APEX Calibration and Validation of Water and Herbicide Transport under Southern Atlantic Coastal Plain (USA) Conditions

Stephen Plotkin, University of Massachusetts Extension, Natural Resources Conservation Service, Amherst, MA.

Xiuying Wang, Texas A&M University, Blackland Research and Extension Center, Temple, TX

Thomas L. Potter, USDA, Agricultural Research Service Research Southeast Watershed Research Laboratory, Tifton, GA.

David D. Bosch, USDA, Agricultural Research Service Research Southeast Watershed Research Laboratory, Tifton, GA.

Jimmy R. Williams, Blackland Research and Extension Center, Temple, TX

Eric S. Hesketh, USDA, Natural Resources Conservation Service, Amherst, MA

Joseph K. Bagdon, USDA, Natural Resources Conservation Service, Amherst, MA

March 2, 2011

Abstract

Simulation modeling is widely used to assess water contamination risk associated with pesticide use and for evaluating effectiveness of agricultural conservation practices. Currently the Agricultural Policy/Environmental eXtender (APEX) model is being used for this purpose in the USDA Conservation Effects Assessment Project (CEAP) Cropland National Assessment. In support of the CEAP modeling effort, APEX was calibrated and validated using a 9-year record (1999-2007) of surface runoff and tile flow, and an 8-year record (1999-2006) of soluble pendimethalin and fluometuron herbicide losses from fields in a cotton-peanut rotation located in the Atlantic Coastal Plain region of south-central Georgia (USA). Conventional and strip tillage management were directly compared. Monthly surface runoff was calibrated by adjusting three variables: the Curve Number Index Coefficient (CNIC), which is a driver of the Natural Resources Conservation Service Runoff Curve Number; the runoff curve number for the average soil moisture condition 2 (CN2); and Irrigation Runoff Ratio (IRR). Monthly statistics met satisfactory criteria between observed and simulated surface runoff for both tillage types, with R^2 values from 0.64 to 0.79 and Nash-Sutcliffe efficiency (NSE) values from 0.55 to 0.73 during calibration and validation periods. Monitored and predicted annual runoff and fluometuron and pendimethalin runoff losses for both tillage systems and the tile drainage from the strip-till system were well aligned. Values of R^2 ranged from 0.57 to 0.93 and NSE values from 0.51 to 0.89 based on annual comparisons between simulated and observed values. APEX correlation was less satisfactory for annual tile flow from the conventional tillage system, and relatively poor for fluometuron transport in tile flow from both tillage systems. Overall, APEX effectively replicated annual means for these three variables with simulated annual means within 10% of the observed values. The percent bias statistical parameter, PBIAS, was below 26% for all annual

mean correlations indicating that APEX did a reasonable job in replicating annual means for runoff, tile flow and pesticide losses. Results demonstrate APEX's strength in simulating runoff in this landscape and relative weakness in examining tile flow temporally.

Introduction

Simulation modeling is widely used to assess water contamination risks imposed by agricultural pesticide use. Over 1000 pesticides are currently registered, but only a few dozen are even periodically monitored nationwide. National surveys conducted in 2003 to 2006 by the Conservation Effects Assessment Project (CEAP) indicated that 348 different pesticides were applied to U.S. agricultural fields during that four year period. Modeling is needed to augment monitoring programs that are limited nationwide in scale and scope to assess potential contamination from these pesticides and risk to humans and the environment. Additionally, computer modeling provides a predictive aspect of pesticide levels that could occur under varying weather and hydrologic conditions.

In this study we examined the utility of the physical process and environmental fate model, Agricultural Policy/Environmental eXtender or (APEX) (Williams et al., 2006, 2008; Williams and Izaurralde, 2006; Gassman et al., 2009, 2010). APEX was designed to simulate agricultural management strategies for a single field, farms containing multiple contiguous fields, grassed waterways, filter strips and buffers, and small watersheds. The model operates with continuous simulations for as many years as desired using a daily time-step. Weather, soil conditions, hydrology, erosion/sedimentation, crop growth, weed competition, grazing, irrigation, tillage operations, agricultural management and nutrient and pesticide dynamics are simulated. APEX hydrology components include overland and channel runoff, subsurface flow, deep percolation, field sediment losses and evapotranspiration.

Currently, APEX is being used by CEAP in a national effort to assess the effectiveness of conservation practices. The model is being used to simulate nutrient, pesticide and sediment losses under conditions of agricultural practices based upon national farmers' surveys from 2003-2006 at selected National Resources Inventory (NRI) sample points. A second set of simulations reassess pollutant losses after existing conservation practices have been removed. By comparing these two scenarios, CEAP evaluates the impact of conservation practices on levels of soil organic carbon, nutrients, sediment, and pesticide losses from farm fields as well as impact on loading to river basins.

Like all models, APEX calibration and validation is necessary to improve simulation accuracy. To this end, simulations of hydrology and pesticide losses were compared to measured values from USDA-Agricultural Research Service research plots located at the University of Georgia Gibbs Farm near Tifton, GA. Research that began in 1999 has made quantitative assessments of water and transport of the herbicides fluometuron and pendimethalin in surface runoff and tile-drainage leachate as a function of tillage type (Potter et al. 2004 and Bosch et al. 2005, 2006). Cotton and peanut crops were produced in rotation. Two tillage systems, conventional tillage and strip-till, a conservation tillage practice, were compared. Strip tillage is very common in the region and like most conservation tillage systems helps to decrease erosion and sediment loss. Conservation tillage also tends to hold water on the field, thereby reducing pesticide runoff, but augmenting water infiltration, and may increase pesticide leaching as has been found for herbicides like fluometuron at the Tifton plots and research plots at Bnei Darom, Israel (Sagiv, 2008).

EPA relies in part on simulation models for environmental fate and exposure assessments of fluometuron and pendimethalin. Modeling results are used to help quantify potential risks to wildlife and humans (Federal Register, Sept. 19, 2007; USEPA OPPT, 2005). EPA has concluded that fluometuron requires specific restrictions and mitigation measures on its formulated product label to address identified concerns. Specifically, EPA identified human drinking water concerns based on the potential for groundwater contamination due to fluometuron's mobility in soil and relative persistence in the environment. Fluometuron modeling for cotton production in Mississippi, North Carolina, Texas, and California indicated that there was the potential for concentrations in ponds to exceed EPA's acute Level of Concern (LOC) for endangered aquatic animal species, which have a lower threshold LOC than species that are not endangered. Furthermore, modeled surface water concentrations were found to exceed the freshwater fish acute LOC for Mississippi, and acute freshwater invertebrate LOC for Mississippi, Texas and North Carolina (USEPA OPPT, 2005).

In contrast to fluometuron, pendimethalin binds strongly to soil organic carbon, and thus is unlikely to reach groundwater. However, it is transported from farm fields dissolved in runoff and bound to sediment. EPA modeling indicated that it is not likely to reach concentrations in drinking water that will pose a threat to human health (USEPA, 1997). At a common application rate of 1.1 kg ha^{-1}, pendimethalin is not expected to be an acute risk to fish, invertebrates or aquatic plants, but may pose a risk to endangered species. Pendimethalin concentrations may reach acutely toxic levels when applied at higher application rates, such as to sugarcane, alfalfa and onions. EPA long-term modeling mostly indicated minimal chronic risk to fish and invertebrates.

APEX and its field scale model predecessor, the Environmental Policy Impact Climate (EPIC) model (Williams, 1990) have been extensively tested. EPIC has been used for a variety of conditions in the U.S. and other countries (Gassman et al., 2005), and even at a global level (Liu at al., 2007). APEX can be used as a Best Management Practice (BMP) model by simulating a variety of land management scenarios (Borah et al., 2006). Since its inception in 1996, APEX has been used in dozens of studies to evaluate the impact of agricultural practices (e.g., Ramanarayanan et al., 1997; Gassman et al., 2002; Harman et al., 2004) and is being used in numerous watershed and river basin studies in CEAP (Kellogg et al., 2011a, 2011b).

APEX has been calibrated and validated in previous studies. Wang et al. (2006) tested the model for parameter sensitivity to determine variables that had the greatest impact on simulated hydrology. A two-year calibration/validation of APEX was previously performed on the Tifton research plots using monitored data from 2000 – 2001 by Plotkin et al. (2009). Results from this study indicated good correlation between monthly measured data and simulated results of water runoff, and fluometuron and pendimethalin runoff from conventionally tilled plots. APEX was calibrated by Flowers et al. (1996) for dairy waste application fields. Ramanarayanan et al. (1998) calibrated and validated APEX hydrology and soil loss for three small watersheds. Wang et al. (2008) calibrated and validated the model using 20 years of measured data (1976–1995) from two watersheds at the USDA Deep Loess Research Station near Treynor, Iowa. Continuous corn was grown in the watersheds using a conventional tillage system and the conservation tillage system, ridge-till. Results showed good statistical agreement with measured levels for both tillage systems for runoff, sediment yield, soil organic carbon and crop yield. The model further predicted that ridge-till versus conventional tillage had 36% to 39% surface runoff reduction, 82 – 86% sediment yield reduction, 63 – 67% reduction in cumulative soil carbon losses and a corn grain yield increase of 3.8%.

