EVALUATION OF EPIC FOR ASSESSING CROP YIELD, RUNOFF, SEDIMENT AND NUTRIENT LOSSES FROM WATERSHEDS WITH POULTRY LITTER FERTILIZATION

X. Wang, R. D. Harmel, J. R. Williams, W. L. Harman

ABSTRACT. *Faced with limited comprehensive data on the economic, agronomic, and environment effects of land-applying animal wastes, water quality models are increasingly used to explore management and policy alternatives. However, thorough evaluation of these models is needed to assess their predictive ability for this resource issue. The EPIC (Environmental Policy Integrated Climate) model version 3060 was evaluated using data collected from six cultivated small watersheds (4.0 to 8.4 ha) near Riesel, Texas. The study watersheds were fallow in 2001, cropped with corn (*Zea mays *L.) in 2002 and 2003, and planted to winter wheat (*Triticum aestivum *L.) in 2004. A target poultry litter application rate from 0 to 13.4 Mg ha^{-1} was randomly assigned to each of the watersheds. Monthly data of runoff, sediment, and soluble P for 2001-2002 from one watershed (Y13) were used to calibrate the initial CN2, erosion control practice factor, RUSLE C factor coefficient, and phosphorus sorption ratio. The modeling efficiency (EF) for the calibrated period was 0.90 for runoff, 0.65 for sediment, and 0.94 for soluble P. EPIC was validated using the 2001-2004 measured data for the other five watersheds and the remaining data for Y13. It successfully predicted surface runoff on an annual, monthly, and daily basis for all watersheds, with EF values larger than 0.5 and R^2 larger than 0.7. The sediment, organic N and P, soluble P, and NO_3-N losses simulated by EPIC were satisfactory, with EF values ranging from 0.59 to 0.87 based on annual comparisons and larger than 0.4 (in 25 out of 30 tests) based on monthly comparisons. EF was 0.96 for crop yields. Paired t-tests based on monthly comparisons of runoff, sediment and nutrient losses, and annual crop yields indicated that the differences between predicted and observed values were not significantly different from zero at the significance level of α = 0.05, except for soluble P losses for the control watershed. Both parametric and nonparametric statistical tests for EF values of monthly comparisons of runoff, sediment and nutrient losses, and percent errors of crop yields indicated that the reliability of the model was not significantly different among the poultry litter application watersheds and the control watershed, with the exception of soluble P losses for the control watershed. These statistical tests indicate that EPIC was able to replicate the runoff, water quality, and crop yield impacts of poultry litter application.*

Keywords. *Animal manure, Crop yield, EPIC model, Nutrient loss, Runoff, Sediment loss, Water quality.*

Nonpoint-source (NPS) pollution is transported primarily by runoff from urban development, agricultural land, mining areas, and construction sites (Brannan et al., 2000). NPS pollution causes tens of billions of dollars in damage in the U.S. every year (Lovejoy et al., 1997). Sediments, nutrients, pesticides, and animal wastes are the primary NPS pollutants from agricultural activities. Agricultural decision makers are encountering increasingly complex challenges, which require consideration of management and policy alternatives based on potential economic and environmental impacts (Chung et al., 1999). As a result of the shift to fewer and larger confined animal operations, environmental and economic issues associated with utilization or disposal of animal manures and litters has become a focal point of conservation efforts (Ribaudo et al., 2003; USDA and USEPA, 1999). Manure has been used effectively for crop production and soil improvement, and land application is usually the most desirable method of utilizing the nutrients and organic matter in manure (Eghball and Power, 1994; USDA and USEPA, 1999).

Comprehensive field-scale studies on the crop yield, hydrological, and environmental effects of land-applied animal manures, however, are limited. The considerable expense and collection difficulties caused by natural rainfall variation, substantial land area requirements, field personnel, and automated sampling equipment requirements (Gilley and Risse, 2000; Harmel et al., 2003) often make field studies unfeasible. Faced with this limitation, hydrologic and water quality models that have been sufficiently evaluated are powerful alternatives for evaluation of agronomic and environment effects and management options. The synthesis and understanding that models provide is increasingly important in the policy arena (Bobba et al., 1995). However, it is necessary to more thoroughly evaluate the capability of water quality models to predict the environmental outcomes resulting from manure application. Therefore, model field

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testing and evaluation for a wide range of soils, climatic, and agricultural conditions is an essential step to increase the reliability of these models (Wang et al., 2006).

One of the most widely used simulation models for agricultural policy analysis is the Erosion Productivity Impact Calculator (EPIC) model (Williams and Sharpley, 1989; Williams, 1990). EPIC was developed in the early 1980s to simulate the impacts of soil erosion on soil productivity in the U.S. (Williams et al., 1984; Williams, 1995). EPIC has since evolved into a comprehensive agro-ecosystem model that includes the major soil and water processes related to crop growth and environmental effects of farming activities, and it continues to be modified and refined. Current versions of EPIC have incorporated many advanced functions related to water quality and global climate/CO_2 change, which has resulted in its name change to the Environmental Policy Integrated Climate model (Mitchell et al., 1996). Environmental indicators that can be simulated with EPIC include, but are not limited to, the transport and fate of nutrients from fertilizer and animal manure applications with eroded sediment, in runoff, and in leached water; the impact of atmospheric carbon levels on crop yield; and carbon sequestration in soil.

EPIC has been applied throughout the U.S. and many other countries (Bernardo et al., 1993; Sugiharto et al., 1994; King et al., 1996; Potter et al., 1998; Brown and Rosenberg, 1999; Pierson et al., 2001; Bernardos et al., 2001; Rinaldi, 2001; Chung et al., 2002; Apezteguía et al., 2002). The model has been integrated into the Resources and Agricultural Policy System (RAPS) designed to evaluate the economic and environmental impacts of agricultural polices for the north central U.S. (Babcock et al., 1997). The flexibility of EPIC has led to its adoption within the Conservation Effects Assessment Project (CEAP) as the modeling tool for national assessment. The CEAP project will evaluate conservation practices and management systems related to nutrient, manure, and pest management; buffer systems; tillage, irrigation, and drainage practices; wildlife habitat establishment; and wetland protection and restoration (Mausbach and Dedrick, 2004). Although EPIC has proven to be a robust tool within RAPS (Chung et al., 1999), an ongoing need exists to test the model with as much field-specific data as possible for continuing CEAP modeling efforts, especially to use the model to evaluate water quality impacts of poultry litter application.

The objective of this study was to evaluate the performance of EPIC version 3060 to simulate crop yield, runoff, and sediment and nutrient losses for six cultivated watersheds with poultry litter fertilization by: (1) calibrating the model using observed values of monthly runoff, sediment, and soluble P losses for one watershed (Y13) for the period 2001 to 2002; (2) validating the simulated crop yield, runoff, sediment and nutrient (NO_3-N, ortho-P, organic P, and organic N) losses using the measured data of 2001-2004 for the other five watersheds and the remaining data for Y13; and (3) statistically testing whether EPIC performs significantly different among different poultry litter application rates.

Materials and Methods

Description of Watersheds

The data used in this study were collected from the USDA-ARS Grassland, Soil and Water Research Laboratory near Riesel, Texas (31.1° N, 97.32° W) (Harmel et al., 2004). The dominant soils at the site are Houston Black clays (fine, smectitic, thermic Udic Haplusterts). These soils are classic Vertisols and, thus, shrink and swell considerably as moisture changes (Allen et al., 2005). The six cultivated field-scale watersheds are homogeneous land use fields, denoted as watersheds Y6, Y8, Y10, Y13, W12, and W13 (fig. 1). The study fields received similar management and crop patterns for the last ten years. They range in size from 4.0 to 8.4 ha and

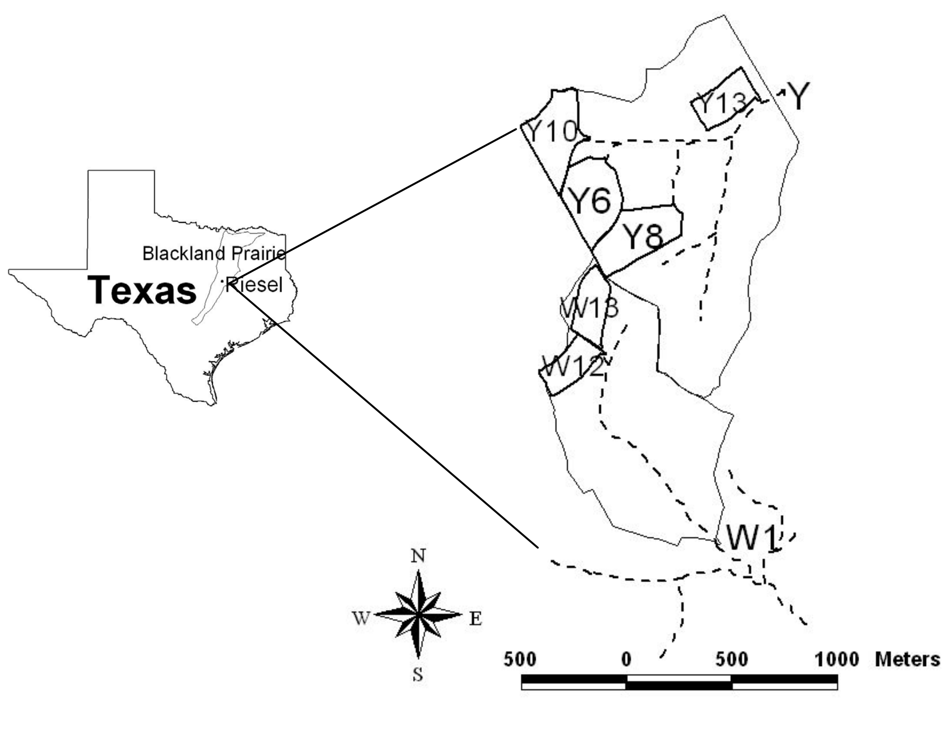

Figure 1. Location of the edge-of-field watersheds used in the study.

in slope from 1.1% to 3.2%. These watersheds are terraced and planted on the contour, and each has an established grass waterway. Target annual poultry litter application rates from 0.0 (for a control watershed) to 13.4 Mg ha^{-1} were chosen to encompass and exceed the entire range of expected application rates used by farmers and were determined a priori and then randomly assigned to each of the watersheds (Harmel et al., 2004).

