92	0.82	0.72
Simulated (Mg ha^{-1})	Mean	0.13	0.15	0.25	0.15	0.17	0.16
	SD	0.30	0.39	0.60	0.35	0.33	0.35
N_{SE}		0.50	0.60	−2.92	0.48	0.46	0.60
R^2		0.53	0.61	0.44	0.72	0.62	0.74
P-value[a]		0.97	0.73	0.94	0.11	0.41	0.23
Organic N loss							
Measured (kg ha^{-1})	Mean	0.28	0.33	0.24	0.55	0.39	0.34
	SD	0.63	0.98	0.50	1.51	1.05	0.83
Simulated (kg ha^{-1})	Mean	0.26	0.34	0.25	0.55	0.40	0.36
	SD	0.56	0.88	0.57	1.25	0.78	0.82
N_{SE}		0.57	0.66	0.28	0.80	0.67	0.78
R^2		0.58	0.67	0.48	0.80	0.67	0.79
P-value[a]		0.66	0.52	0.93	0.39	0.28	0.90
NO_3-N loss							
Measured (kg ha^{-1})	Mean	1.2	0.94	1.8	1.26	0.67	0.91
	SD	4.3	2.1	4.96	3.29	1.8	2.4
Simulated (kg ha^{-1})	Mean	1.1	0.94	1.7	1.30	0.70	0.93
	SD	1.3	1.7	2.52	2.29	1.2	1.7
N_{SE}		0.22	0.46	0.069	−0.62	0.13	0.42
r^2		0.26	0.46	0.10	0.092	0.19	0.42
P-value[a]		0.39	0.30	0.047[b]	0.17	0.18	0.26
Organic P loss							
Measured (kg ha^{-1})	Mean	0.09	0.12	0.066	0.21	0.16	0.13
	SD	0.21	0.42	0.14	0.66	0.46	0.34
Simulated (kg ha^{-1})	Mean	0.09	0.12	0.064	0.21	0.16	0.12
	SD	0.20	0.34	0.15	0.56	0.35	0.32
N_{SE}		0.59	0.65	0.47	0.82	0.61	0.89
R^2		0.61	0.65	0.56	0.83	0.61	0.89
P-value[a]		0.81	0.50	0.77	0.34	0.39	0.91
Soluble P loss							
Measured (kg ha^{-1})	Mean	0.023	0.12	0.11	0.081	0.07	0.13
	SD	0.049	0.31	0.23	0.17	0.16	0.33
Simulated (kg ha^{-1})	Mean	0.024	0.12	0.10	0.073	0.07	0.13
	SD	0.054	0.25	0.20	0.16	0.15	0.27
N_{SE}		0.29	0.80	0.81	0.87	0.80	0.90
R^2		0.47	0.80	0.81	0.87	0.80	0.92
P-value[a]		0.75	0.23	0.67	0.98	0.88	0.98

[a] P-value: Ho: the mean of the measured monthly values is not significantly different from the mean of the simulated values; Ho is not accepted if the P value is less than the level of significance (α = 0.05).

[b] The only value that failed to be accepted (α = 0.05).

Table 13. Measured and simulated water quality constituent monthly summary statistics per subwatershed in Riesel, Texas for the years 2000, 2001, 2003, and 2004.

Statistical Measure		Subwatershed					
		Y6	Y8	Y10	Y13	W12	W13
Sediment							
Measured (Mg ha^{-1})	Mean	0.14	0.16	0.11	0.29	0.26	0.22
	SD	0.34	0.59	0.25	0.92	0.82	0.72
Simulated (Mg ha^{-1})	Mean	0.13	0.15	0.25	0.15	0.17	0.16
	SD	0.30	0.39	0.60	0.35	0.33	0.35
N_{SE}		0.50	0.60	−2.92	0.48	0.46	0.60
R^2		0.53	0.61	0.44	0.72	0.62	0.74
P-value[a]		0.97	0.73	0.94	0.11	0.051	0.23
Organic N loss							
Measured (kg ha^{-1})	Mean	0.28	0.33	0.24	0.55	0.39	0.34
	SD	0.63	0.98	0.50	1.5	1.1	0.83
Simulated (kg ha^{-1})	Mean	0.26	0.34	0.25	0.55	0.40	0.36
	SD	0.56	0.88	0.57	1.2	0.78	0.82
N_{SE}		0.57	0.66	0.28	0.80	0.67	0.80
R^2		0.58	0.67	0.48	0.80	0.67	0.79
P-value[a]		0.66	0.52	0.93	0.39	0.28	0.90
NO_3-N loss							
Measured (kg ha^{-1})	Mean	1.2	0.94	1.8	1.3	0.67	0.91
	SD	4.3	2.1	5.0	3.3	1.8	2.4
Simulated (kg ha^{-1})	Mean	1.1	0.94	1.7	1.3	0.70	0.93
	SD	1.3	1.7	2.5	2.3	1.2	1.7
N_{SE}		0.22	0.46	0.07	−0.60	0.13	0.42
R^2		0.26	0.46	0.10	0.09	0.19	0.42
P-value[a]		0.39	0.30	0.023[b]	0.17	0.18	0.26
Organic P loss							
Measured (kg ha^{-1})	Mean	0.09	0.12	0.07	0.21	0.16	0.13
	SD	0.21	0.42	0.14	0.66	0.46	0.34
Simulated (kg ha^{-1})	Mean	0.09	0.12	0.06	0.21	0.16	0.12
	SD	0.20	0.36	0.15	0.56	0.35	0.32
N_{SE}		0.59	0.65	0.47	0.82	0.61	0.89
R^2		0.61	0.65	0.56	0.83	0.61	0.89
P-value[a]		0.81	0.50	0.77	0.34	0.39	0.91
Soluble P loss							
Measured (kg ha^{-1})	Mean	0.02	0.12	0.11	0.08	0.07	0.13
	SD	0.05	0.31	0.23	0.17	0.16	0.33
Simulated (kg ha^{-1})	Mean	0.02	0.12	0.10	0.07	0.07	0.13
	SD	0.05	0.25	0.20	0.16	0.15	0.27
N_{SE}		0.29	0.80	0.81	0.87	0.80	0.90
R^2		0.47	0.80	0.81	0.87	0.80	0.92
P-value[a]		0.75	0.23	0.67	0.98	0.88	0.98