This study further evaluated the ability of APEX to simulate field hydrology and pesticide losses following calibration with monitored data from fields in rotational cotton and peanut production under conventional and conservation tillage management. Objectives were to: (1) calibrate and validate APEX using nine years of measured data (1999–2007) from the USDA, Agricultural Research Service research plots at the University of Georgia Gibbs Farm near Tifton, GA, and (2) quantify soluble losses of the herbicides fluometuron and pendimethalin in runoff and percolation (tile drained) using conventional tillage versus a strip-till conservation tillage system in a cotton-peanut crop rotation.

Methods

APEX Modeling

Interactive-APEX (I_APEX) (Siemers, 2007), that uses APEX for its base model was used to populate all input data and perform preliminary simulations before initiating the calibration and validation procedures in APEX. Model input parameters are presented in Table 1 including site characteristics, hydrology parameters, soil type, crop rotation, pesticides and soil management.

Gibbs Farm Research Plot Characteristics

Three 0.14-ha (approximately 59 m long X 24 m wide) conventionally tilled (CT) plots and three strip-tilled (ST) plots were established in 1999 at the University of Georgia Gibbs Farm in Tift County, Tifton, Georgia (31^0 26’ N, 83^0 35’) as depicted in Figure 1. Conventionally tilled plot replicates were designated 1, 3 and 5, while strip-tilled plots included replicates 2, 4 and 6. Plots were each surrounded by 0.6-meter tall earthen berms that directed surface runoff downslope to metal H-flumes. Lateral subsurface flow was intercepted by 15 cm (i.d.) tile drains buried to a depth of 1.2 m, with flow and water quality samples collected at metal H-flumes installed at tile-drain outlets. An interceptor drain was installed upslope of the plots to cut off external lateral subsurface flow. Additional descriptions of the plots can be found in Potter et al. (2004) and Bosch et al. (2005, 2006).

Weather

Daily precipitation (using a tipping bucket rain gage), and daily temperature minimums and maximums were collected on site (Bosch et al., 2005). All other daily weather data including humidity, solar radiation and wind speed were obtained from a station maintained by the Georgia Automated Environmental Monitoring Network in Tifton, GA, located 8.3 km from the research site. Average monthly weather data including wind speed and direction, solar radiation and mean air temperatures needed for modeling were estimated using the weather generating program WXPM (Williams et al., 2006) based on historical daily weather data collected at Tifton, GA. Evapotranspiration was simulated using the Hargreaves equation (Hargreaves and Samani, 1985) which is appropriate for warm and humid weather conditions (Table 1).

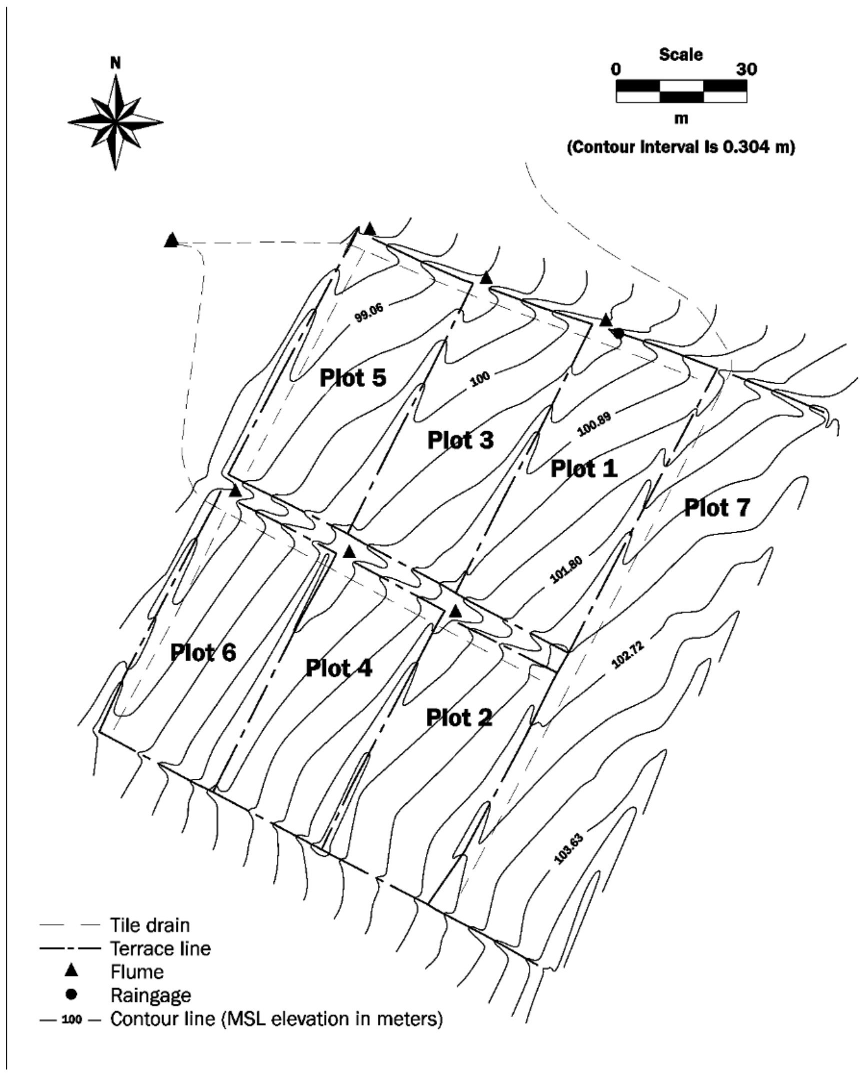

Figure 1. Topography and site layout of Gibbs Farm research facility near Tifton, GA

Plot Soil

Soil was classed as Tifton Loamy Sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults). There is a restrictive argillic layer (higher clay percentage and bulk density) that varies in depth from about 25 to 50 cm below the surface. Slopes range from 3 – 4%. A median slope of 3.5% was used in the simulations.

Soil bulk density was measured with depth at the top of the slope in Plot 1 (conventionally tilled) and Plot 2 (strip-tilled) 1999, 2002 and 2003. Bulk density values used in APEX modeling were

Table 1: Parameter values used in APEX simulations

Parameter Name	Value
Time period modeled	1999-2007
Weather	Daily local precipitation, temperature, relative humidity
Plot length	59 m
Plot width	24 m
Field slope	0.035 m/m
Hydrologic condition	Good
Irrigation runoff ratio (conventionally tilled plot)	0.05 – 0.25
Irrigation runoff ratio (strip-tilled plot)	0.01 – 0.20
Runoff Curve Number method	Variable daily CN soil moisture index
Curve number index coefficient (CNIC) after calibration	0.9
CN2 (conventionally tilled plot)	72-89
CN2 (strip-tilled plot)	65-84
Tile drainage depth	1200 mm
Evapotranspiration equation	Hargreaves PET
Soil type	Tifton loamy sand
Crop rotation	Cotton – Peanuts
Fertilizer	Poultry (1999-2002, 2005, 2007)
Pesticides applied	Pendimethalin, Fluometuron
Pendimethalin properties: Water solubility K_{oc} Aerobic soil $t_{1/2}$ (conventionally tilled) Aerobic soil $t_{1/2}$ (strip-tilled) Foliar half-life Foliar wash-off fraction	 0.275 mg L^{-1} 16,000 mL g^{-1} 96 days 71 days 30 days 0.4
Fluometuron properties Water solubility K_{oc} Aerobic soil $t_{1/2}$ (conventionally tilled) Aerobic soil $t_{1/2}$ (strip-tilled) Foliar half-life Foliar wash-off fraction	 110 mg L^{-1} 100 mL g^{-1} 75 days 62 days 30 days 0.5

obtained from plot samples collected August 21, 2003 and from Perkins et al. (1987) data collected in soil pits at the Gibbs Farm. These two sets of bulk density values appeared to best represent the argillic layer. Other soil physical parameters required to run APEX include field capacity, wilting point and saturated conductivity. These parameters were estimated from the Saxton-Rawls Equation (Saxton and Rawls, 2006) using texture analyses from Plots 1 and 2 sampled on March 23, 1999, soil organic carbon sampled on November 20, 2002 from Plots 1 and 2, gravel content for Tifton loamy sand from the USDA, NRCS Soil Survey Geographic (SSURGO) database for Tift County (May 23, 2007) and bulk density measurements as previously noted. Soil organic carbon content is of particular relevance in that higher levels tend to decrease bulk density and thereby allow increased water infiltration.