The fields were not fertilized in 2000 to establish pre-treatment conditions for the study watersheds. Annual poultry litter application began in 2001. Over the study period (2001 to 2004), the management consisted of tillage, planting, harvest, and application of nutrients, including poultry litter and/or inorganic N and P. The poultry litter nutrient analysis is shown in table 1. For corn production, available N rates were matched for all fields with a combination of litter and inorganic N (table 2). Watershed Y6 served as the control field and received only inorganic fertilizer. The target available N rates were set at approximately 170 kg ha^{-1}, which is a typical N rate in the area and follows corn production recommendations (Gass, 1987). Supplemental N (as urea ammonium nitrate, 50% liquid urea and 50% ammonium nitrate) was applied in February 2002 and January 2003 to reach the 170 kg ha^{-1} N target. Supplemental P of 36 kg ha^{-1} was added to the Y6 control watershed in January 2003. For wheat production, no inorganic N was applied to the fields with litter application. The Y6 control watershed received 67 kg N ha^{-1} and 34 kg P ha^{-1} in October 2003 prior to planting wheat (table 2).

Flow rate and water quality were measured at the six edge-of-field watersheds. Flow data were recorded continuously on 5 min intervals with stage sensors installed in the flow control structure at each watershed outlet. Intensive, automated water quality sampling strategies were used to quantify water quality. For 2001-2002, discrete samples were taken on variable time intervals with more samples early in runoff events to adequately capture the first flush and fewer samples later to adequately sample throughout the event duration. In general, the first sample was collected after 5 min, and then four samples were taken on 15 min intervals, four on 30 min intervals, four on 60 min intervals, and 11 on 120 min intervals. In 2003-2004, the sampling protocol was converted to composite, flow-interval sampling (1.32 mm volumetric depth) with a single collection bottle. Both of these intensive sampling strategies produce appropriate quantification of runoff water quality (Harmel et al., 2003; Harmel and King, 2005). An average of more than 77 samples were taken for each field each year. Water quality samples were analyzed for NO_3-N, ortho-P, particulate N, particulate P, and sediment, as described in Harmel et al. (2004).

Table 1. Poultry litter nutrient analysis (values represent the mean of 4 to 6 replications).

Year	Total N (%)	Total P (%)	Water Extractable (mg kg^{-1}) NO_3	NH_4	SRP P	Water (%)	Organic C (%)
2001	2.32	2.14	211	1170	895	49.5	28.4
2002	3.05	3.47	857	3775	1234	9.8	31.2
2003	3.27	1.67	265	4726	778	32.1	28.9
2004	2.27	1.99	510	2917	799	28.0	28.4

Table 2. Poultry litter and supplemental fertilizer application.

Watershed	Poultry Litter (Mg ha^{-1}) 2001	2002	2003	2004	Inorganic Fertilizer kg N ha^{-1} 2002	kg N ha^{-1} 2003	kg P ha^{-1} 2003
Y6[a]	0	0	0	0	156	175 (Jan.) 67 (Oct.)	36 (Jan.) 4 (Oct.)
Y13	4.7	4.1	4.8	4.1	119	119	
Y10	7.4	6.8	6.8	5.9	94	94	
Y8	15.1	11.3	13.6	12.1	22	21	
W12	8.6	7.9	6.3	6.3	83	68	
W13	11.0	9.7	9.7	9.7	60	46	

[a] Control watershed.

Input Data

The major simulation components in EPIC are weather, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control (Williams, 1995). EPIC is a field-scale model, designed to simulate drainage areas up to 100 ha that are characterized by homogeneous weather, soil, landscape, and land use (Williams et al., 1996). EPIC simulates processes extending only to the bottom of the root zone and the edge of the field. Detailed descriptions of the EPIC components and the mathematical relationships used to simulate the processes can be found in Williams (1995). Information on historical EPIC development can be found in Gassman et al. (2004). EPIC requires soil, weather, field management, and site information. The model includes parameter data files for major crops, fertilizers, and tillage practices. The input dataset was developed for a 5-year (2000-2004) continuous simulation period for each watershed, but only the 2001-2004 results were compared due to incomplete observations in 2000.

The initial soil C, N, P, and pH values at the site were measured in 2000 (table 3). The soil layer properties, including depth (at bottom of layer), bulk density (BD), and percent sand and silt, were obtained from the Soil Survey Geographic Database (SSURGO) provided by the Natural Resource Conservation Service (NRCS) (table 4). Soil water content at wilting point (WP) and field capacity (FC) were estimated from soil texture in EPIC using the Rawls method (Rawls et al., 1983).

Table 3. Pre-treatment soil properties in 2000.

Watershed	TKN (%)	TKP (%)	Total C (%)	Organic C (%)	pH
Y6	0.13	0.06	3.91	1.53	7.7
Y13	0.12	0.07	2.33	1.32	7.7
Y10	0.13	0.05	2.70	1.45	7.7
Y8	0.12	0.06	4.47	1.46	7.7
W12	0.11	0.05	4.51	1.24	7.7
W13	0.11	0.05	3.98	1.36	7.7

Table 4. Properties by layer for the Houston Black clay soil.

Property	Soil Layer 1	2	3	4	5	6	7	8	9
Depth (m)	0.01	0.18	0.48	0.71	0.91	1.12	1.35	1.51	2.00
BD (Mg m^{-3})	1.25	1.25	1.20	1.25	1.30	1.26	1.30	1.36	1.32
Sand (%)	7.3	7.3	5.4	4.9	3.8	6.0	6.4	5.7	6.6
Silt (%)	35.7	35.7	39.3	37.1	36.8	35.1	38.2	40.2	41.9

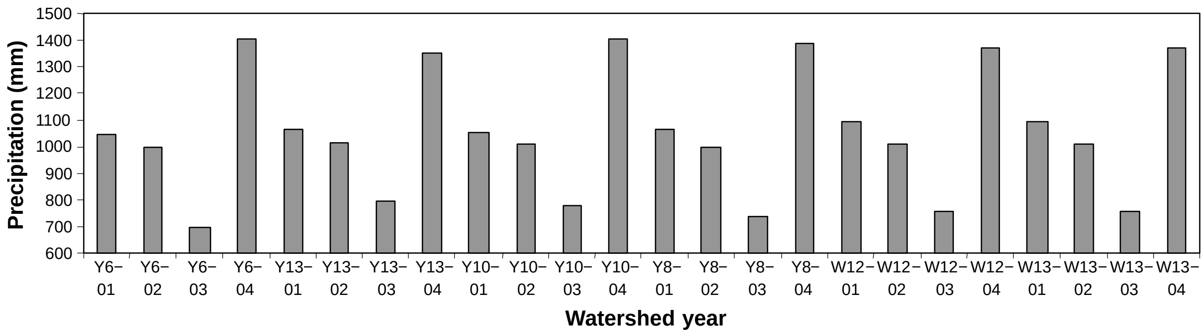

Figure 2. Annual total precipitation of each watershed.

EPIC is driven by observed and/or simulated daily climatic inputs that include: total precipitation, maximum and minimum temperature, total solar radiation, average relative humidity, and average wind velocity. The daily on-site precipitation and temperature values were input for the 5-year (2000-2004) simulation period. The remaining climatic inputs (solar radiation, relative humidity, and wind velocity) were generated in EPIC using historical monthly weather statistics for the site. The mean and standard deviation of annual precipitation (fig. 2) for 2001-2004 per watershed ranged from 1022 to 1062 mm and from 228 to 292 mm, respectively, reflecting the variability in rainfall patterns and amounts that occur within the 2 km distance among the watersheds.

The watershed site information is listed in table 5, and the management activities are summarized in table 6. The management consisted of tillage, planting, harvest, and fertilizer application (poultry litter and/or inorganic N and P). The tillage system consisted of one or two field cultivation operations before planting for seedbed preparation and disk and sweep chisel tillage to incorporate applied fertilizer. Corn was planted in March in both 2002 and 2003 and harvested in late August. Wheat was planted in October 2003 and harvested in May/June 2004. An individual operation input file was developed for each watershed that included the operation dates and corresponding operations (tillage, planting, harvest, fertilizer application) for the individual watershed, fertilizer amounts (listed in table 2), potential heat units (PHU), etc. The PHU (growing degree days in ˚C from planting to maturity) values for corn and wheat were set to 2000 and 1500 based on the values used in Williams et al. (1989) for corn (2000 ˚C PHU) in Bushland, Texas, and for wheat (1502 ˚C PHU) in Temple, Texas.

