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Soil Water Modeling in South Georgia using WEPP Hydrology

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Abstract. *Soil water is a fundamental component of any field or watershed scale water balance. A basin scale soil water model is being assembled using the runoff and water redistribution functions within the WEPP model. The model uses the runoff, infiltration, plant uptake, and water redistribution functions within WEPP to make predictions of soil water within the vadose zone. The WEPP model was evaluated using runoff and soil water data collected from South Georgia experimental plots where the effects of conservation tillage were examined. WEPP model simulations of surface runoff from the plots were within 30% of the observed annual runoff for the years used for calibration but varied considerably for the years used for model validation. In general, results were better for the simulations of the strip tillage system than for the conventional tillage system. Simulations of soil water in the upper profile were useful for examining seasonal patterns and for examining differences between the two tillage systems.*

Keywords. *soil moisture, infiltration, runoff, computer simulation, conservation tillage*

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Soil Water Modeling in South Georgia using WEPP Hydrology[1,2]

David D. Bosch, Dennis C. Flanagan, and Frank M. Davis

Introduction

Soil moisture can have a dominant impact upon runoff processes. Wet surface soil conditions can dramatically increase the probability of extreme runoff events, whereas dry surface conditions can enhance infiltration. Natural resource models require accurate predictions of soil moisture for simulations of runoff, water quality, crop growth, and many other natural processes.

The USDA-Agricultural Research Service (ARS) initiated the Watershed Erosion Prediction Project (WEPP) to develop new and improved erosion prediction technology (Lane and Nearing, 1989). The model is considered state-of-the-art technology for the prediction of runoff, infiltration, and erosion. Two scales currently exist, the hillslope or landscape version, and the watershed scale version. Both versions were released in 1995 (Flanagan and Livingston, 1995; Flanagan and Nearing, 1995). Since that time, the hillslope model has undergone considerable testing of the hydrology and the erosion components (Zhang et al., 1996; Bjorneberg et al., 1999; Yu, 1999; Oztekin et al, 2001; Zhang, 2004).

The objectives of this research were:

1. Evaluate the components within the WEPP model which simulate soil moisture conditions

2. Test the soil moisture components using data collected for a typical South Georgia upland field

3. Compare the effects of conservation tillage using the WEPP simulations

Methods

The hydrology component of the WEPP hillslope model was used to simulate hydrologic conditions in two plot sized fields in South Georgia. Components describing surface runoff, infiltration, and redistribution of soil moisture within the upper soil profile were tested using data collected at the site.

Field Site Description

A 1.9 ha parcel on the University of Georgia Gibbs Farm located in Tift County, GA was used for the analysis. The field site has been used to collect hydrologic and water quality data for comparing conventional and conservation tillage systems (Bosch et al., 2005). The site has been in a cotton / peanut rotation since 1998. The parcel was divided into six 0.2 ha plots with a seventh 0.4 ha plot at the top of the hillslope set aside for companion rainfall simulation studies (Fig. 1). Plots 1, 3, and 5 were in conventional tillage while plots 2, 4, and 6 were strip tilled (Bosch et al., 2005). Data from plots 1-6 were used for this analysis. Precipitation, surface runoff, and subsurface tile flow from 1999 through 2005 were used for this analysis. Runoff data collection, surface and subsurface tile flow, began on 18 March 1999. Precipitation data

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[1] Contribution from the USDA-ARS, Southeast Watershed Research Laboratory, P.O. Box 748, Tifton, GA 31793, in cooperation with Univ. of Georgia Coastal Plain Exp. Stn.

[2] All programs and services of the U.S. Department of Agriculture are offered on a nondiscriminatory basis without regard to race, color, national origin, religion, sex, age, marital status, or handicap.

collection began on 1 January 1999. Annual evapotranspiration rates from the plots were estimated by assuming the change in storage within the soil was negligible over the year and taking the difference between the water inputs (precipitation and irrigation) and the water outputs (surface runoff and subsurface tile flow).