Plots 1 and 2 soil texture and organic matter from the 1999 sampling were used in the modeling (Table 2). These measurements were performed four years prior to bulk density sampling in 2003. Texture measurements performed in the plots at other times during 2000-2007 showed little change from year to year. Sampling of soil organic carbon indicated variation from year to year depending upon cropping and tillage practices, soil moisture, solar radiation and temperature. APEX varies soil organic carbon over the duration of a simulation based on these environmental variables. Soil texture in the upper 0.33 m was predominantly sand with about 88% sand content (Table 2). The location of the restrictive argillic layer may be evident by the significant increase in soil clay content at a depth of 0.3 m – 0.7 m for each plot. The organic carbon content of 0.4% in the conventionally tilled plot was lower than in the strip-tilled plot of 0.9%, due to the organic matter building effects of conservation tillage.

APEX simulations were conducted using combined hydrologic responses and pesticides losses of the three conventionally tilled and the three strip-tilled plots, respectively. Soil characterization data obtained from Plot 1 were used to represent the conventionally tilled plots, while data from Plot 2 were used to represent the strip-tilled plots (Table 3). This was necessary due to the fact that bulk density measurements were only available for these two plots.

Crops and Plot Management

A cotton (*Gossypium hirsutum L.*) and peanut (*Arachis hypogaea* L.; variety Georgia Green) rotation was used on all plots. Cotton was planted in 1999 – 2001, 2003, 2005 and 2007 (Table 4). The cotton growing season ranged from 18 – 22 weeks. Peanuts were grown in 2002, 2004 and 2006. The peanut growing season was between 17 – 19 weeks. Sprinkler irrigation was applied based on crop demands. Nutrient and pest management were based on University of Georgia recommendations. The two herbicides investigated in this study were applied individually or in a tank mixture by ground-boom at planting (Table 4). A rye cover crop (*Secale cereale L.*) was planted after harvest each fall. In 2004, the rye was mixed with crimson clover (*Trifolium incarnatum*).

Conventionally tilled plots were disk harrowed and bedded prior to planting. The soil surface was free of crop residue. On strip-till plots, crops were planted into 15 cm strips of tilled cover crop residue. All plots were para-tilled in the fall of 2002. Strip-till plots were also para-tilled during the fall of 2004 and 2007.

Table 2: Tifton loamy sand texture parameters used in APEX for simulations of conventionally tilled Plot 1 and strip-tilled Plot 2

Plot Type	Layer Depth (m)	Sand (%)*	Silt (%)*	Clay (%)*	Organic Carbon (%)**	Coarse Fragments (% volume)***
Conventionally Tilled Plot 1	0.02	88.2	8.8	3.0	0.413	14
	0.08	88.2	8.8	3.0	0.506	14
	0.15	88.2	8.8	3.0	0.506	17
	0.33	88.2	8.8	3.0	0.479	18
	0.63	72.6	12.1	15.3	0.71	25
	1.10	64.3	11.8	23.9	0.171	4
	1.27	60.8	11.7	27.5	0.164	9
Strip-Tilled Plot 2						
	0.02	88.5	8.9	2.6	0.917	14
	0.08	88.5	8.9	2.6	0.581	14
	0.15	88.5	8.9	2.6	0.348	17
	0.32	88.5	8.9	2.6	0.347	19
	0.68	78.5	13.4	8.1	0.445	26
	1.19	62.8	11.9	25.3	0.171	5
	1.45	57.8	13.6	28.6	0.020	9

*texture sampled in Plots 1 and 2 on March 23, 1999
**organic carbon sampled in Plots 1 and 2 on November 20, 2002
***coarse fragments for Tifton LS from USDA, NRCS NASIS soils database

Herbicide Properties

Pendimethalin has a low water solubility of 0.275 mg L^{-1} and high organic carbon-water partition coefficient (K_{oc}), 16,000 mL g^{-1} (Table 1). The K_{oc} was based on measurements reported for pendimethalin sediment-water partitioning at the study site (Potter et al., 2008). This value is in the upper part of the range of values compiled by Hornsby et al. (1995). The compound's high K_{oc} enables sorption to soil organic matter making it essentially immobile in soil except via soil macropores. Runoff losses are primarily associated with detached sediment, but pendimethalin's solubility is high enough to enable significant levels to remain dissolved in runoff. Pendimethalin's relatively long aerobic soil half-life measured in incubation studies using soil collected from the plots was 71 to 96 days (Potter, unpublished, 2007). The long half-life can cause pendimethalin losses to occur for months after application.

Fluometuron has a relatively high water solubility of 110 mg L^{-1} and low K_{oc} of 100 mL g^{-1} (Plotkin et al. 2010). These properties make it highly mobile in soil and useful for tracking leachate to the tile drainage system. The aerobic soil half-life was nearly as long as that of pendimethalin, as measured in incubations of soil obtained from the plots at 62 to 75 days (Potter, unpublished, 2007).

Table 3: Tifton loamy sand water holding capacity parameters used in APEX for simulations of conventionally tilled Plot 1 and strip-tilled Plot 2

Plot Type	Layer Depth (m)	Bulk Density (g/cc)*	Field Capacity (%)**	Wilting Point (%)**	Saturated Conductivity (mm/hr)**
Conventionally Tilled Plot 1	0.02	1.60	0.07	0.02	129.5
	0.08	1.60	0.07	0.02	125.8
	0.15	1.85	0.05	0.02	60.1
	0.33	2.01	0.04	0.02	30.5
	0.63	2.03	0.15	0.10	5.9
	1.10	1.90	0.21	0.14	1.5
	1.27	1.93	0.24	0.17	0.5
Strip-Tilled Plot 2	0.02	1.53	0.08	0.03	139.0
	0.08	1.53	0.08	0.02	152.0
	0.15	1.89	0.05	0.01	57.0
	0.32	2.10	0.03	0.01	23.0
	0.68	2.14	0.08	0.05	8.0
	1.19	2.00	0.21	0.15	0.2
	1.45	2.03	0.24	0.17	0.01

*measured on-site in 2003
**estimated using Saxton-Rawls equation (Saxton and Rawls, 2006)

Table 4. Crop/cover planting, harvest and pesticide application schedule (1999 – 2007) on Gibbs Farm research plots

Year	Crop	Plant	Harvest	Cover Crop* Plant Date	Herbicide Appl. Date	Fluometuron Rate (g ha^{-1})	Pendimethalin Rate (g ha^{-1})
1999	cotton	6-May	16-Sep	1-Nov	6-May	1121	448
2000	cotton	1-May	11-Sep	1-Dec	1-May	1121	897
2001	cotton	7-May	5-Oct	11-Dec	7-May	1121	897
2001	cotton				18-Jun	1401	not applied
2002	peanut	10-May	10-Sep	25-Nov	10-May	not applied	1121**
2003	cotton	12-May	22-Oct	25-Nov	12-May	1121	897
2004	peanut	10-May	15-Sep	5-Oct	10-May	not applied	not applied
2005	cotton	23-May	1-Nov	16-Nov	23-May	1121	897
2006	peanut	16-May	27-Sep	31-Oct	16-May	not applied	1121
2007	cotton	1-May	8-Oct	15-Oct	1-May	1121	1053

*Cover crops in strip-tilled plots killed by two applications of herbicides prior to planting crop. Cover crops in conventional tilled plots killed by disk harrowing prior to planting crop.
**Pendimethalin applied only to strip-tilled plots.

APEX Calibration and Validation

The model was calibrated using monthly runoff data from April 1999 to December 2003 for both tillage treatments. Pesticide data were used for validation only. Monthly runoff data from January 2004 to December 2007 were used for validation. Three parameters that significantly affect partitioning of runoff and percolation were varied to optimize correlation between simulated and measured runoff including: Curve Number Index Coefficient (CNIC); Natural Resources Conservation Service Runoff Curve Number for the average soil moisture condition 2 (CN2); and Irrigation Runoff Ratio (IRR). Runoff simulation in APEX is strongly influenced by CNIC and CN2 (Wang et al., 2005, 2006). CNIC is the weighting coefficient used to calculate the S retention parameter in determination of the daily runoff curve number (CN) in APEX and is dependent upon plant evapotranspiration (Wang et al., 2009). CN2 values required occasional adjustments during the 9-year runs to achieve optimal runoff correlation. An earlier study performed on-site determined that similar variation in CN2 values was necessary in order to represent plot flow patterns (Feyereisen et al, 2008). Runoff is also affected by the APEX IRR which partitions irrigation water between runoff and infiltration (e.g., a ratio of 0.1 would partition 10% of the irrigation water to runoff and 90% to infiltration). CNIC and IRR were adjusted within model recommended ranges (CNIC: 0.5-1.5; IRR: 0.0-1.0; Williams et al., 2006) during the calibration period.