Simulation Methodology

EPIC operates on a daily time step to simulate hydrologic, weather, soil, nutrient, crop practices, and management. EPIC was run continuously for the duration of the study

Table 5. Characteristics of watersheds.

Characteristic	Watershed					
	Y6	Y13	Y10	Y8	W12	W13
Area (ha)	6.6	4.6	7.5	8.4	4.0	4.6
Upland slope (m m^{-1})	0.032	0.023	0.019	0.022	0.02	0.011
Channel slope (m m^{-1})	0.021	0.015	0.014	0.022	0.013	0.008
Channel length (km)	0.44	0.35	0.52	0.46	0.32	0.40

Table 6. Management activities for the study watersheds.

Date	Management Activity
2000	
3-8 Aug.	Corn harvest, shred stalks (Y6, Y13, W12, W13)
14 Aug. − 22 Sept.	Tillage
2-4 Oct.	Tillage
11-13 Oct.	Terrace work
2001	
27 Mar. − 27 Apr.	Tillage
29 May − 1 June	Tillage
11-17 July	Poultry litter application
11-17 July	Tillage (incorporation)
18-21 Sept.	Herbicide application
26-28 Sept.	Tillage
29-30 Oct.	Tillage
2 Nov.	Herbicide application
2002	
20-21 Feb.	Supplemental fertilizer appl. and incorporation
6-7 Mar.	Corn planting (Pioneer 31R88, 27 in. rows, 26000 seeds/ac)
11 Mar.	Herbicide application
22-24 Apr.	Tillage
19-24 Aug.	Corn harvest
28-30 Aug.	Shred stalks
3-5 Sept.	Poultry litter application
3-5 Sept.	Tillage (incorporation)
23-27 Sept.	Tillage
2003	
30-31 Jan.	Supplemental fertilizer appl. and incorporation
17-19 Mar.	Tillage
17-20 Mar.	Corn planting (Pioneer 31R88, 27 in. rows, 23140 seeds/ac)
17-20 Mar.	Herbicide application
29 Apr.	Pesticide application
20-25 Aug.	Corn harvest, shred stalks
9 Sept.	Tillage (Y6)
25-27 Sept.	Poultry litter application
29-30 Sept.	Tillage (Y8, Y10, Y13, W12, W13)
1 Oct.	Supplemental fertilizer appl. and incorp. (Y6)
30 Sept. − 2 Oct.	Tillage
21-22 Oct.	Tillage
22-24 Oct.	Plant wheat (Coronado Hard Wheat, 100 lb seed/ac)
23-24 Oct.	Herbicide application
2004	
21 May - 7 June	Harvest wheat (Y8, Y10, Y13, W12, W13)
29 June	Shred wheat (Y6); yield estimated by plot data
16 July	Herbicide application
4-5 Aug.	Tillage
30 Aug. − 1 Sept.	Poultry litter application
30 Aug. − 2 Sept.	Tillage (incorporation)

period for each of the watersheds. The Hargreaves method (Hargreaves and Samani, 1985) was used to estimate the potential evaporation. Daily potential soil water evaporation and plant transpiration were then calculated as a function of the potential evaporation and leaf area index (LAI, area of plant leaves relative to the soil surface area) in EPIC (Williams, 1995). Actual soil water evaporation is estimated using exponential functions of soil depth and water content.

Plant growth is simulated with a basic heat unit system that correlates plant growth with temperature. Annual crop growth occurs from planting date to harvest date or until the accumulated heat units (growing degree days) equal the potential heat units (PHU) for the crop (Williams, 1995). Accumulated heat units drive potential growth, and actual growth is reduced from potential growth by factors that constrain plant growth, including temperature, solar radiation, soil moisture, soil aeration, labile nitrogen (N) and phosphorus (P), and soil strength. The processes simulated during the crop growth include leaf interception of solar radiation; conversion to biomass; division of biomass into roots, aboveground mass, and economic yield; root growth; water use; and nutrient uptake (Williams et al., 1989; Williams, 1995).

Runoff volume was estimated using a modification of the Soil Conservation Service (SCS) curve number (CN) technique (Mockus, 1969). The curve number retention parameter is estimated each day as a nonlinear function of potential evapotranspiration, precipitation, runoff, the previous day's retention parameter, and the maximum value of the retention parameter (associated with CN1, dry condition) for the site. The average moisture condition curve number (CN2) is input and used to calculate CN1 (Williams, 1995).

The tillage practice effects were simulated in EPIC by incorporating nutrients and crop residues within the plow depth, changing soil bulk density, and converting standing residue to flat residue. Water-induced erosion was simulated using MUST, which was in theory developed from sediment concentration basis (Williams, 1995). The equation is linked to, interacts with, and drives the other model components that act upon the soil profile.

Nutrient cycles were simulated for both the organic and mineral fractions of N and P. In EPIC, the fractions are subdivided into pools. Then nutrient additions, losses, and transformations between the different pools are calculated on a daily time-step through a series of coupled equations solved within a mass balance framework. These equations are closely tied to other model components including the hydrology component, which controls most of the transport processes, and the plant growth component, which handles nutrient uptake. Detailed descriptions of the mathematical relationships used to simulate nutrient dynamics can be found in Williams (1995).

MODEL CALIBRATION

The initial CN2, erosion control practice factor (PEC), RUSLE C factor coefficient (Parm(23)), and phosphorus sorption ratio (PSP) were identified to be influential to model outputs for this study site. These parameters were calibrated using observed monthly values of runoff (for calibrating the initial CN2), sediment (for calibrating PEC and Parm(23)), and soluble P losses (for calibrating PSP) for watershed Y13 in 2001-2002. The precipitation in the two calibration years represents intermediate values of precipitation for the study period (fig. 2). Both fallow and cropped conditions occurred in the calibration years, allowing the remaining five watersheds in 2001-2004 and the remaining data for Y13 in 2003-2004 to be used for validation. Calibration of organic N and P and NO_3-N losses and crop yield were not performed because they are driven by water and sediment dynamics. This procedure also reflects the typical EPIC nutrient load estimation for ungauged watersheds.

MODEL EVALUATION METHODS

The performance of EPIC was evaluated using statistical analyses to determine the quality and reliability of the predictions compared to observed values. Summary statistics, goodness-of-fit measures, and statistical tests were selected for the model evaluation based on suggestions given by Loague and Green (1991). These statistical measures, including ranges, best values, and interpretation of the statistical measures, were presented in Wang et al. (2006). Observed and simulated mean and standard deviation values were calculated to evaluate EPIC's reliability in replicating the probability distribution of measured data. The percent error (PE) was used to assess the systematic under- or over-prediction and the magnitude of error. The Nash-Sutcliffe efficiency or modeling efficiency (EF) (Nash and Sutcliffe, 1970) was used to compare predicted values to the mean of observed data. The EF describes the proportion of the variance of the observed values that is accounted for by the model. The square of the Pearson's product-moment correlation coefficient (R^2) was used to evaluate how accurately the model tracks the variation of observed values. The main difference between EF and R^2 is that EF can interpret the model performance in replicating individual observed values, while R^2 cannot. The standard error (SE) or root mean square error was used to estimate the standard deviation of prediction errors. The average deviation (AD) or mean absolute error was used to calculate the average difference between the predicted and observed values. The mathematical expressions for these analysis measures are:

$$\mathrm{PE} = \frac{P_i - O_i}{O_i} \times 100 \tag{1}$$

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

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

$$\mathrm{SE} = \sqrt{\sum_{i=1}^{n} \left(O_i - P_i\right)^2 / n} \tag{4}$$

$$\mathrm{AD} = \frac{1}{n} \sum_{i=1}^{n} \left|O_i - P_i\right| \tag{5}$$

where n is number of observations during the simulated period, O_i and P_i are observed and predicted values at each comparison point I, and $\overline{O}$ and $\overline{P}$ are arithmetic means of the observed and predicted values.

The statistics presented can be applied to non-sorted or sorted data. A FORTRAN program was developed to compute all these statistics. In general, the more rigorous tests compare non-sorted observed and predicted values (Loague and Green, 1991). In this study, only the EF and R^2 values were calculated with both non-sorted and sorted data for sediment and nutrient loss variables. In the sorted case, observed and simulated values are sorted independently in ascending order and then compared. Explicit standards for evaluating model performance using statistics such as the EF and R^2 values are not well established because the judgment of model performance is highly dependent on the purpose of the model application (Loague and Green, 1991; Chung et al., 1999, 2002). For this study, the criteria of EF > 0.4 and R^2 > 0.6 were chosen to assess if the model results were satisfactory. The standards are stricter than EF > 0.3 and R^2 > 0.5 as set by Chung et al. (1999, 2002). In addition to the R^2 calculation, linear regression analysis was also conducted to evaluate potential significant relationships between simulated and measured values by testing whether the regression line had a positive slope significantly different from zero at the 95% confidence level.

Model performance was also evaluated by conducting statistical tests using SAS (SAS, 1999). The paired t-test was used to determine if the difference between measured and predicted values was significantly different from zero. The one-way ANOVA and Kruskal-Wallis (non-parametric version of ANOVA) statistical tests were used to determine whether the model performance differed significantly among the poultry litter application watersheds and the control watershed. The EF values for comparing the monthly runoff, sediment and nutrient losses, and the percent errors of annual crop yields were used for this determination. The level of α = 0.05 (95% confidence level) was used in all statistical tests.