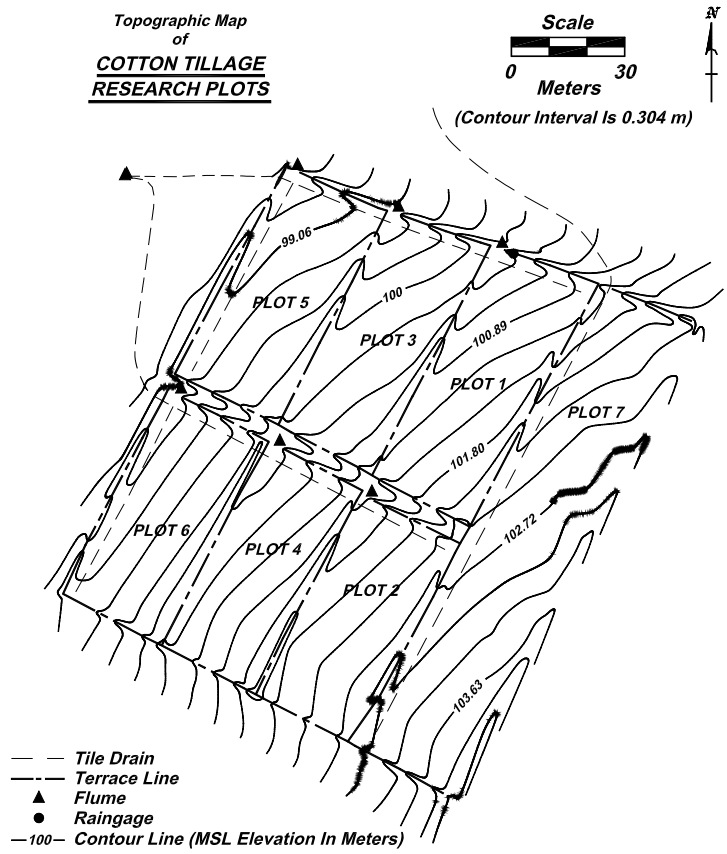

Figure 1. Topographic map of the research plots.

A soil classification of the site was conducted in 1998 prior to establishing the plots. The soil is classified as a Tifton loamy sand. Tifton soils are typically deep and well drained (Calhoun, 1983). Permeability's tend to be moderate and available water capacity medium. The surface soil at the site is well drained, with a sand horizon at the immediate surface extending to approximately 25 cm. The surface horizon is underlain by a loamy sand to a sandy loam layer extending to approximately 50 cm. The subsoil is a sandy loam to a sandy clay loam extending to approximately 3 m. Clay fractions increase with depth, varying from 3% at the surface to 40% in the lower horizons. The depth to the argillic horizon varies from 25 cm to 50 cm across the plots. Textures of the top 30 cm of the profile vary from 75% to 92% sand. Hydraulic conductivity tends to decrease with depth.

Plots 1 through 6, with a surface drainage area of approximately 0.2 ha each, were surrounded by 0.6 m high earthen berms. The berms facilitated surface drainage to the northwest corner of each plot (Fig. 1). The plots are tile drained to capture shallow subsurface drainage at 1.2 m

depth from each of the tillage systems. Detailed descriptions of the hydrologic and climatic measurements collected at the site are provided in Bosch et al. (2005).

Prior data collected at the site indicate the average annual area weighted surface runoff is 304 mm yr^{-1} (29% of the annual rainfall) for the conventionally tilled plots and 168 mm yr^{-1} (16% of the annual rainfall) from the strip tilled plots for the period from 1999 to 2003 (Bosch et al., 2005). Subsurface losses from the conventionally tilled plots were approximately 9% of the annual rainfall while they were 16% of the annual rainfall from the strip tilled plots. Overall, 63 mm more water was lost annually from the conventional tilled plots than from the strip tilled plots.

Soil moisture measurements have been collected at 50, 130, and 300 mm depths in plots 1 (conventional till) and 2 (strip till). Soil moisture data have been collected continuously since March 3, 2000, aside from brief periods when the probes had to be removed for tillage or other operations. Soil moisture was measured using the Stevens-Vitel Hydra probe (Stevens-Vitel Inc.[3]). The Hydra probe is a capacitance based probe which measures the apparent dielectric constant of the soil surrounding the sensor. The dielectric is related to the soil-water content using expressions provided by the manufacturer. The Hydra probe has been tested for the Tifton soil and yielded accurate estimates of soil moisture (Bosch, 2004).