The calibrated model was continuously run through the validation periods. Validation was conducted for surface runoff, tile drain flow, fluometuron and pendimethalin losses in runoff and fluometuron loss in tile drain flow. Pendimethalin's very high K_{oc}, 16,000 mL g^{-1}, makes leaching unlikely. It was not detected in any of the tile-drain samples and therefore was not considered in the tile drainage validation. Statistical measures including mean, standard deviation, R^2, Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), average percent error or percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of observed data (RSR) were used to evaluate the model performance based on criteria suggested by Moriasi et al. (2007).

Results and Discussion

Surface Runoff

Monthly surface runoff calibration resulted in a CNIC of 0.9. Model CN2 values ranged from 72 – 89 for the conventional tillage treatment and 65 – 84 for the strip-till during the calibration and validation periods (Table 1). This represents a median CN2 decrease from 80.5 to 74.5 or 7.5% that can be attributed to the strip tillage system. Irrigation runoff ratios were adjusted from 0.05 – 0.25 for conventional tillage and between 0.01 – 0.20 for the strip tillage. CN2 values for winter cover small grains were lower than values from cotton and peanut row crops. This was due to the much greater plant biomass per square inch of small grains which impedes runoff. Crop residue remaining on the soil surface under strip tillage management, were responsible for the lower range in CN2 values versus the conventional tillage management. Prior research at the study site showed that the strip-tilled plots had an average CN2 of about 71 during the growing season compared to 82 for the conventional tillage plots (Feyereisen et al, 2008). These values nearly matched the median CN2 used in the APEX modeling. Chung et al. (1999) reported a CN2 reduction of about 19% for the conservation tillage system, ridge-till. Wang et al. (2008)

found 6% lower CN2 values with ridge till systems compared to conventional till systems. Studies by Rawls et al. (1980) and Rawls and Richardson (1983) also indicated reduction in CN2 to represent the impacts of different residue cover levels regarding partition of rainfall between surface runoff and infiltration.

Monthly runoff correlations (January, 2004 – December, 2007) were evaluated to test the model's ability to capture mean and standard deviations. R^2 were 0.64 to 0.79 and NSE ranged from 0.55 to 0.73 based on the monthly runoff comparisons between the observed and simulated values for the two tillage systems during the calibration and validation periods (Table 5). Simulated average monthly surface runoff was within ±26% of observed values, while the root mean square errors to the standard deviations of observed data ratios ranged from 0.51 to 0.67 (Table 5). Moriasi et al. (2007) proposed several statistical criteria for establishing satisfactory water quality model performance, including a lower bound for NSE values of 0.5, RSR values of less than 0.70, and PBIAS values within ±25% for monthly flow comparisons. Other criteria for satisfactory model performance have been reported in the literature, including $R^2 > 0.5$ and NSE > 0.3 (Chung et al. 1999; 2001; 2002). Based on these criteria, APEX performance for monthly runoff was satisfactory. In general, simulated monthly runoff followed the observed trend well. However, APEX significantly over-estimated runoff in March 2001 and July 2005 (Figure 2). Both March 2001 and July 2005 had unusually high rainfall.

Table 5. Measured versus simulated monthly surface runoff (mm) for the calibration period (April, 1999-December, 2003) and the validation period (January, 2004-December, 2007)

Treatment		Measured		Simulated		R^2	NSE	PBIAS (%)	RSR‡
		Mean	Std	Mean	Std				
Conventional till	Calibration	9.6	13.4	8.2	14.9	0.79	0.73	-15.0	0.52
	Validation	6.7	10.7	7.8	12.4	0.67	0.55	17.0	0.67
Strip-till	Calibration	4.9	8.4	3.6	7.7	0.64	0.61	-25.9	0.62
	Validation	3.8	8.9	3.8	9.3	076	0.73	0.1	0.51

‡RSR: Ratio of the root mean square error to the standard deviation of observed data.

The simulated means and standard deviations of the annual runoff correlated closely with the measured values for both the conventional tillage (96.1 mm ±40.9 mm vs. 96.8 mm ±52.4 mm) and the strip tillage systems (46.1 mm ±23.9 mm vs. 50.8 mm ±36.7 mm) (Table 6). The R^2 of 0.92 and NSE value of 0.89 for the conventionally tilled plot and R^2 of 0.78 with an NSE of 0.71 for the strip-tilled plot, showed the close correlation between observed and simulated annual runoff. Overall, simulated annual runoff matched well in trend and quantity to observed values (Figure 3).

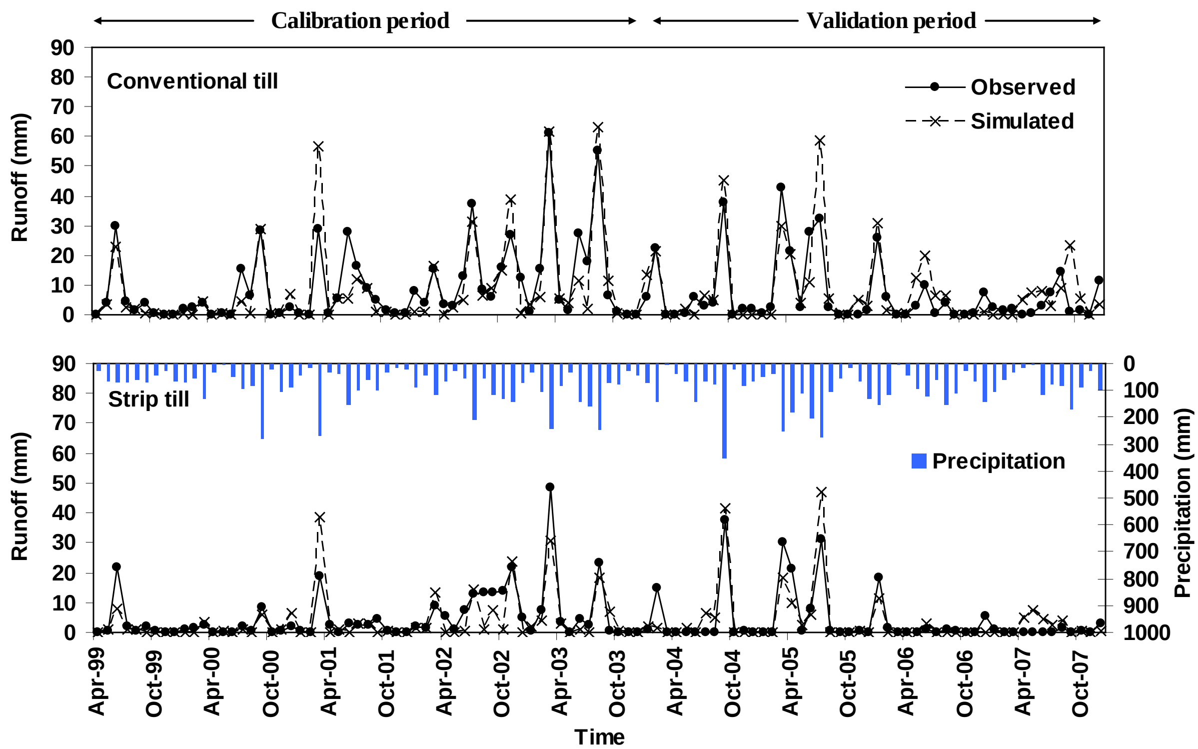

Figure 2. Precipitation and measured vs. simulated monthly runoff from both conventionally tilled and strip-tilled plots near Tifton, GA

Table 6. Summary of measured versus simulated annual runoff and tile flow (1999-2007) and pesticide losses (1999-2006)

	Treatment	Numbers of observations	Measured		Simulated		R^2	NSE	PBIAS (%)	RSR‡
			Mean	Std	Mean	Std				
Surface runoff (mm)	Conventional till	9	96.81	52.39	96.09	40.86	0.92	0.89	-0.74	0.32
	Strip till	9	50.82	36.73	46.12	23.86	0.78	0.71	-9.25	0.51
Tile flow (mm)	Conventional till	9	41.93	22.29	46.11	23.55	0.37	0.13	9.98	0.88
	Strip-till	9	69.95	48.88	66.16	34.23	0.57	0.56	-5.42	0.63
Fluometuron in runoff (g/ha)	Conventional till	8	4.12	5.01	5.19	7.28	0.92	0.63	25.94	0.57
	Strip-till	8	0.91	1.33	1.08	1.65	0.93	0.84	19.19	0.38
Pendimethalin in runoff (g/ha)	Conventional till	8	1.03	0.87	0.92	0.67	0.67	0.65	-10.40	0.55
	Strip-till	8	0.11	0.09	0.10	0.10	0.61	0.51	-13.41	0.66
Fluometuron in tile flow (g/ha)	Conventional till	8	0.47	0.40	0.46	0.32	0.16	0.00	-0.52	0.94
	Strip-till	8	0.92	0.63	0.93	0.86	0.03	-1.38	0.34	1.44