Results and Discussion

Calibration

Calibration of monthly runoff, sediment, and soluble P losses were performed for 2001-2002. The calibration process relied on adjusting the initial CN2, Parm(23), PEC, and PSP for watershed Y13 in 2001-2001 until the PE values were within ±5% and the EF values were ≥0.6 for the monthly comparisons. The calibration resulted in a CN2 value of 88, which is close to the CN value of 87 for these cultivated watersheds given in Harmel et al. (2004). Parm(23) is the exponential coefficient in the RUSLE C factor equation used in estimating the residue effect. For this study, a Parm(23) value of 1.5 was chosen, which is within the recommended range of 0.5 to 1.5 in the model documentation (www. public.iastate. edu/~elvis/epic_input_codes. html). The PEC factor was calibrated as 0.18 for 2001 and 0.1 for 2002. The value of 0.1 in 2002 was used for the remaining years. The values were within the range of 0.1 to 0.3 reported from a field study by Williams and Berndt (1977) for contour farming terraced fields with established grass waterways in Riesel. Terracing combined with contour farming and other conservation practices is more effective than those practices without the terraces (USDA, 1981). The terrace maintenance work for the study watershed started in October 2000. Because of the field construction work, it is reasonable that the PEC factor for 2001 is larger than for 2002-2004. PSP is a function of chemical and physical soil properties, and it is constrained within the limits 0.05 to 0.75 (Sharpley and Williams, 1990). The PSP was calibrated as 0.2.

Table 7. Observed and simulated summary statistics based on monthly values for Y13 for the 2001-2002 calibration period.

	Observed		Simulated		PE		
	Mean	SD	Mean	SD	(%)	EF	R^2
Runoff (mm)	27.35	38.65	26.98	31.36	−1.4	0.90	0.92
Sediment loss (kg ha^{-1})	0.58	1.39	0.61	1.04	5.0	0.65	0.67
Soluble P loss (kg ha^{-1})	0.09	0.16	0.09	0.12	1.8	0.83	0.86

Table 7 shows the summary statistics for the monthly comparisons for watershed Y13 in 2001-2002 after calibration. The percent errors between the simulated and observed mean monthly runoff, sediment, and soluble P losses were all within ±5%, and EF values were all ≥0.6. The variability between months was also captured by the model, as shown by close agreement in standard deviations and R^2 values of over 0.65.

Validation

Crop Yield

EPIC simulated crops yields well for all study fields. The average PE was −0.7% for corn yields in 2002-2003 and −0.8% for wheat yields in 2004 (table 8), and over-predictions occurred as often as under-predictions. The model performed well in predicting wheat yields, as the PE of each

Table 8. Observed and simulated annual crop yields.

Watershed	Year	Crop	Observed (Mg ha^{-1})	Simulated (Mg ha^{-1})	PE (%)
Y6	2002	Corn	5.70	6.08	6.7
	2003	Corn	4.80	5.29	10.2
	2004	Wheat	0.88	0.91	3.4
Y13	2002	Corn	7.20	6.90	−4.2
	2003	Corn	4.48	5.09	13.6
	2004	Wheat	2.30	2.20	−4.3
Y10	2002	Corn	6.91	7.06	2.2
	2003	Corn	5.42	4.93	−9.0
	2004	Wheat	2.34	2.34	0.1
Y8	2002	Corn	6.16	6.03	−2.1
	2003	Corn	5.91	5.61	−5.1
	2004	Wheat	2.08	2.06	−1.0
W12	2002	Corn	6.08	6.15	1.2
	2003	Corn	6.24	5.68	−9.0
	2004	Wheat	2.44	2.37	−2.9
W13	2002	Corn	7.03	7.12	1.3
	2003	Corn	5.71	4.99	−12.6
	2004	Wheat	2.06	2.12	2.9
Mean		Corn	5.97	5.93	−0.7
		Wheat	2.02	2.00	−0.8
P-value[a]		Corn	0.64		
		Wheat	0.55		

[a] Hypothesis H_0: the difference between simulated and observed yields is not significantly different from zero; H_0 is rejected if the P-value is less than the level of significance (α/2 = 0.025).

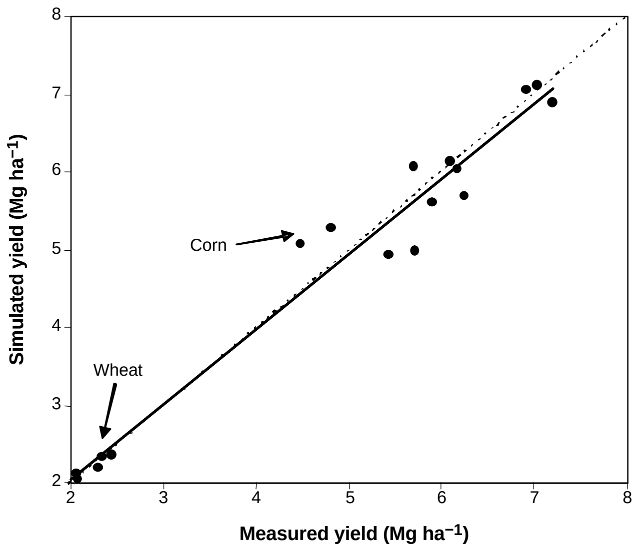

Figure 3. Simulated and measured crop yields.

simulated annual wheat yield was within 5% of the corresponding observed value. The PE values for annual corn yields were within 5% in 5 out of the 12 watershed corn years and within 10% in 9 out of 12 years (table 8). In general, the deviations between the measured and simulated corn yields were smaller in 2002 than in 2003 for all watersheds. This is probably because the 2002 (crop year) data were used for calibrating the model. Even though the crop yield was not calibrated, the yield is a direct function of water balance.

The EF, R^2, SE, and AD calculations were not performed for individual watersheds because only three years of yield data were available for each watershed for the study period. However, these statistical measures were calculated across the watersheds, for a total of 18 observations. The EF was 0.96 and R^2 was 0.97 for annual crop yields for all watersheds (fig. 3 and table 9). The observed and simulated means and standard deviations were in good agreement. The paired t-test for corn yields had a P-value of 0.64 and 0.55 for wheat yields, indicating that the simulated corn and wheat yields agree well with observed values. Thus, the null hypothesis, that the difference between simulated and observed values is not significantly different from zero, was accepted at the significance level of $\alpha = 0.05$. These statistical measures indicate that EPIC has the ability to accurately simulate corn and wheat yields for the study site under both inorganic and poultry litter fertilization.

Table 9. Statistics for simulated and measured crop yields (fig. 3).

No. of Obs.	Observed (Mg ha^{-1}) Mean	SD	Simulated (Mg ha^{-1}) Mean	SD	PE (%)	EF	R^2	SE	AD
18	4.65	2.06	4.61	2.02	−0.8	0.96	0.97	0.34	0.25

Table 10. Observed and simulated runoff summary statistics for each watershed based on annual values for the validation period.

Watershed	Observed (mm y^{-1}) Mean	SD	Simulated (mm y^{-1}) Mean	SD	PE (%)	EF	R^2
Y6	280.0	141.2	271.6	120.5	−3.0	0.95	0.97
Y13	295.7	265.9	280.2	207.0	−5.2	0.94	0.99
Y10	318.8	123.1	282.3	126.7	−11.4	0.83	0.95
Y8	238.7	119.3	259.0	110.5	8.5	0.93	0.97
W12	242.5	139.3	253.4	107.5	4.5	0.89	0.94
W13	257.8	137.3	248.7	107.5	−3.5	0.93	0.98

Runoff

The summary statistics of observed and simulated surface runoff based on annual values are compared by watershed in table 10. The model closely matched measured runoff with EF values larger than 0.8 and R^2 values larger than 0.9 for all watersheds. The simulated 4-year average annual runoff was consistent with observed values, as shown by the PE values of less than 5%. The errors are larger for watersheds Y8 (8.5%) and Y10 (−11.4%) but are well within the acceptable range.

Annual time series of observed and simulated surface runoff are plotted in figure 4. The comparisons between the observed and simulated annual runoff indicated that EPIC reliably tracked the annual observed runoff for all watersheds. The simulated annual runoff vs. annual precipitation ratios ranged from 15% to 37%, close to the observed runoff vs. precipitation ratios of 13% to 40%.

The time-series comparisons between observed and simulated monthly runoff are shown by watershed in figure 5. The EPIC-simulated values followed the observed trends reasonably well for all watersheds, although deviations were obvious across all watersheds for July 2002 and April 2004 when the runoff was over-predicted. On average, the watersheds received 44.8 mm rainfall on 16 July 2002, and the model simulated 9.2 mm runoff (20.5% runoff to

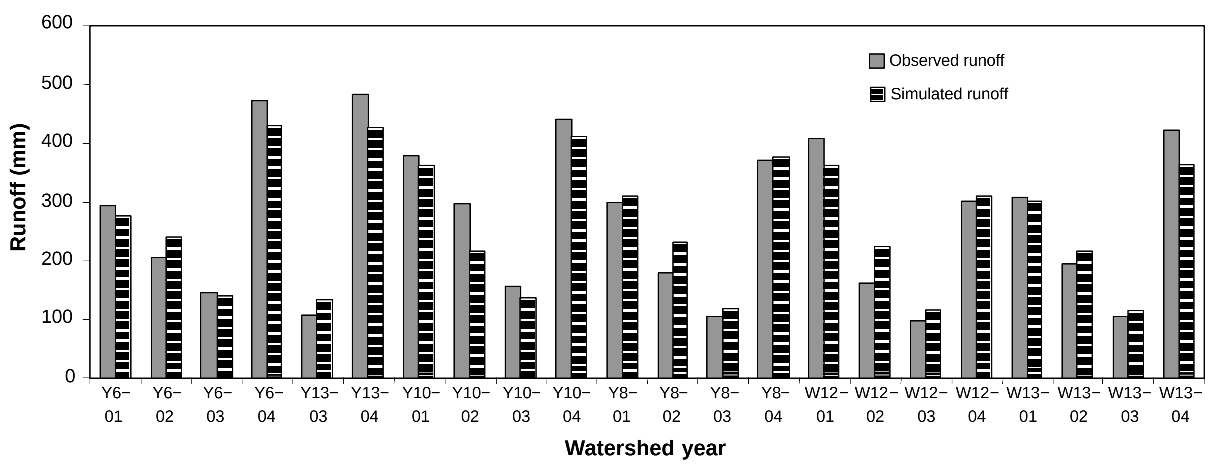

Figure 4. Observed and simulated annual runoff for the validation period.