A comparison was made between observed soil water conditions in the top 400 mm of the profile and the simulated soil water conditions. The WEPP model divides the soil layers into 100 mm layers down to 200 mm and into 200 mm layers between 200 mm and 1800 mm depth. The model reports equivalent soil water (mm) for each of these layers. The soil water measurements collected from the plots were converted into equivalent water for comparison to the model output. Soil water measurements made at 50 mm were assumed representative of the layer from 0 to 100 mm, those measured at 130 mm representative of the layer from 100 to 200 mm, and those measured at 300 mm representative of the layer from 200 to 400 mm. For both the model simulations and the observed data, the equivalent soil water in all of the layers was summed to derive the equivalent soil water in the top 400 mm of the profile.

WEPP Soil Moisture Components

The hydrology component of WEPP computes infiltration, runoff, soil evaporation, plant transpiration, soil water percolation, plant and residue interception of rainfall, depressional storage, and soil profile drainage by subsurface tiles (Savabi and Williams, 1995). Infiltration is calculated using a modified Green and Ampt infiltration equation (Green and Ampt, 1911). Runoff is computed using the kinematic wave equations or an approximation to the kinematic wave solutions obtained for a range of rainfall intensity distributions, hydraulic roughness, and infiltration parameter values. The water balance routines are a modification of the SWRRB water balance (Williams et al., 1985). Additional details of the infiltration and runoff component are provided in Savabi and Williams (1995).

The cropland plant growth routines in WEPP are based on the EPIC model (Williams et al., 1989). The model uses daily accumulated heat units and photosynthetic active radiation for estimating biomass production, and a harvest index for dividing biomass at harvest between grain and residue. Canopy height, canopy cover, and leaf area index are all functions of above ground live biomass (Arnold et al, 1995).

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[3] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the products listed by USDA.

The input files required by WEPP include: climate, slope, soils, plant and land management, and irrigation. The climate data includes daily or breakpoint precipitation, temperatures, solar radiation, and wind information. Input can be provided using the climate generator program, CLIGEN (Nicks, 1985), or developed from observed data. The slope input file contains information about the landscape geometry. The soils input file contains all of the textural and infiltration related coefficients for the surface soil and subsurface layers. The plant and management input file contains all of the information needed by the WEPP model related to plant parameters, tillage sequences, and tillage implement parameters, plant and residue management, initial conditions, contouring, subsurface drainage, and crop rotations.

Climatic input

Precipitation data were collected at the field site and used for the simulation period from 1999 to 2005. Daily precipitation data were used. The climate generator routine, CLIGEN, was used to generate climatic inputs for the simulation other than daily precipitation, daily maximum temperature, and daily minimum temperature (Flanagan and Livingston, 1995). Data collected at a University of Georgia climate station located at the Gibbs Farm were used for air temperatures. Other data were derived by the CLIGEN program using data from the Tifton, GA station built into the WEPP model.

Slope input

Required information for the slope file, including slope orientation, slope length, and slope steepness were derived directly from topographic data collected at the site. A uniform slope of 3.1% was used, with a slope length of 59 m. The representative width was assumed to be 20 m.

Soils input

Soils data for the site was obtained from a survey conducted in 1998 and from classification maps made of the Gibbs farm (Perkins et al., 1986). The Tifton loamy sand has a high infiltration rate at the surface and is well to moderately well drained. Basic soil characteristics for the simulation were derived from available data and from recommendations listed in the WEPP User Summary (Flanagan and Livingston, 1995). Soil characteristics of the surface horizon are shown in Table 1.

Soil albedo was calculated using the formula provided in the WEPP manual (Flanagan and Livingston, 1995):

$$SALB = \frac{0.6}{\exp(0.4 * ORGMAT)} \tag{1}$$

where SALB is the soil albedo for a dry surface and ORGMAT is the percent organic matter at the surface soil (%). The organic matter concentration was calculated as 1.724 times the organic carbon percentage (Knisel, 1993). Organic carbon in the conventional till plots was 0.45% and it was 0.55% in the strip till plots (Unpublished data).