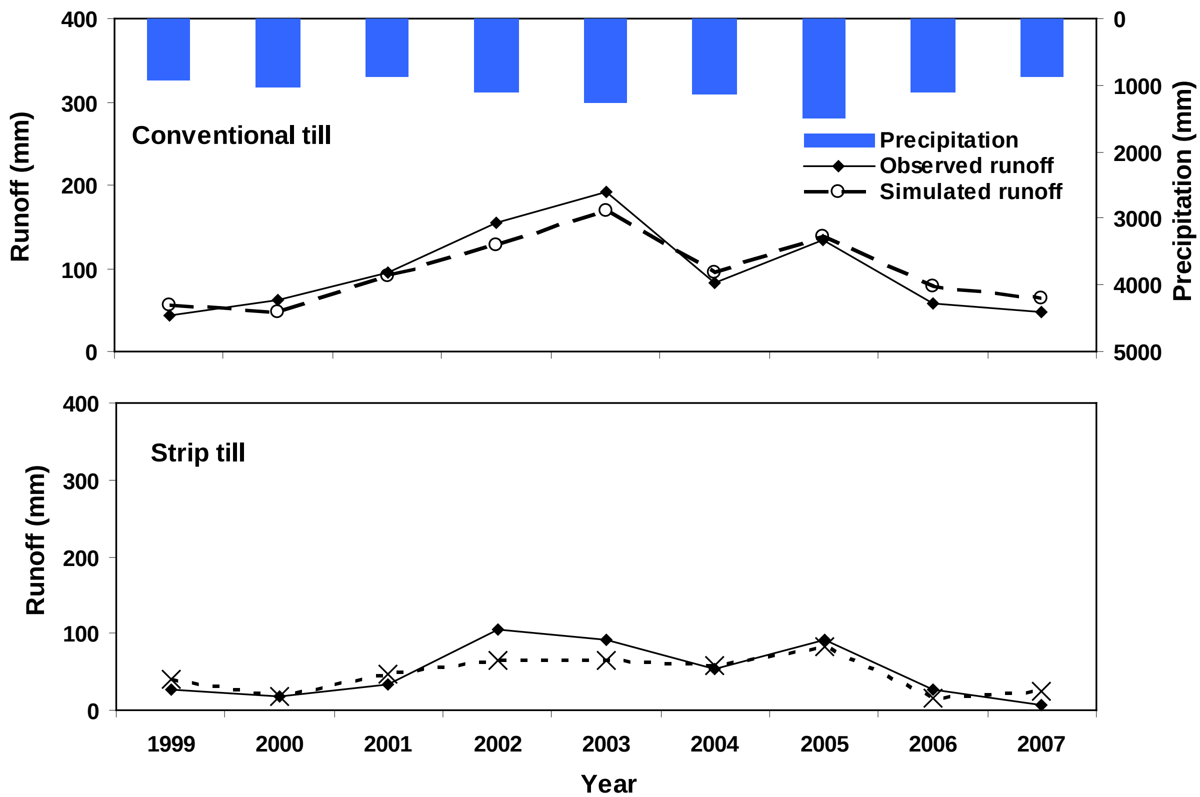

Figure 3. Precipitation and measured vs. simulated annual runoff from conventionally tilled and strip-tilled plots near Tifton, GA.

Tile Flow

Tile flow from the strip tillage system was significantly greater than that from the conventional tillage system. This was presumably due to lower strip tillage system runoff and greater infiltration. Simulated versus observed annual tile flows are shown in Figure 4. Statistical measures indicate that APEX did a better job of predicting tile flow for strip tillage than for the conventional tillage system. The strip tillage system R^2 was 0.57 and NSE, 0.56, compared to the conventional tillage system R^2, 0.37, and NSE, 0.13 (Table 6). The strip tillage values met the criteria for satisfactory performance.

Although the fit of the data did not meet satisfactory criteria with the conventional tillage system, predicted tile flow trends were actually better than with the strip tillage system (Figure 4). The net difference in annual tile flow between measured and simulated points was smaller most years than the net differences between the strip-tilled data points. The lower statistical correlation was partly a result of low flow values in the conventionally tilled plot. With the model using estimated soil field capacity and wilting point values and the variation in depth to the argillic layer within the plots, the model only has to be slightly incorrect in estimating such low tile flow to result in a significant discrepancy by percentage. Another potential source of error comes from APEX estimates of flow leakage between "typical" tile drainage pipes. Actual leakage may vary from site to site depending upon how tightly tile drains are positioned. Even with these potential sources of error, and the difficulty with accurately simulating low flow, the simulated average annual tile-flow mean of 46.11 mm was within 10% of the measured annual mean, 41.93 mm.

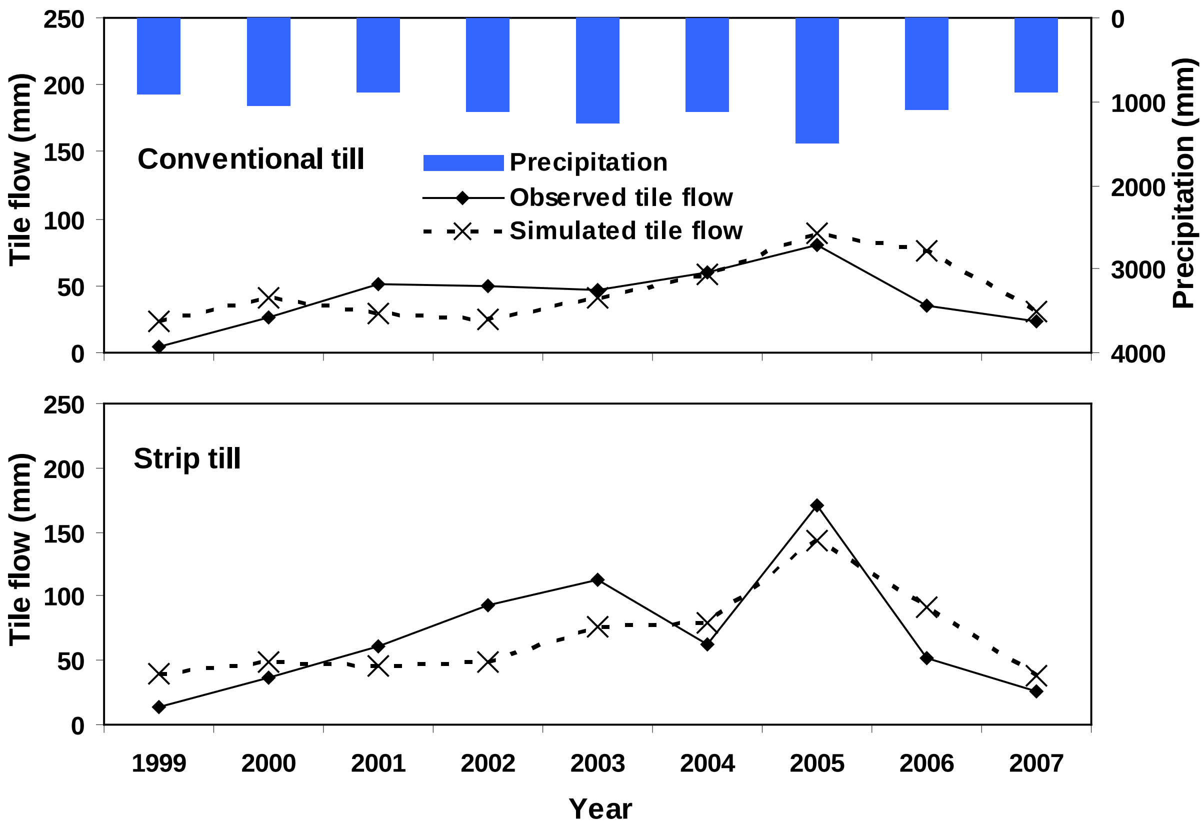

Figure 4. Precipitation and measured vs. simulated annual tile flow from conventionally tilled and strip-tilled plots near Tifton, GA.