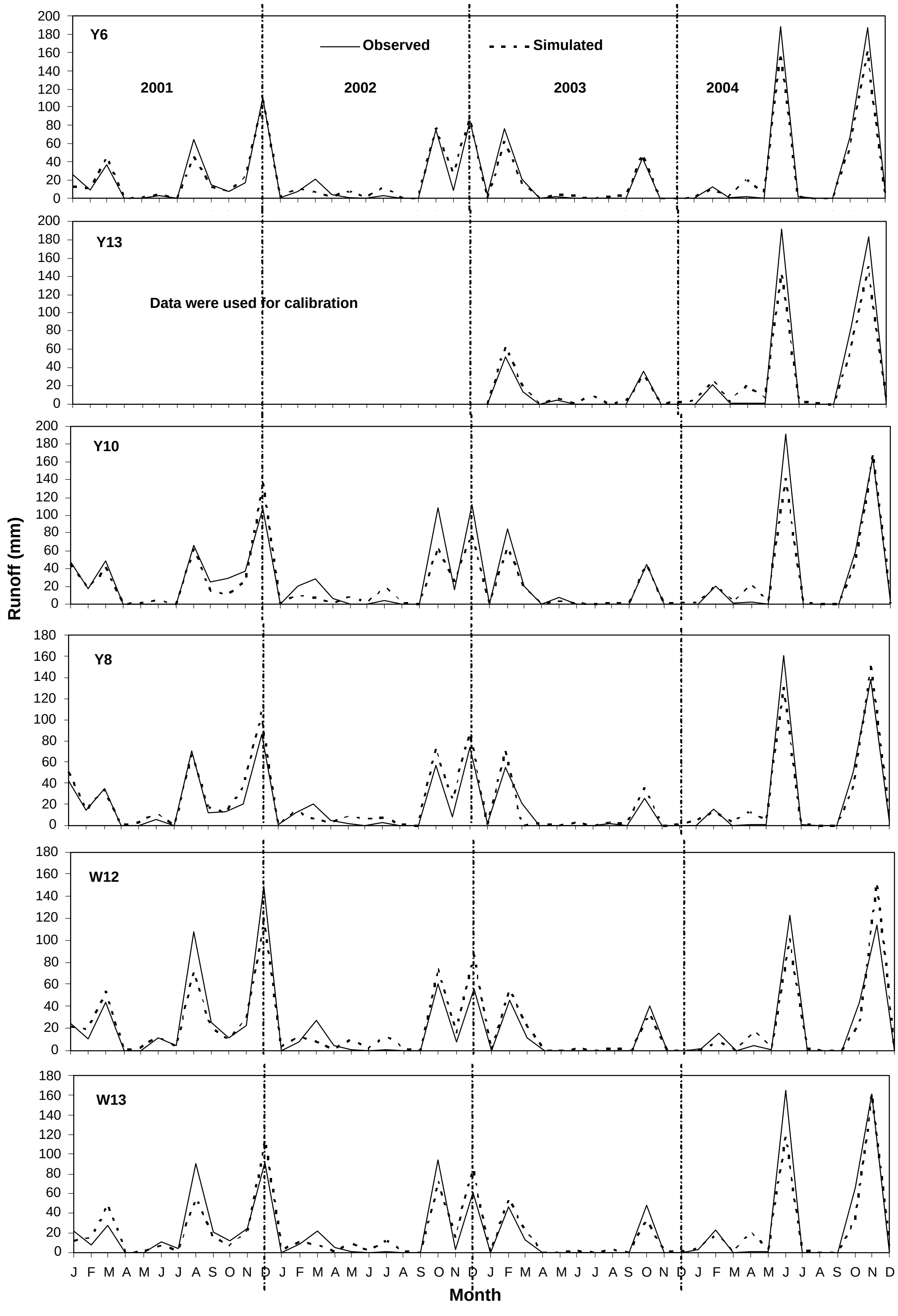

Figure 5. Observed and simulated monthly runoff for the six watersheds for the validation period.

rainfall ratio); however, the average measured runoff was only 1.7 mm (3.7% runoff to rainfall ratio). On 24 April 2004, the watersheds received 60.3 mm rainfall, and the model simulated 15 mm runoff (24.9% runoff over rainfall ratio); however, the average observation was only 1.3 mm (2.2% runoff over rainfall ratio). On a daily basis, the ratios of observed runoff vs. precipitation for both days (3.7% and 2.2%) were much lower than the lower boundary of the ratios for the

Table 11. Summary statistics for each watershed based on monthly runoff for the validation period.

Statistical Measure		Y6	Y13	Y10	Y8	W12	W13
		Watershed					
Number of observations		48	24	48	48	48	48
Observed (mm)	Mean	23.3	24.6	26.6	19.9	20.2	21.5
	SD	44.0	54.2	44.3	35.2	35.6	39.5
Simulated (mm)	Mean	22.6	23.3	23.5	22.4	21.1	20.7
	SD	38.7	42.2	39.0	36.1	34.7	35.5
PE (%)		−3.0	−5.2	−11.4	12.7	4.5	−3.5
EF		0.96	0.93	0.90	0.93	0.88	0.89
R^2		0.97	0.98	0.91	0.94	0.88	0.89
Regression slope		1.12	1.27	1.09	0.94	0.97	1.05
SE (mm $month^{-1}$)		8.8	13.7	13.6	9.4	12.1	13.2
AD (mm $month^{-1}$)		5.2	7.5	7.7	6.2	7.2	7.8
P−value[a]		0.59	0.62	0.12	0.06	0.61	0.70

[a] Hypothesis H_0: the difference between simulated and observed runoff is not significantly different from zero; H_0 is rejected if the P-value is less than the level of significance (α/2 = 0.025).

Table 12. Observed and simulated runoff summary statistics for each watershed based on daily values for the validation period.

Water-shed	Year	N	Observed ($mm\ d^{-1}$) Mean	Observed SD	Simulated ($mm\ d^{-1}$) Mean	Simulated SD	EF	R^2
Y6	2001	365	0.81	5.64	0.76	4.92	0.94	0.95
	2002	365	0.57	3.31	0.66	3.54	0.80	0.82
	2003	365	0.41	3.27	0.38	3.25	0.96	0.96
	2004	366	1.29	6.8	1.18	5.81	0.92	0.93
Y13	2003	365	0.30	2.61	0.32	2.59	0.94	0.94
	2004	366	1.32	6.68	0.99	5.24	0.82	0.84
Y10	2001	365	1.04	5.20	0.99	6.12	0.86	0.91
	2002	365	0.81	4.46	0.60	3.13	0.76	0.79
	2003	365	0.43	3.48	0.38	3.04	0.96	0.97
	2004	366	1.21	5.64	1.12	5.59	0.87	0.88
Y8	2002	365	0.82	4.51	0.96	5.64	0.84	0.90
	2001	365	0.49	2.70	0.63	3.58	0.56	0.76
	2003	365	0.29	2.15	0.33	2.71	0.72	0.83
	2004	366	1.02	5.25	1.02	5.08	0.91	0.91
W12	2001	365	1.12	8.07	0.99	6.10	0.89	0.94
	2002	365	0.45	2.90	0.62	3.42	0.70	0.78
	2003	365	0.27	2.69	0.32	2.64	0.89	0.89
	2004	366	0.83	4.76	0.85	4.89	0.84	0.85
W13	2001	365	0.85	5.62	0.82	5.55	0.88	0.89
	2002	365	0.53	3.69	0.59	3.32	0.78	0.78
	2003	365	0.29	3.06	0.32	2.59	0.84	0.85
	2004	366	1.15	6.50	0.99	5.24	0.85	0.87

annual totals (13%). However, the simulated ratios for both days (20.5% and 24.9%) were within the range of the ratios for the annual totals (13% to 40%). The daily time step, where the input is the daily total precipitation, might be the possible reason for the deviations.

The overall model performance was satisfactory on a monthly basis, with EF and R^2 larger than 0.85 for all watersheds (table 11). The P-values of the paired t-test indicated that the simulated surface runoff agrees well with observed values for all watersheds.

To further assess EPIC's performance, simulated daily runoff was compared with observed daily values. The statistical measures are summarized by watershed and year in table 12. The EF values for daily performance were larger than 0.55. The R^2 values were larger than 0.75 for all 22 watershed years. The goodness-of-fit measures indicated that the daily variations in the observed surface runoff were satisfactorily explained by the model.