[a] P-value: Ho: the mean of the measured monthly values is not significantly different from the mean of the simulated values; Ho is not accepted if the P value is less than the level of significance (α = 0.05).

[b] The only value that failed to be accepted (α = 0.05).

subwatersheds that received smaller amounts of commercial fertilizer and/or poultry litter lost more sediment, organic N, and organic P than the subwatersheds that received the higher litter and/or fertilizer treatments. Overall, SWAT simulated the hydrology and the water quality constituents at the subwatershed scale more adequately when all of the data were used to simulate the model, as evidenced by statistical measures.

CONCLUSIONS

The SWAT model, version 2005, was used to assess its ability to simulate runoff, sediment, and nutrient loss data from small-scale watersheds in Texas. Six subwatersheds (HUC-8; 12070101) were evaluated for sediment and nutrient water quality effects from poultry litter randomly applied at rates of 0 to 13.4 Mg ha^{-1}. Monthly data from 2002 were used for parameter initialization and calibration purposes, while 2000, 2001, 2003, and 2004 were used for validation. The autocalibration and parameter sensitivity analysis procedure embedded in SWAT was used to obtain an optimal parameter fit to determine the relative ranking of the most sensitive parameter to input variability. The analysis resulted in a slight variability among the six subwatersheds, with CN2 and ESCO alternating as the most responsive parameter and with the SURLAG and FFCB parameters being less sensitive.

The model simulated monthly and daily runoff well with all of the subwatersheds; monthly and daily N_{SE} and R^2 runoff values were at least 0.82 and 0.86, and 0.81 and 0.80, respectively. Percent error measurements showed that the SWAT model tended to overestimate runoff in the dry periods and underestimation in the wet periods. The goodness-of-fit measures demonstrated that SWAT simulations explained the monthly and daily runoff variations in the measured data well ($N_{SE} > 0.4$ and $R^2 > 0.5$).

The monthly simulated sediment and nutrient (organic N and P, NO_3-N, and soluble P) N_{SE} and R^2 values were generally above 0.4 and 0.5, respectively, with deviations explained by field management issues (cleaning channels of sediment, supplemental fertilizer applications) or a model simulation inability (NO_3-N leaching when a large rainfall event occurs following commercial fertilizer application on bare soil). Paired t-tests for monthly sediment and nutrient losses and soluble P losses showed that their respective SWAT means were not significantly different from the measured values ($\alpha = 0.05$), except for NO_3-N losses for the Y10 subwatershed.

The control subwatershed's water quality results were significantly different ($\alpha = 0.05$) from the treated subwatersheds. Almost all of the subwatersheds that had poultry litter applied resulted in higher sediment, organic N, organic P, and soluble P losses than the control subwatershed upon averaging the monthly validation values. Organic N and P follow sediment movement in both the measured and simulated values when runoff events occur. The subwatersheds that received smaller amounts of commercial fertilizer and/or poultry litter lost more sediment than the subwatersheds that received the higher litter treatments due to more groundcover exposure. With N_{SE} values above 0.8 for the monthly and daily runoff and generally above 0.4 for sediment and nutrients, this study has shown that SWAT's runoff and water quality processes and output are reasonable and can be used at the subwatershed level. Currently, SWAT does not differentiate between manure/poultry litter sediment and soil-sediment transport. Having a longer period of discharge and nutrient and sediment data records may improve the simulation results in that anomalies in the data may not be abnormal in the long term.

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