Pesticide Losses

Model performance statistics for annual simulated soluble fluometuron losses (1999-2006) in runoff were stronger than for soluble pendimethalin runoff losses (Table 6). Annual soluble fluometuron runoff losses from the conventionally tilled plot (5.19 g ha^{-1}) and strip-tilled plot (1.08 g ha^{-1}) were closely correlated with observed losses as indicated by the R^2 values of 0.92 and 0.93 and NSE values of 0.63 and 0.84, respectively. Performance statistics were not as good for pendimethalin soluble runoff losses; but still met the criteria for satisfactory model performance (Chung et al., 1999, 2001, 2002). Simulated average annual soluble pendimethalin runoff loss from the conventionally tilled system was 0.92 g ha^{-1} yr^{-1}, and 0.1 g ha^{-1} yr^{-1} from the strip-tilled system. These values closely correlated with average annual observations of 1.03 g ha^{-1} yr^{-1} and 0.11 g ha^{-1} yr^{-1}, respectively. The R^2 for soluble pendimethalin runoff were 0.67 and 0.61 and the NSE, 0.65 and 0.51, for the conventional tillage and strip tillage systems, respectively. Dissolved fluometuron runoff was much greater than pendimethalin runoff due to fluometuron's greater solubility in water and lower tendency to sorb to soil and sediment. Increased water runoff associated with conventional tillage management led to greater herbicide runoff losses compared to the strip tillage system. In general, both fluometuron and pendimethalin simulated and observed annual surface runoff losses showed similar trends (Figures 5 and 6).

Only fluometuron was detected in tile flow for both the observed and simulated results. As noted, pendimethalin binds strongly to soil allowing minimal or no leaching. The observed versus simulated trends were relatively poor for fluometuron leachate for both tillages. The R^2 for the conventional and strip tillage were only 0.16 and 0.03, respectively. However, it is noteworthy that mean annual mass losses were very close (within a 2% differential) between observed and simulated losses. Tile drainage fluometuron average annual measured and simulated losses for the conventionally tilled plot were 0.47 g ha^{-1} yr^{-1} and 0.46 g ha^{-1} yr^{-1}, respectively. Fluometuron levels were higher in the strip tillage system leachate due to the increased water infiltration. Measured and predicted annual losses were 0.92 g ha^{-1} yr^{-1} and 0.93 g ha^{-1} yr^{-1}, respectively.

Harmel et al. (2006) found that model results within 10% to 31% of measured values are within the average uncertainty range of water quality data measured with a typical "quality assurance/quality control" effort. Modeling of low levels can be less accurate due to inexact soil and pesticide properties input into the model. Accuracy in measuring and modeling low contaminant levels may be of particular concern when the contaminant is highly toxic. For example, the pesticide diflubenzuron has been found to be chronically toxic to aquatic invertebrates at the extremely low level 0.00025 µg/L (USEPA, 2011). The PBIAS values shown in Table 6 were all below 26%, indicating that the APEX model did a reasonable job in replicating the annual means for runoff, tile flow and pesticide losses.

Measured runoff and subsurface drainage variability between replicate plots may have been a factor accounting for the relatively poor trend correlation between observed and simulated results for fluometuron leachate, and for tile flow from the conventionally tilled plots. Measured water flows and pesticide losses were combined, essentially treating the three replicates as a single field. Also, a plot median slope of 3.5% was used in the model simulations even though the slopes varied within the plots from 3 to 4%.

Another possible explanation for uncertainty in the pesticide results may have been from imperfect representation of soil parameters in the simulations. Soil physical parameters for the simulations were based on sampling that was performed on Plot 1 (conventionally tilled) and Plot 2 (strip-tilled) as representative of the combined replicate plots. With the exception of bulk density, soil water holding capacity parameters were estimated for the model simulations. Also, bulk density sampling was quite variable between sampling years and from the several cores taken within each plot and sampling year.

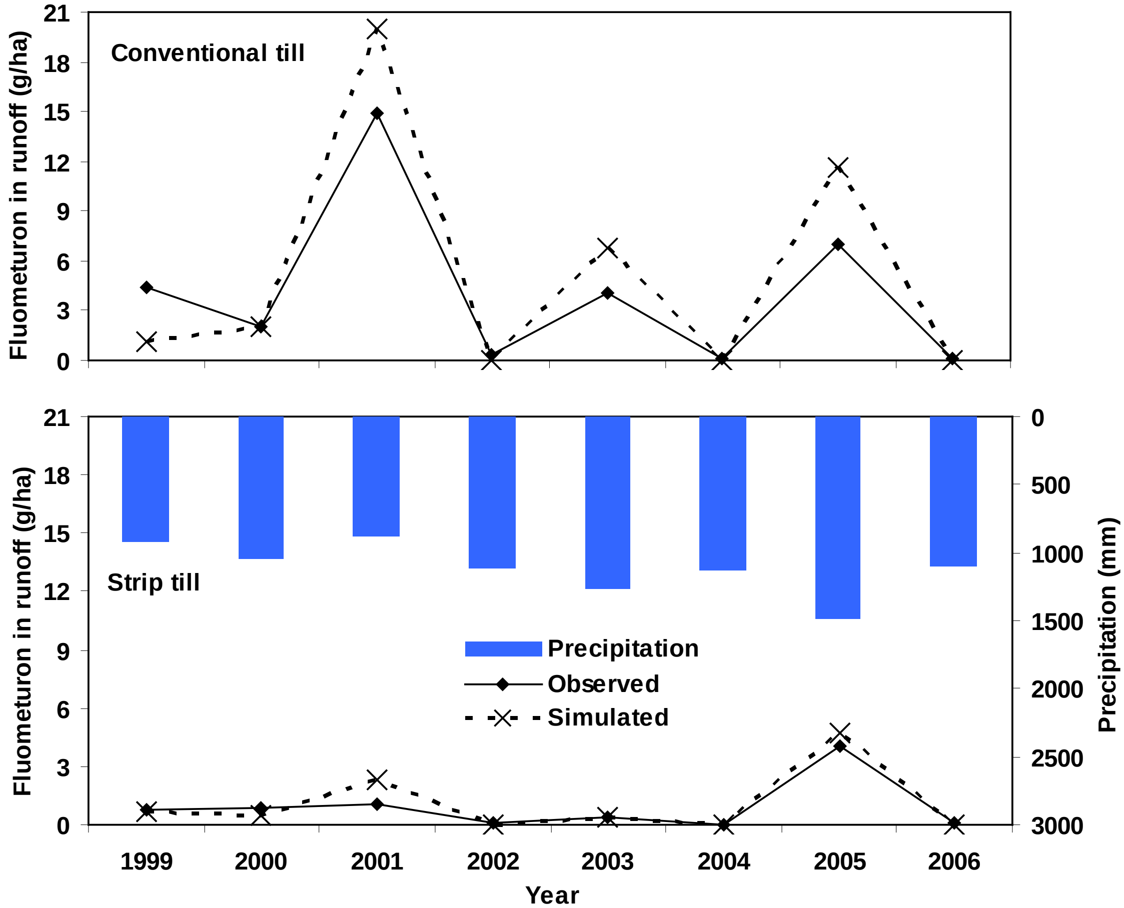

Figure 5. Precipitation and measured vs. simulated annual fluometuron loss in runoff from both conventionally tilled and strip-tilled plots near Tifton, GA