Sediment and Nutrient Losses

EPIC satisfactorily simulated annual sediment, organic N and P, soluble P, and NO_3-N losses with R^2 values ranging from 0.63 to 0.94 (fig. 6). The slopes were significantly different from zero at the 95% confidence level. The summa−

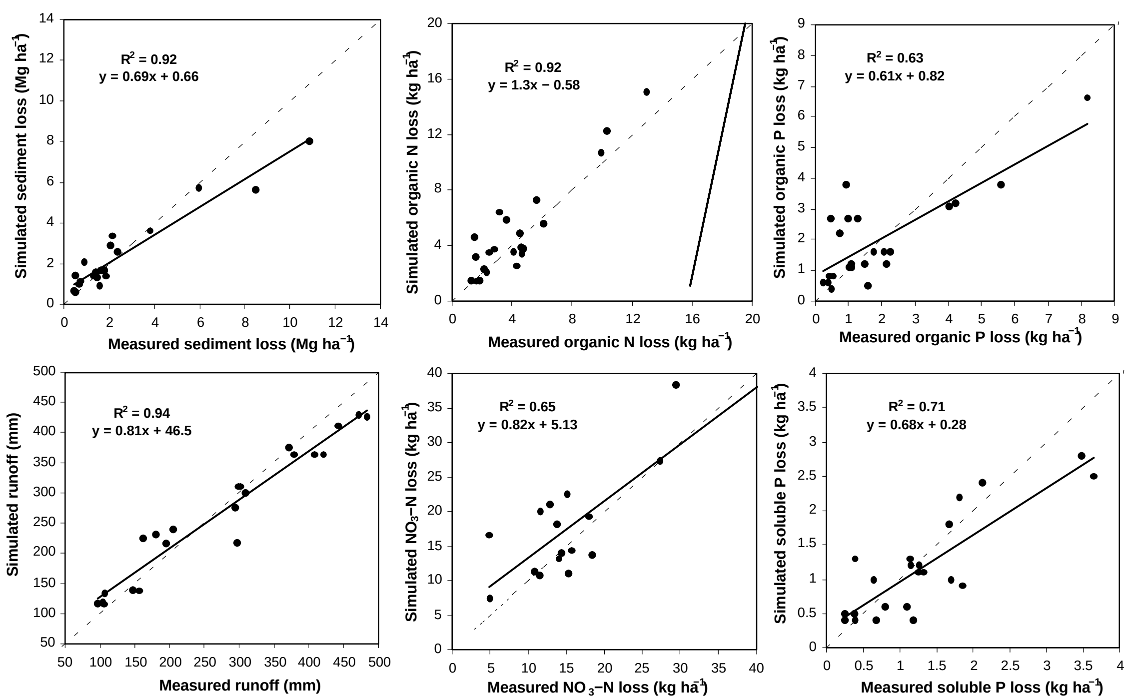

Figure 6. Simulated and measured annual runoff, sediment, and nutrient losses for the six watersheds for the validation period.

Table 13. Observed and simulated sediment and nutrient losses summary statistics based on average annual total values for the validation period.

Loss	Observed		Simulated						
	Mean	SD	Mean	SD	SE	AD	PE (%)	EF	R^2
Sediment (Mg ha^{-1})	2.41	2.69	2.31	1.90	0.99	0.61	−4.1	0.86	0.92
Organic N (kg ha^{-1})	4.96	4.30	5.85	5.93	2.23	1.44	17.9	0.72	0.92
Organic P (kg ha^{-1})	1.81	1.91	1.91	1.46	1.14	0.85	5.5	0.63	0.63
NO_3-N (kg ha^{-1})	18.59	12.33	20.38	12.53	7.69	5.48	9.7	0.59	0.65
Soluble P (kg ha^{-1})	1.30	0.92	1.16	0.74	0.50	0.38	−10.3	0.69	0.71

ry statistics of observed and simulated average annual sediment, organic N and P, soluble P, and NO_3-N losses are compared in table 13. The simulated average values are in good agreement with the measured values for sediment, N, and P losses. The model performance was satisfactory, with EF values larger than 0.55 and R^2 values larger than 0.6.

Figure 7 shows the time-series comparisons between the observed and simulated annual total sediment losses and organic N losses for each watershed year. The time-series comparisons between observed and simulated annual total organic and soluble P and NO_3-N losses are shown in figures 8 and 9. The simulated values followed the observed trends reasonably well. A great amount of sediment was lost during 2001 (fig. 7), although 2004 had higher precipitation

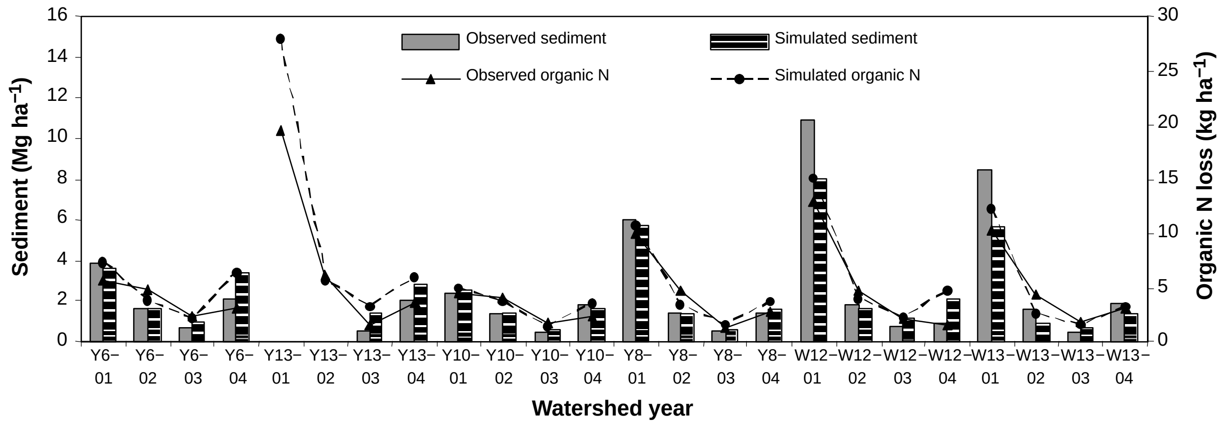

Figure 7. Observed and simulated annual sediment and organic N losses for the validation period.

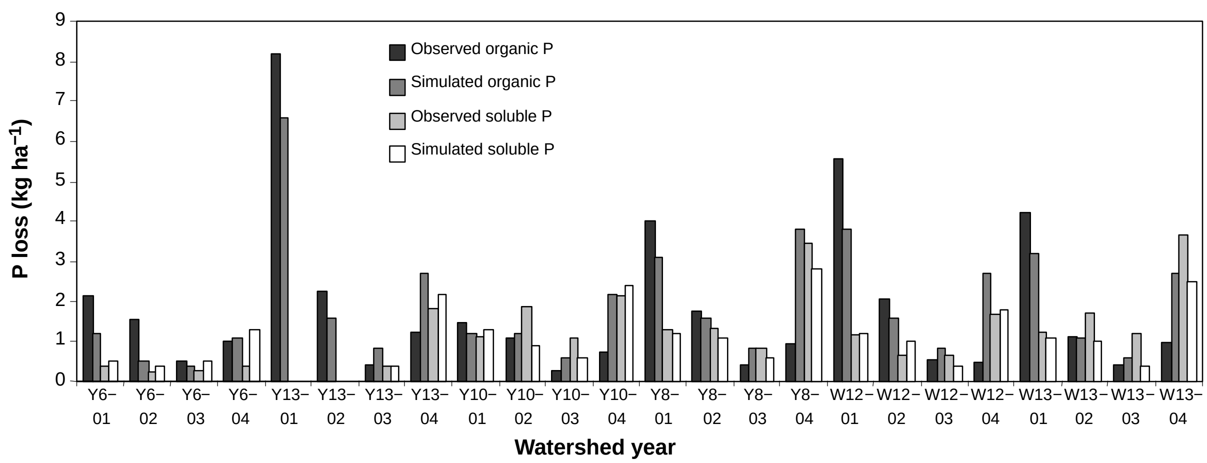

Figure 8. Observed and simulated annual organic P and soluble P losses for the validation period.

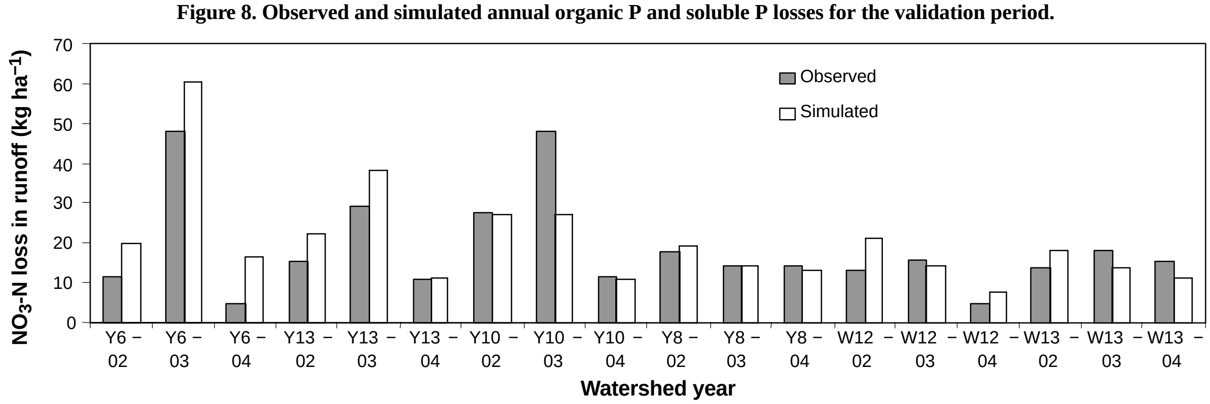

Figure 9. Observed and simulated annual NO_3-N losses via surface runoff for the validation period.