Soil characteristics for each of the soil layers were interpreted from survey data (Table 2). Input characteristics for the strip till simulations were the same except the organic matter content for the top layer was assumed to be 0.95%.

Table 1. Initial basic soils input parameters and data source for plots 1 and 2.

Parameter	Source	Conventional Tillage Plot	Strip Tillage Plot
Soil Name	Soil survey	Tifton loamy sand	Tifton loamy sand
Soil Texture	Soil survey	Loamy sand	Loamy sand
Number of soil layers	Soil survey	8	8
Surface Layer Organic Matter (%)	Observed data	0.78	0.95
Albedo	WEPP user summary	0.44	0.41
Initial Saturation level (m/m)	Observed data	0.20	0.20
Baseline inter-rill erodibility - K_i (kg s m^{-4})	WEPP user summary (sand)	5641494	5641494
Baseline rill erodibility - K_r (s m^{-1})	WEPP user summary (sand)	0.0248	0.0248
Baseline critical shear - τ_{auc} (N m^2)	WEPP user summary (sand)	2.1	2.1
Effective hydraulic conductivity of surface soil - K_e (mm hr^{-1})	WEPP user summary (Tifton soil optimized value)	9.0	10.5

Table 2. Initial input for the soils layers, conventional tillage plot.

Layer Bottom (mm)	Sand (%)	Clay (%)	Organic Matter (%)	Cation Exchange Capacity (meq per 100 g soil)	Rock Fragment Volume (%)
180	85.6	3.5	0.78	2.6	3.6
580	64.1	19.8	0.1	3.0	2.7
890	55.7	29.7	0.1	4.9	2.7
1280	67.1	23.0	0.1	4.0	6.3
1400	74.1	20.2	0.1	3.0	6.3
1670	73.3	16.2	0.1	3.0	6.3
2000	72.8	15.9	0.1	3.0	6.3
2240	75.3	12.7	0.1	3.0	6.3

Plant/Management input data

WEPP management files were created to simulate production on the plots. The plots have been in a Cotton/Peanut rotation for the entire simulation period. Cotton was planted in 1999, 2000, 2001, and 2003, and peanuts were planted in 2002 and 2004. The conventionally tilled plots were chisel plowed to 20 cm approximately three weeks before planting, followed by a disk harrowing to 8 cm to form the beds for planting. A subsoiler was used on the strip till plots to create a narrow 15 cm strip for planting with tillage to 20 cm. Planting, fertilization, and pesticide treatment on all of the plots were identical and based upon University of Georgia recommendations. All plots were planted with a rye grain cover crop each fall (approximately December 1). The cover crop was killed in the spring prior to planting (approximately April 1). The cover crop on the conventionally tilled plots was killed by disk-harrowing while the cover on the strip tilled plots was killed by spraying with herbicide. Both the conventional and the strip till

plots were paratilled to approximately 45 cm on 1 November 2002. The paratilling was done to increase porosity and to relieve compaction. Some soil disturbance also occurred on the strip tilled plots during peanut harvest. Additional management information such as irrigation, tillage, fertilization, and pesticide application were available from management records.

Model Calibration / Validation

Observed surface runoff data from three years, 2001, 2002, and 2005, were used for calibration purposes. These three years constituted a dry, an average, and a wet year. Cotton was grown in 2001 and 2005 while peanuts were grown in 2002. Effective hydraulic conductivity was adjusted to provide the best fit to the observed annual surface runoff data for the three year period.