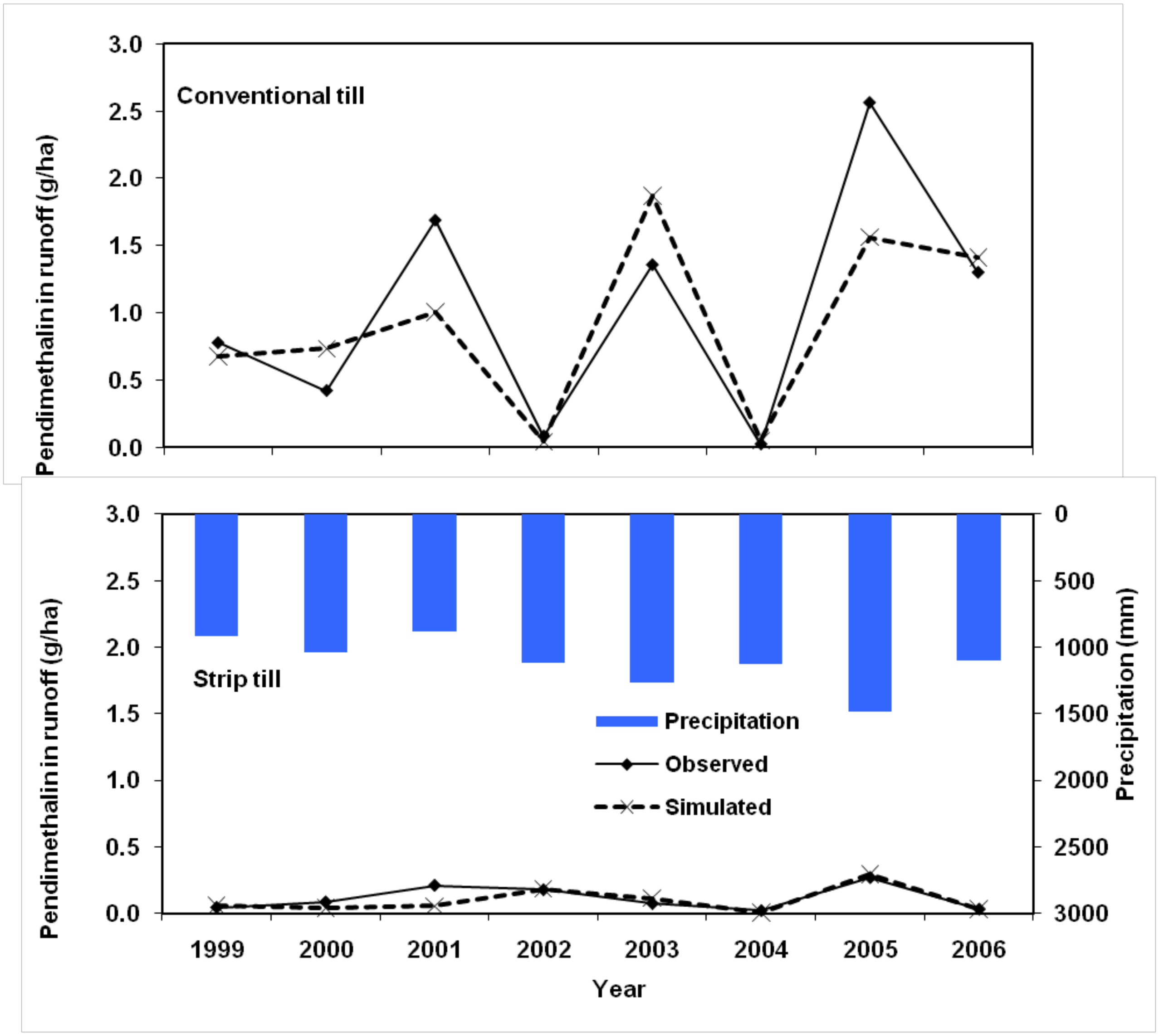

Figure 6. Precipitation and measured vs. simulated annual pendimethalin in runoff from both conventionally tilled and strip tilled plots near Tifton, GA

Summary and Conclusions

The APEX model was tested using measured data from research plots at the Gibbs Farm research facility near Tifton, GA. Measured data included a 9-year record (1999-2007) of surface runoff, and tile flow and an 8-year record (1999-2006) of soluble pendimethalin and fluometuron herbicide losses. Two tillage systems were investigated including strip tillage and conventional tillage in a cotton and peanut rotation.

APEX was calibrated and validated for monthly runoff for both tillage treatments. Model parameters adjusted in the calibration phase included the Curve Number Index Coefficient and Irrigation Runoff Ratio. A CNIC of 0.9 was found to be optimal in the monthly calibration period (April 1999 to December 2003). Adjusted CN2 values ranged from 72 – 89 and 65 – 84 for the conventional and strip tillage systems, respectively during 9-year calibration and validation. APEX runoff calibration indicated that it was necessary to adjust Irrigation Runoff Ratios between 0.05 – 0.25 for the conventionally tilled plot and between 0.01 – 0.20 for the strip-tilled plot. R^2 ranged from 0.64 to 0.79 and NSE from 0.55 to 0.73 based on the monthly runoff comparisons between the observed and simulated values for the two tillage systems during the calibration and validation periods.

Average annual simulated runoff correlated closely with the measured values for both the conventionally tilled plot (96.1 mm ±40.9 mm versus 96.8 mm ±52.4 mm) and the strip-tilled plot (46.1 mm ±23.9 mm versus 50.8 mm ±36.7 mm). An R^2 of 0.92 and NSE of 0.89 for the conventionally tilled plot, and R^2 of 0.78 and 0.71 NSE for the strip-tilled plot corroborated close correlation and trending with observed surface runoff data.

The model replicated percolation (tile drainage) in the strip tillage system reasonably well with an R^2 of 0.57 and NSE equal to 0.56. These values met the criteria for satisfactory correlation of $R^2 > 0.5$ and NSE > 0.3 established by Chung et al. (1999, 2001 and 2002). The APEX model's performance did not meet these criteria for annual tile flow in the conventionally tilled plot (R^2 value of 0.37 and NSE value of 0.13), but still indicated statistical significance and good trend prediction. The lower correlation was attributed in part to inaccurate estimates of soil water holding capacity parameter model inputs, variation in depth to the argillic layer within the plots and difficulty in simulating low flow conditions. In spite of these uncertainties, the simulated average annual tile flow with conventional tillage was within 10% of the observed values. The fact that tile flow statistics were satisfactory for the strip-till plots indicated that APEX is capable of simulating acceptable tile flows if model soil inputs are reasonably accurate and flows are not too low.

Annual fluometuron and pendimethalin soluble runoff were validated with R^2 ranging from 0.61 to 0.93 and NSE 0.51 to 0.89. R^2 and NSE values met established criteria for satisfactory correlation. The APEX model's performance was relatively poor for fluometuron leaching in tile flow for both conventional and strip-tilled plots. This may have been due to problems with modeling of low tile flow in the conventionally tilled plot as previously noted, and the uncertainty in measuring and modeling very low pesticide mass losses. Simulated annual averages of fluometuron in tile drainage in both plots were within 2% of observed values indicating close correlation.

The statistical parameter, PBIAS, was below 26% for all annual mean correlations demonstrating that APEX did a reasonable job in replicating annual means for runoff, tile flow and pesticide losses.

APEX is being used in the USDA-NRCS CEAP Cropland National Assessment to evaluate the effectiveness of conservation practices. One of the components of this effort is to evaluate the impact of conservation practices on pesticide losses from farm fields. Results from the current study indicate that conservation tillage tended to significantly decrease water runoff and soluble pesticide losses in runoff. Percolation to tile drainage at 1.2 m depth increased moderately, while infiltration of a mobile pesticide nearly doubled.

References

Borah, D.K., Yagow, G., Saleh, A., Barnes, P.L., Rosenthal, W., Krug, E.C., Hauck, L.M., 2006. Sediment and nutrient modeling for TMDL development and implementation. Trans. ASABE 49 (4), 967–986.

Bosch D.D. 2010. Personal Communication. USDA, Agricultural Research Service Gibbs Farm Research Plots Hydrology Monitoring Results, and Recorded Daily Weather Data. Agricultural Research Service Research Southeast Watershed Research Laboratory, Tifton, GA.

Bosch, D.D., D.C. Flanagan, and F.M. Davis. 2006. Soil water modeling in South Georgia using WEPP hydrology. ASABE Paper No. 062227. Presented at the American Society of Agricultural and Biological Engineers Annual International Meeting, Portland, Oregon, July 10-12, 2006. St. Joseph, MI: American Society of Agricultural and Biological Engineers.

Bosch, D.D., T.L. Potter, C.C. Truman, C.W. Bednarz, and T.C. Strickland. 2005. Surface runoff and lateral subsurface flow as a response to conservation tillage and soil-water conditions. Transactions of the ASAE 48(6):2137-2144.

Chung, S. W., P. W. Gassman, D. R. Huggins, and G. W. Randall. 2001. EPIC tile flow and nitrate loss predictions for three Minnesota cropping systems. J. Environ. Qual. 30(3): 822-830.

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.

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.

Federal Register. September 19, 2007. Pendimethalin; Pesticide Tolerance. A Rule by the Environmental Protection Agency. The Daily Journal of the United States.

Feyereisen, G.W., T.C. Strickland, D.D. Bosch, C.C. Truman, J.M. Sheridan, and T.L. Potter. 2008. Curve number estimates for conventional and conservation tillages in the southeastern Coastal Plain. Journal of Soil and Water Conservation, 63(3):120-128.

Flowers, J.D., J.R. Williams, and L.M. Hauck. 1996. "NPP: Calibration of the APEX model for dairy waste application fields." A report from the Livestock and the Environment: National Pilot Project, Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, TX.

Gassman, P.W., E. Osei, A. Saleh, and L.M. Hauck. 2002. "Application of an environmental and economic modeling system for watershed assessments." J. of the American Water Resources Association, Vol. 38, No. 2, pp. 423-438, April.

Gassman P.W., Williams, J.R., Benson, V.W., Izaurralde, R.C., Hauck, L., Jones, C.A., Atwood, J.D., Kiniry, J., Flowers, J.D., 2005. Historical development and applications of the EPIC and APEX models. Working Paper 05 WP-397. Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa. Available at: http://www.card.iastate.edu/publications/synopsis.aspx?id=763. Accessed 28 September 2007.