Table 14. Observed and simulated environmental indicator summary statistics based on monthly values for the validation period.

Statistical Measure		Y6	Y13	Y10	Y8	W12	W13
Sediment							
Observed ($Mg\ ha^{-1}$)	Mean	0.17	0.11	0.13	0.20	0.30	0.26
	SD	0.37	0.28	0.27	0.65	0.90	0.79
Simulated ($Mg\ ha^{-1}$)	Mean	0.20	0.18	0.13	0.19	0.27	0.18
	SD	0.34	0.32	0.21	0.37	0.50	0.37
Non-sorted	EF	0.40	0.56	0.72	0.47	0.60	0.47
	R^2	0.47	0.72	0.72	0.50	0.67	0.57
Sorted	EF	0.95	0.77	0.81	0.66	0.71	0.60
	R^2	0.96	0.83	0.95	0.75	0.84	0.79
P-value[a]		0.52	0.16	0.84	0.98	0.72	0.34
Organic N loss							
Observed ($kg\ ha^{-1}$)	Mean	0.33	0.64	0.27	0.39	0.44	0.41
	SD	0.70	1.67	0.52	1.09	1.15	0.91
Simulated ($kg\ ha^{-1}$)	Mean	0.41	0.89	0.28	0.40	0.54	0.41
	SD	0.60	1.42	0.39	0.63	0.85	0.69
Non-sorted	EF	0.31	0.65	0.51	0.48	0.45	0.63
	R^2	0.38	0.67	0.51	0.50	0.46	0.64
Sorted	EF	0.91	0.85	0.88	0.66	0.92	0.87
	R^2	0.94	0.88	0.92	0.74	0.85	0.91
P-value[a]		0.35	0.08	0.80	0.92	0.42	0.99
Organic P loss							
Observed ($kg\ ha^{-1}$)	Mean	0.11	0.25	0.07	0.15	0.18	0.15
	SD	0.23	0.73	0.15	0.46	0.51	0.37
Simulated ($kg\ ha^{-1}$)	Mean	0.07	0.25	0.11	0.19	0.18	0.16
	SD	0.10	0.40	0.20	0.33	0.31	0.29
Non-sorted	EF	0.27	0.50	−0.18	0.14	0.25	0.43
	R^2	0.33	0.55	0.37	0.22	0.26	0.44
Sorted	EF	0.61	0.61	0.73	0.75	0.79	0.90
	R^2	0.95	0.71	0.91	0.79	0.90	0.95
P-value[a]		0.13	0.93	0.16	0.47	0.97	0.90
Soluble P loss							
Observed ($kg\ ha^{-1}$)	Mean	0.03	0.09	0.13	0.14	0.09	0.16
	SD	0.05	0.21	0.25	0.34	0.18	0.36
Simulated ($kg\ ha^{-1}$)	Mean	0.06	0.11	0.11	0.12	0.09	0.10
	SD	0.12	0.22	0.21	0.24	0.18	0.22
Non-sorted	EF	−1.40	0.96	0.74	0.82	0.86	0.74
	R^2	0.73	0.97	0.75	0.88	0.87	0.89
Sorted	EF	0.41	0.96	0.89	0.90	0.98	0.79
	R^2	0.94	0.98	0.92	0.99	0.98	0.96
P-value[a]		0.007[b]	0.28	0.26	0.25	0.48	0.03
NO_3-N loss							
Observed ($kg\ ha^{-1}$)	Mean	1.80	1.54	2.42	1.29	0.93	1.32
	SD	5.21	3.84	6.11	2.59	2.18	2.95
Simulated ($kg\ ha^{-1}$)	Mean	2.70	2.01	1.83	1.29	1.20	1.20
	SD	7.96	5.28	4.11	2.03	2.08	2.01
Non-sorted	EF	0.44	0.51	0.80	0.66	0.52	0.67
	R^2	0.84	0.77	0.88	0.66	0.57	0.69
Sorted	EF	0.46	0.64	0.85	0.93	0.90	0.84
	R^2	0.86	0.86	0.96	0.97	0.92	0.92
P-value[a]		0.16	0.29	0.18	0.99	0.30	0.66

Watershed columns: Y6, Y13, Y10, Y8, W12, W13.

[a] Hypothesis H_0: the difference between simulated and observed values is not significantly different from zero; H_0 is rejected if the P-value is less than the level of significance ($\alpha/2 = 0.025$).

[b] The only result with H_0 rejected.

Table 15. Statistical tests for hypothesis H_0: the EPIC performances for different poultry litter application rates are not significantly different.

	One-way ANOVA		Kruskal-Wallis Test	
	P-value	Result	P-value	Result
Crop yield	0.40	Do not reject H_0	0.25	Do not reject H_0
Runoff	0.12	Do not reject H_0	0.1	Do not reject H_0
Sediment	0.59	Do not reject H_0	0.72	Do not reject H_0
Organic N loss	0.07	Do not reject H_0	0.06	Do not reject H_0
Organic P loss	0.17	Do not reject H_0	0.35	Do not reject H_0
Soluble P loss	<0.0001	Reject H_0	0.01	Reject H_0
NO_3-N loss	0.42	Do not reject H_0	0.17	Do not reject H_0

(see annual precipitation plotted in fig. 2). Correspondingly, more organic N and P transported by sediment were lost in 2001 than in 2004 (figs. 7 and 8). A greater amount of soluble P was lost in 2004 than in 2001 (fig. 8) due to higher precipitation and higher runoff in 2004. Although 2003 had the lowest precipitation and runoff, more NO_3-N was lost through surface runoff in 2003 than in other years (fig. 9), except for Y8. EPIC simulated all of these variations reasonably well. These results indicate that EPIC can accurately predict sediment loss and nutrient fate and transport from fields with poultry litter fertilization.

The EF values based on monthly comparisons between the observed and simulated environmental indicators were generally larger than 0.4 (in 25 out of 30 tests) (table 14). However, the sorted EF values were all above 0.4, and the sorted R^2 values were all above 0.6. The P-values of the paired two-tailed t-test indicated that the simulated sediment, organic N and P, and soluble P, and NO_3-N losses agree well with observed values on the monthly basis. The null hypothesis, that the difference between observed and simulated values is not significantly different from zero, was accepted for all watersheds at the significance level of α = 0.05, except for the soluble P losses for watershed Y6. However, the variability between months was captured by EPIC for the soluble P losses for watershed Y6, as evidenced by the R^2 value of 0.73.

Statistical Test of Model Performance for Different Poultry Litter Rates

The statistical tests to determine if the EPIC version 3060 performance differed among different poultry litter application rates are shown in table 15. Both the one-way ANOVA and the Kruskal-Wallis (nonparametric version of ANOVA) tests for EF values of monthly comparisons of runoff, sediment and nutrient losses, and PE values of crop yields indicated that the reliability of the model is not significantly different among the poultry litter application watersheds and the control watershed, except soluble P losses due to the relative low EF values for the control watershed (see EF values in table 14).

CONCLUSIONS

Calibration of monthly runoff, sediment, and soluble P losses were performed for 2001-2002 for watershed Y13 near Riesel, Texas. The calibration process relied on adjusting the initial CN2, Parm(23), PEC, and PSP until the percent errors (PE) were within ±5% and the modeling efficiencies (EF) were ≥0.6 for the monthly comparisons. Calibrations of organic N, organic P, and NO_3-N losses and crop yield were not performed because they are largely determined by water and sediment dynamics. The remaining five watersheds in 2001-2004 and the remaining data in 2003-2004 for Y13 were used to validate EPIC.

The calibrated model simulated annual wheat yields within 5% of the measured yields. Simulated annual corn yields were within 5% in 5 out of the 12 watershed corn years and within 10% in 9 out of the 12 watershed corn years. The PE values for both annual average corn yield and average wheat yield across six watersheds were under 1%. The EF was 0.96, and R^2 was 0.97 based on annual crop yields.

The statistical tests and graphical displays of the observed and simulated surface runoff revealed that the runoff values predicted by EPIC on an annual, monthly, and daily basis were satisfactory for all watersheds. Both the EF and R^2 values were larger than 0.8 for the annual runoff comparison and larger than 0.85 for the monthly comparison. The EF values for daily performance measure were larger than 0.55, and R^2 values ranged from 0.76 to 0.97. The goodness-of-fit measures indicated that the daily variations in the observed surface runoff were satisfactorily explained by the model.

The sediment, organic N and P, soluble P, and NO_3-N losses predicted by EPIC on an annual basis were satisfactory. The R^2 values based on the annual comparisons across all watersheds for these environmental indicators ranged from 0.63 to 0.92, and the slopes were significantly different from zero at the 95% confidence level. The EF values ranged from 0.59 to 0.87. The EF values based on monthly comparisons between the observed and simulated environmental indicators were generally larger than 0.4 (in 25 out of 30 tests). However, the sorted EF values were all above 0.4, and the sorted R^2 values were all above 0.6.