Three fit statistics were used to assess the optimum fit for the three year period. The first was the sum of the squared error (SSE) between the observed and simulated annual runoff volumes for the three year period. The SSE is calculated as:

$$\mathrm{SSE} = \sum_{i}^{n} (O_i - S_i)^2 \tag{2}$$

where O_i and S_i are the observed and simulated annual runoff for the *i*th year, respectively, and *n* is the total number of years. For the different simulation scenarios, the mean absolute error (MAE; Weglarczyk, 1998) was calculated as:

$$\mathrm{MAE} = \frac{\sum_{i}^{n} ABS(O_i - S_i)}{n} \tag{3}$$

Both SSE and MAE approach zero as the accuracy of the simulation improves. The model efficiency (*E*; Nash and Sutcliffe, 1970) was also calculated:

$$E = 1 - \frac{\sum_{i}^{n} (O_i - S_i)^2}{\sum_{i}^{n} (O_i - O')^2} \tag{4}$$

where *O'* is the mean of the observed annual flow over the simulation period. The efficiency can be thought of as the sum of the deviations of observations from a linear regression line with a slope of 1. Efficiencies equal to 1 indicate a perfect fit between the observed and predicted data, while values equal to 0 indicate that the model is predicting no better than using the average of the observed data. Negative efficiencies generally indicate that the average value of the output is a better estimate than the model prediction. The optimum simulation was assessed as the simulation which produced E closest to 1 and the minimum of SSE and MAE, or the simulation which came the closest to satisfying the three objective functions. Using the optimum parameter set, a comparison was then made between the observed runoff and soil moisture data for the remaining four years, 1999, 2000, 2002, and 2004.

Results

Simulations were conducted for the period from January 1, 1999 to December 31, 2005. Precipitation was below the area long-term yearly average for the first three years of the study and near the long term average for the period from 2002-2004 (Table 3). Rainfall in 2005 was

well above the long term average, with particularly high rainfall in March, April, June and July of 2005.

Table 3. Observed and simulated results for the conventional and strip till plots. 2001, 2002, and 2005 were calibration years, 1999, 2000, 2003, and 2004 validation years.

		Conventional tillage			Strip Tillage		
	Precipitation + Irrigation (mm)	Observed Runoff (mm)	Simulated Runoff (mm)	Difference (mm)	Observed Runoff (mm)	Simulated Runoff (mm)	Difference (mm)
1999*[v]	795	120	149	29	80	93	13
2000 [v]	1148	171	276	105	54	202	148
2001 [c]	1115	254	242	-12	90	133	43
2002 [c]	1323	396	352	-44	302	219	-83
2003 [v]	1271	498	257	-241	270	177	-93
2004 [v]	1258	194	258	64	155	198	43
2005 [c]	1564	357	402	45	287	302	15

* data from 18 March 1999 to 31 December 1999

[v,c] validation (v) and calibration (c) years

Model Calibration

Data from 2001, 2002, and 2005 were used for calibrating the model to the observed surface runoff data. The only adjustments made to the input data were with the baseline effective conductivity parameter, K_e. Separate calibrations were conducted for the conventional till and the strip till plots. While the WEPP option of using a single fixed K_e was examined, the option allowing the model to adjust K_e based upon the expected temporal effects of tillage, plant growth, residue management, and other structural soil changes (Rawls et al. 1995) was selected because it produced superior results.

Conventional Till Plots

The baseline effective conductivity was adjusted from 6 to 10 mm hr^{--1} and the objective criteria examined for simulation of the conventional till plots. The K_e value which produced the minimum SSE for the annual runoff (4107 mm^2) and the maximum E for the annual runoff (0.78) was 9.0 mm hr^{--1}. The MAE for this K_e value was 33.7 mm, slightly greater than the minimum MAE obtained (30.6 mm) when a K_e value of 8.5 mm hr^{--1} was examined.

Strip Till Plots

The baseline effective conductivity was adjusted from 6 to 11 mm hr^{--1} for the strip till plots. The K_e value which produced the minimum SSE for the annual runoff (8936 mm^2), the minimum MAE for annual runoff (46 mm), and the maximum E for the annual runoff (0.75) was 10.5 mm hr^{--1}. As indicated by the SSE and E, the calibration for the strip till plots did not indicate as good a fit to the annual runoff as was observed for the conventional till plots.

Model Validation

Conventional Till Plots

A comparison between the observed and the simulated surface runoff indicates fairly good agreement for all years except 2000 and 2003 (Table 3, Fig. 2). Surface runoff was overestimated in 2000 and underestimated in 2003. Evapotranspiration was underestimated in 2000 and overestimated in 2003 (Fig. 3).