Gassman, P.W., J.R. Williams, S. Wang, A. Saleh, E. Osei, L. Hauck, C. Izaurralde, and J. Flowers. 2009. The Agricultural Policy Environmental Extender (APEX) model: An emerging tool for landscape and watershed environmental analyses. Technical Report 09-TR

49. CARD, Iowa State Univ., Ames, IA. At: http://www.card.iastate.edu/publications/synopsis.aspx?id=1101.

Gassman, P.W., J.R. Williams, S. Wang, A. Saleh, E. Osei, L. Hauck, C. Izaurralde, and J. Flowers. 2010. The Agricultural Policy Environmental Extender (APEX) model: An emerging tool for landscape and watershed environmental analyses. Trans. of the ASABE. Vol. 53(3): 711-740.

Georgia Agricultural Statistic Service. 2003. Agricultural Statistics Database [Online]. Available at http://www.nass.usda.gov:81/ipedb/(verified 2 Aug. 2004). Georgia Agric. Stat. Serv., Athens, GA.

Hargreaves, G.H. and Z.A. Samani. 1985. Reference crop evapotranspiration from temperature. Applied Engr. Agric. 1:96-99.

Harman, W.L. J.R. Williams, M. Magre, and E. Wang. 2004. Enviro-friendly cattle feedlots: Reducing nutrient losses with the APEX-feedlot model. Submitted to J. Environ. Qual.

Harmel, R.D., R.J. Cooper, R.M. Slade, R.L. Haney, and J.G. Arnold. 2006. Cumulative uncertainty in measured streamflow and water quality data for small watersheds. Trans. ASABE 49 (3), 689–701.

Hornsby, A.G., R.D. Wauchope, and A.E. Herner. 1995. Pesticide properties in the environment. Springer, New York.

Kellogg, R. L., et al. 2011a. Assessment of the effects of conservation practices on cultivated cropland in the Upper Mississippi River Basin. In Process. Conservation Effects Assessment Project. USDA, Natural Resources Conservation Service. Washington D.C.

Kellogg, R.L., et al. 2011b. Assessment of the effects of conservation practices on cultivated cropland in the Chesapeake Bay Watershed. In Process. Conservation Effects Assessment Project. USDA, Natural Resources Conservation Service. In Process. Washington D.C.

Liu, J., Williams, J.R., Zehnder, A.J.B., Yang, H., 2007. GEPIC—modeling wheat yield and crop water productivity with high resolution on a global scale. Agric. Syst. 94 (2), 478–493.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Binger, R.D. Harmel, and T. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50(3): 885-900.

Nash, J.E. and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models. Part 1: A discussion of principles. Journal of Hydrology 10(3), 282–290.

Perkins, H.F. 1987. Characterization data for selected Georgia Soils. The Georgia Agr. Exp. Stations College of Agriculture, The University of Georgia. Special Publication 43. Pedon 21, pg 468-469.

Plotkin, S., T.L. Potter, D.D. Bosch. J.K. Bagdon, and E.S. Hesketh. March, 2009. APEX Calibration and validation using research plots in Tifton, Georgia. USDA, Natural Resources Conservation Service, Amherst, MA. At: http://www.nrcs.usda.gov/technical/nri/ceap.

Plotkin, S.P., J.K. Bagdon, and E.S. Hesketh. 2010. USDA, NRCS/UMass Extension Pesticide Properties Database. USDA, Natural Resources Conservation Service. Amherst, MA.

Potter, T.L. March 23, 2006. Personal Communication. Pesticide properties for fluometuron and pendimethaln. Agricultural Research Service Research Southeast Watershed Research Laboratory, Tifton, GA.

Potter, T.L. 2007. Soil half-life of pendimethalin and fluometuron. Agricultural Research Service Research Southeast Watershed Research Laboratory, Tifton, GA. Unpublished.

Potter, T.L. 2010. Personal Communication. USDA, Agricultural Research Service Gibbs Farm Research Plots monitoring results and field operations. Agricultural Research Service Research Southeast Watershed Research Laboratory, Tifton, GA.

Potter, T.L., C.C. Truman, D.D. Bosch, and Craig Bednarz. 2004. Organic compounds in the environment. fluometuron and pendimethalin runoff from strip and conventionally tilled cotton in the Southern Atlantic Coastal Plain. J. Environ. Qual. 33:2122-2131.

Potter, T.L., C.C. Truman, D.D. Bosch, T.C. Strickland, and T.M. Webster, 2008. . Herbicide incorporation by irrigation and tillage impact on runoff loss. J. Environ. Qual. 37:839-847.

Ramanarayanan, T. S., J. R. Williams, W.A. Dugas, L.M. Hauck, and A.M.S. McFarland. 1997. "Using Apex to identify alternative practices for animal waste management." Presented at the ASAE International Meeting, Minneapolis, MN, August 10-14.

Ramanarayanan, T.S., M.V. Padmanabhan, G. N. Gajanan, and J.R. Williams. 1998. "Comparison of simulated and observed runoff and soil loss on three small United States watersheds." NATO ASI Series 1(55):76-88.

Rawls, W.J., Onstad, C.A., Richardson, H.H., 1980. Residue and tillage effects on SCS runoff curve numbers. Trans. ASAE 23, 357–361.

Rawls, W.J., Richardson, H.H., 1983. Runoff curve number for conservation tillage. J. Soil Water Conser. 38, 494–496.

Sagiv, Y., B. Rubin and B. Chefetz. 2008. Effects of irrigation with treated wastewater on the efficacy and fate of soil applied herbicides in cotton. Weed Science Society of America. Annual Meeting. Paper Number 165.

Saxton, K.E. and W.J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70:1569–1578.

Siemers, M. February, 2007. **I**_APEX Users Guide Using APEX2110 Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa

Soil Survey Geographic (SSURGO) database for Tift County. May 23, 2007. U.S. Department of Agriculture, Natural Resources Conservation Service. Fort Worth, Texas. At: URL:http://SoilDataMart.nrcs.usda.gov/.

USEPA. February 10, 2011. Office of Pesticide Programs' Aquatic Life Benchmarks. U.S. Environmental Protection Agency. Office of Pesticide Programs. Washinton D.C. Available at: http://www.epa.gov/oppefed1/ecorisk_ders/aquatic_life_benchmark.htm. Accessed 16 February, 2011.

USEPA. September, 2005. Reregistration Eligibility Decision (RED) – Fluometuron. Case Number 0049. USEPA, Office of Prevention, Pesticides And Toxic Substances. Washington DC.

USEPA. June, 1997. Reregistration Eligibility Decision (RED) – Pendimethalin. EPA 738-R-97-007. USEPA, Office of Prevention, Pesticides And Toxic Substances. Washington DC.

Wang, X., He, X., J.R. Williams, R.C. Izaurralde, and J.D. Atwood, J.D. 2005. Sensitivity and uncertainty analyses of crop yields and soil organic carbon simulated with EPIC. Transactions of the American Society of Agricultural and Biological Engineers 48 (3), 1041–1054.

Wang, X., P. W. Gassman, J. R. Williams, S. Potter, and A.R. Kemanian. 2008. Modeling the impacts of soil management practices on runoff, sediment yield, maize productivity, and soil organic carbon using APEX. Soil Tillage Res. 101:78-88.

Wang, X., S.R. Potter, J.R. Williams, J.D. Atwood, and T. Pitts. 2006. Sensitivity analysis of APEX for national assessment. Transactions of the American Society of Agricultural and Biological Engineers. 49(3), 679–688.

Wang, X., D. W. Hoffman, J. E. Wolfe, J. R. Williams, and W. E. Fox. 2009. Modeling the effectiveness of conservation practices at Shoal Creek watershed, Texas, using APEX. Transactions of the American Society of Agricultural and Biological Engineers. 52(4): 1181-1192.

Williams, J. R., and R. C. Izaurralde. 2006. The APEX model. In *Watershed Models*, 437-482. V. P. Singh and D. K. Frevert, eds. Boca Raton, Fla.: CRC Press

Williams, J. R., R. C. Izaurralde, and E. M. Steglich. 2008. Agricultural Policy/Environmental eXtender model: Theoretical documentation version 0604. BREC Report # 2008-17. Temple, TX: Texas AgriLIFE Research, Texas A&M University, Blackland Research and Extension Center. Available at: http://epicapex.brc.tamus.edu/downloads/user-manuals.aspx. Accessed 31 January 2010.

Williams, J.R., 1990. The erosion-productivity impact calculator (EPIC) model: a case history. Philos. Trans.: Biol. Sci. 329 (1255), 421–428.

Williams, J.R., E. Wang, A. Meinardus, W.L. Harman, M. Siemers, and J.D. Atwood. 2006. APEX users guide. V.2110. Temple, TX: Texas A&M University, Texas Agricultural Extension Service, Texas Agricultural Experiment Station, Blackland Research Center.