Paired t-tests for annual crop yield, monthly runoff, monthly sediment, and nutrient losses showed that the EPIC-simulated values were not significantly different from that of observed values at the significance level of $\alpha = 0.05$, except for monthly soluble P losses for Y6. The one-way ANOVA and the Kruskal-Wallis tests for EF values of monthly comparisons of runoff, sediment and nutrient losses, and PE values of crop yields indicated that the reliability of the model is not significantly different among the poultry litter application watersheds and the control watershed, except soluble P losses due to the relative low EF values for the control watershed. These statistical tests indicate that EPIC was able to replicate the environmental impacts of poultry litter application on runoff, water quality, and crop yields.

REFERENCES

Allen, P. M., R. D. Harmel, J. G. Arnold, B. Plant, J. Yeldermann, and K. W. King. 2005. Field data and flow system response in clay (vertisol) shale terrain, north central Texas, USA. *Hydrological Processes* 19(14): 2719-2736.

Apezteguía, H. P., R. C. Izaurralde, and R. Sereno. 2002. Simulation of soil organic matter dynamics as affected by land use and agricultural practices in semiarid Córdoba, Argentina. *Agronomy Abstracts*, CD-ROM. Madison, Wisc.: ASA-CSSA-SSSA.

Babcock, B. A., J. Wu, T. Campbell, P. W. Gassman, P. D. Mitchell, T. Otake, M. Siemers, and T. M. Hurley. 1997. *RAPS 1997: Agriculture and the Environmental Quality.* Ames, Iowa: Iowa State University, Center for Agricultural and Rural Development.

Bernardo, D. J., H. P. Mapp, G. J. Sabbagh, S. Geleta, K. B. Watkins, R. L. Elliott, and J. F. Stone. 1993. Economic and environmental impacts of water quality protection policies: 2. Application to the Central High Plains. *Water Resources Res.* 29(9): 3081-3091.

Bernardos, J. N., E. F. Viglizzo, V. Jouvet, F. A. Lértora, A. H. Pordomingo, and F. D. Cid. 2001. The use of EPIC model to study the agroecological change during 93 years of farming transformation in the Argentine pampas. *Agric. Syst.* 69(3): 215-234.

Bobba, A. G., V. P. Singh, and L. Bengtsson. 1995. Application of uncertainty analysis to groundwater pollution modeling. *Environ. Geol.* 26(2): 89-96.

Brannan, K. M., S. Mostaghimi, P. W. McClellan, and S. Inamdar. 2000. Animal waste BMP impacts on sediment and nutrient losses in runoff from the Owl Run watershed. *Trans. ASAE* 43(5): 1155-1166.

Brown, R. A., and N. J. Rosenberg. 1999. Climate change impacts on the potential productivity of corn and winter wheat in their primary United States growing regions. *Climatic Change* 41(1): 73-107.

Chung, S. W., P. W. Gassman, L. A. Kramer, J. R. Williams, and R. Gu. 1999. Validation of EPIC for two watersheds in southwest Iowa. *J. Environ. Qual.* 28(3): 971-979.

Chung, S. W., P. W. Gassman, R. Gu, and R. S. Kanwar. 2002. Evaluation of EPIC for assessing tile flow and nitrogen losses for alternative agricultural management systems. *Trans. ASAE* 45(4): 1135-1146.

Eghball, B., and J. F. Power. 1994. Beef cattle feedlot manure management. *J. Soil and Water Conserv.* 49(2): 113-122.

Gass, W. B. 1987. *Plant Soil and Water Testing Laboratory Recommendations.* College Station, Texas: Texas Agricultural Extension Service.

Gassman, P. W., J. R. Williams, V. W. Benson, R. C. Izaurralde, L. M. Hauck, C. A. Jones, J. D. Atwood, J. R. Kiniry, and J. D. Flowers. 2004. Historical development and applications of the EPIC and APEX models. ASAE Paper No. 042097. St. Joseph, Mich.: ASAE.

Gilley, J. E., and L. M. Risse. 2000. Runoff and soil loss as affected by the application of manure. *Trans. ASAE* 43(6): 1583-1588.

Hargreaves, G. H., and Z. A. Samani. 1985. Reference crop evapotranspiration from temperature. *Applied Eng. in Agric.* 1(2): 96-99.

Harmel, R. D., and K. W. King. 2005. Uncertainty in measured sediment and nutrient flux in runoff from small agricultural watersheds. *Trans. ASAE* 48(5): 1713-1721.

Harmel, R. D, K. W. King, and R. M. Slade. 2003. Automated storm water sampling on small watersheds. *Applied Eng. in Agric.* 19(6): 667-674.

Harmel, R. D., H. A. Torbert, B. E. Haggard, R. Haney, and M. Dozier. 2004. Water quality impacts of converting to a poultry litter fertilization strategy. *J. Environ. Qual.* 33(6): 2229-2242.

King, K. W., C. W. Richardson, and J. R. Williams. 1996. Simulation of sediment and nitrate loss on a vertisol with conservation tillage practices. *Trans. ASAE* 39(6): 2139-2145.

Loague, K., and R. E. Green. 1991. Statistical and graphical methods for evaluating solute transport models: Overview and application. *J. Contaminant Hydrology* 7(1-2): 51-73.

Lovejoy, S. B., J. G. Lee, T. O. Randhir, and B. A. Engel. 1997. Research needs for water quality management in the 21st century: A special decision support system. *J. Soil and Water Conserv.* 52(1): 18-22.
Mausbach, J. M., and A. R. Dedrick. 2004. The length we go: Measuring environmental benefits of conservation practices in the CEAP. *J. Soil and Water Conserv.* 59(5): 96A.
Mitchell, G., R. H. Griggs, V. Benson, and J. Williams. 1996. EPIC user's guide version 5300: The EPIC model environmental policy integrated climate (formerly erosion productivity impact calculator). Temple, Texas: The Texas Agricultural Experiment Station, Blackland Research Center.
Mockus, V. 1969. Hydrologic soil-cover complexes. In *SCS National Engineering Handbook: Section 4. Hydrology,* 10.1-10.24. Washington, D.C.: USDA Soil Conservation Service.
Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part I − A discussion of principles. *J. Hydrology* 10(3): 282-290.
Pierson, S. T., M. L. Cabrera, G. K. Evanylo, P. D. Schroeder, D. E. Radcliffe, H. A. Kuykendall, V. W. Benson, J. R. Williams, C. S. Hoveland, and M. A. McCann. 2001. Phosphorus losses from grasslands fertilized with broiler litter: EPIC simulations. *J. Environ. Qual.* 30(5): 1790-1795.
Potter, K. N., J. R. Williams, F. J. Larney, and M. S. Bullock. 1998. Evaluation of EPIC's wind erosion submodel using data from southern Alberta. *Canadian J. Soil Sci.* 78(3): 485-492.
Rawls, W. J., D. L. Brakensiek, and B. Soni. 1983. Agricultural management effects of soil water processes: Part I − Soil water retention and Green and Ampt infiltration parameters. *Trans. ASAE* 26(6): 1752-1753.
Ribaudo, M. O., N. R. Gollehon, and J. Agapoff. 2003. Land application of manure by animal feeding operations: Is more land needed? *J. Soil and Water Conserv.* 58(1): 30-38.
Rinaldi, M. 2001. Application of EPIC model for irrigation scheduling of sunflower in southern Italy. *Agric. Water Manage.* 49(3): 185-196.
SAS. 1999. SAS/STAT user's guide, Version 8.2. Cary, N.C.: SAS Institute, Inc.
Sharpley, A. N., and J. R. Williams. 1990. EPIC − Erosion/productivity impact calculator: 1. Model documentation. Technical Bulletin No. 1768. Washington, D.C.: USDA Agricultural Research Service.
Sugiharto, T., T. H. McIntosh, R. C. Uhrig, and J. J. Lardinois. 1994. Modeling alternatives to reduce dairy farm and watershed nonpoint-source pollution. *J. Environ. Qual.* 23(1): 18-24.
USDA. 1981. Predicting rainfall erosion losses: A guide to conservation planning. Washington, D.C.: USDA.
USDA and USEPA. 1999. Unified national strategy for animal feeding operations. Washington, D.C.: USDA and USEPA.
Wang, X., C. T. Mosley, J. R. Frankenberger, and E. J. Kladivko. 2006. Subsurface drain flow and crop yield predictions for different drain spacings using DRAINMOD. *Agric. Water Manage.* 79(2): 113-136.
Williams, J. R. 1990. The erosion-productivity impact calculator (EPIC) model: A case history. *Phil. Trans. Royal Soc. London* 329: 421-428.
Williams, J. R. 1995. The EPIC model. In *Computer Models of Watershed Hydrology,* 909-1000. V. P. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.
Williams, J. R., and H. D. Berndt. 1977. Sediment yield prediction based on watershed hydrology. *Trans. ASAE* 20(6): 1100-1104.
Williams, J. R., and A. N. Sharpley. 1989. EPIC − Erosion/productivity impact calculator: 1. Model documentation. Technical Bulletin No. 1768. Washington, D.C.: USDA Agricultural Research Service.
Williams, J. R., C. A. Jones, and P. T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Trans. ASAE* 27(1): 129-144.
Williams, J. R., C. A. Jones, J. R. Kiniry, and D. A. Spanel. 1989. The EPIC crop growth model. *Trans. ASAE* 32(2): 497-511.
Williams, J. R., M. Nearing, A. Nicks, E. Skidmore, C. Valentin, K. King, and R. Savabi. 1996. Using soil erosion models for global change studies. *J. Soil Water Conserv.* 51(5): 381-385.