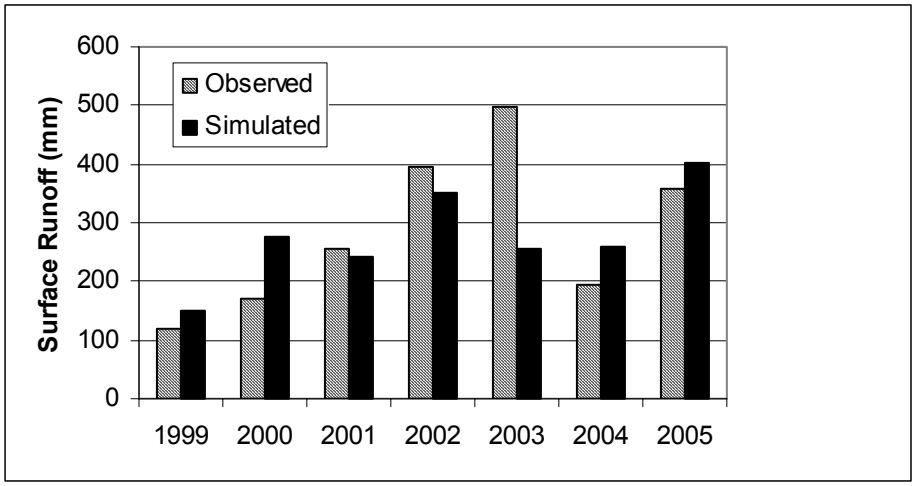

Figure 2. Comparison between the observed and the simulated surface runoff for the 7 year period for the conventional till plots.

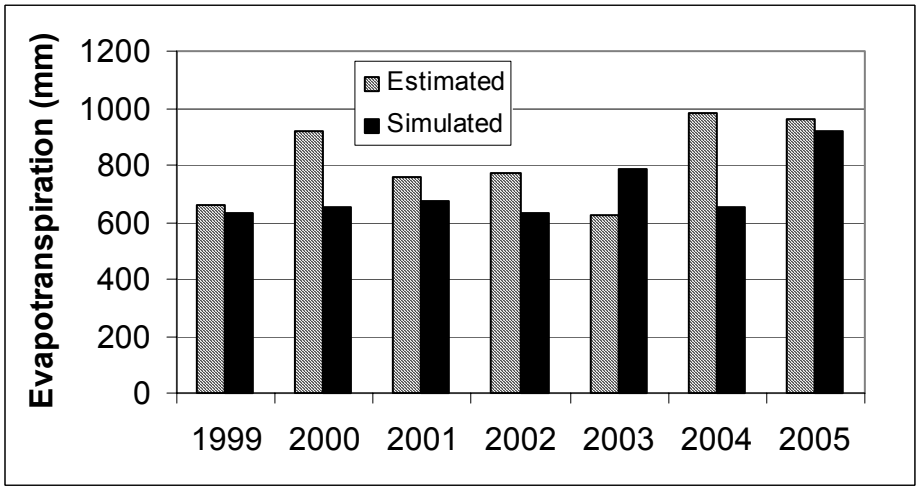

Figure 3. Comparison between the estimated and the simulated evapotranspiration for the 7 year period for the conventional till plots.

The ratio of the annual runoff to the annual precipitation is frequently used as an indicator of the likelihood of runoff from fields and watersheds. The observed ratios from the conventional till plots varied from 0.15 to 0.40, while the simulated ratios varied from 0.19 to 0.27 (Table 4). For the calibration years, 2001, 2002, and 2005, the simulated ratios matched the observed ratios fairly closely (Table 4). However, for the validation years of 2000 and 2003 the results were poor. This is also illustrated by the squared error (SE), the square of the difference between the observed and the predicted annual runoff for each year (Table 4). Comparison between the

daily observed runoff and the daily simulated runoff from the conventional till plots for 2000 indicates that most of the poorest estimates of runoff occurred from October 1 until the end of November. During this period small runoff events were observed on the plots while none were predicted. This was the period between cotton harvest and plot tillage for planting rye. In 2003, very large runoff volumes were observed from the conventional till plots during the months of March, June, and August. The model significantly under predicted these events, leading to the discrepancy observed.

Table 4. Observed and simulated ratios between annual surface runoff and water inputs (precipitation and irrigation) and the SE for annual runoff for the calibration years (2001, 2002, and 2005) and the validation years (2000, 2003, and 2004).

	Conventional Tillage			Strip Tillage		
	Observed ratio	Simulation Ratio	SE (mm^2)	Observed ratio	Simulation Ratio	SE (mm^2)
1999*	0.15	0.19	860	0.10	0.12	160
2000	0.15	0.24	10966	0.05	0.18	21795
2001	0.23	0.22	148	0.08	0.12	1850
2002	0.30	0.27	1969	0.23	0.17	6862
2003	0.40	0.20	57932	0.21	0.14	8623
2004	0.16	0.21	4113	0.12	0.16	1834
2005	0.23	0.26	1991	0.18	0.19	224

* incomplete year

Strip Till Plots

A comparison between the observed and the simulated surface runoff for the strip till plots indicates fairly good agreement for all years except 2000, 2002, and 2003 (Figure 4). Surface runoff was overestimated in 2000 and underestimated in 2002 and 2003. The greatest error was observed in 2000.

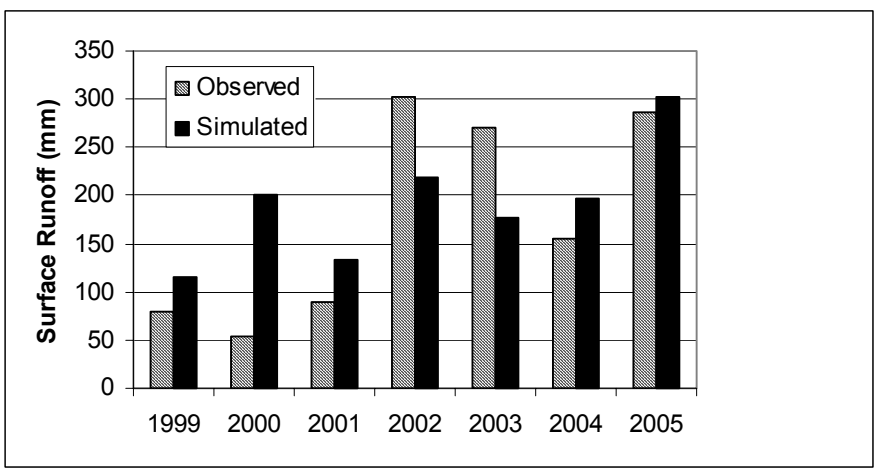

Figure 4. Comparison between the observed and the simulated surface runoff for the 7 year period for the strip till plots.

The observed ratios from the strip till plots varied from 0.05 to 0.23, while the simulated ratios varied from 0.12 to 0.19 (Table 4). There was fairly good agreement (+/- 7%) for all of the years except 2000. In 2000, the two deviated by 13%

Soil Water

A comparison was made between WEPP simulated and the observed equivalent water in the top 400 mm of the profile for the both the strip tillage and the conventional tillage systems for 2001 and 2002 (Fig. 5). These comparisons were made without any adjustments to the soil characteristics which effect water holding capacity within the profile. The only parameter adjustments made were in K_e when calibrations were made based upon annual runoff. For these preliminary simulations, the water holding capacities in both the conventional till and the strip till plots were assumed to be the same other than the organic carbon fraction in the surface layer. Thus, equivalent water in the profile is only affected by the amount of water infiltrated, differences in evapotranspiration, and differences in percolation.

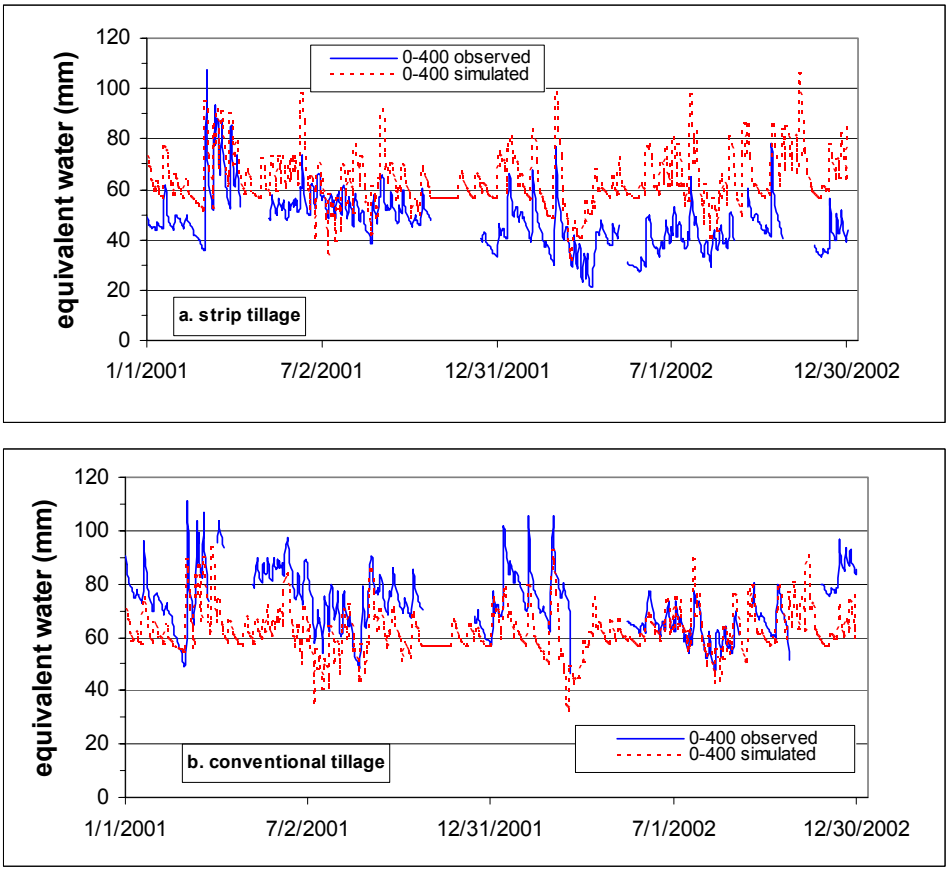

Figure 5. Simulated and observed equivalent soil water (mm) in the top 400 mm of the soil profile for the (a) strip till and the (b) conventional till plots.

WEPP simulated equivalent soil water was fairly representative of the seasonal patterns observed on the plots (Fig. 5). Results for the conventional till plots agreed well with the

observed data for the 2002 growing season when peanuts were grown. In general, equivalent soil water was over-predicted for the strip till conditions and under predicted for the conventional till plots. This is likely due to a slightly higher clay content in the surface soil in the conventional till plots and a slightly lower clay content in the strip till plots. The soil textures that were used for the base-line simulation assumed the same texture for both the conventional and the strip till plots. These textures represented an average condition for the entire study area. Site specific inputs for the conventional till and for the strip till plots would be expected to produce more accurate estimates of soil water. In addition, detailed estimates of organic matter with depth would also be expected to improve the simulations.

Conclusion

Results from this preliminary assessment of the WEPP model for the local conditions appear promising. The model accurately simulated seasonal trends in runoff and soil water. As a first assessment of runoff and equivalent soil water for the Tifton Loamy sand plots, the WEPP model produced useful estimates. Minimal adjustments were made to the input parameter sets for these simulations. The simulated ratio of the annual runoff to the annual water inputs (precipitation and irrigation) tracked the observed ratio to within 9% for all years but one for the conventional and to within 7% for all years but one for the strip till. Higher errors were observed in 2000 and 2003 for both tillage's. Significant deviations from the observed runoff were observed for both of these years for both tillage systems. Further investigation is necessary to evaluate the source of these errors.

This was considered a preliminary assessment for this soil and for the regional climatic conditions. Additional work is necessary to develop site specific soil hydrologic and plant evapotranspiration characteristics. It is anticipated that the runoff and the soil water estimates can be improved through calibration of a wider set of parameters and a more detailed input characterization. Future research will also examine the use of break-point rainfall data to see if improvements in the estimates can be made through use of these data.

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