APEX Model Assessment of Variable Landscapes on Runoff and Dissolved Herbicides

A. Mudgal, C. Baffaut, S. H. Anderson, E. J. Sadler, A. L. Thompson

Abstract. *Variability in soil landscapes and their associated properties can have significant effects on erosion and deposition processes that affect runoff and transport of pesticides. Simulation models are one way in which the effects of landscapes on these processes can be assessed. This simulation study evaluated the effects of variations in landscape position on runoff and dissolved atrazine utilizing a calibrated farm- and field-scale Agricultural Policy/Environmental eXtender (APEX) model. Twelve agricultural plots (18 m × 189 m) in the Goodwater Creek watershed, a 7250 ha agricultural area in north-central Missouri, were simulated. Plots were treated with three tillage and herbicide management systems for two grain crop rotations. Each plot contained three landscape positions (summit, backslope, and footslope) along with two transition zones. Runoff was measured and samples were collected from 1997 to 2002 during the corn year of the crop rotations. Runoff samples were analyzed for dissolved atrazine. The model was calibrated and validated for each plot with event data from 1997 to 1999 and from 2000 to 2002, respectively. APEX reasonably simulated runoff and dissolved atrazine concentrations, with coefficients of determination (r^2) values ranging from 0.52 to 0.98 and from 0.52 to 0.97, and Nash-Sutcliffe efficiency (NSE) values ranging from 0.46 to 0.94 and from 0.45 to 0.86 for calibration and validation, respectively. The calibrated model was then used to simulate variable sequencing of landscape positions and associated soil properties as well as variable lengths of landscape positions. Simulated results indicated that the runoff and the atrazine load at the plot outlet increased when the backslope length increased while keeping the steepness constant. The maximum simulated runoff among different sequences of landscape positions occurred when the backslope position was located adjacent to the outlet. Results from this study will be helpful to managers in placement of conservation practices on sensitive landscapes for improvement in water quality.*

***Keywords.** APEX, Atrazine, Backslope, Critical areas, Footslope, Landscape position, Landscape sequence, Runoff, Summit.*

Soil and water management are an indispensable part of agriculture. However, the use of agrichemicals such as fertilizers and herbicides in modern agricultural production systems often increases nonpoint-source pollution. Runoff and subsequently soil erosion are two hydrologic processes responsible for water and soil quality deterioration and are impacted by local soil conditions. Claypan soils characterized by low subsoil permeability naturally possess a significant runoff potential and are especially vulnerable to elevated runoff losses of surface-applied herbicides (Ghidey et al., 2005).

Interactions between agrichemicals and soils are variable due to many factors, including the environment, soil type, chemical species, and method of application. Determining the interactions of agrichemicals within soils is an important step in efficiently managing fertilizer and herbicide applications. Several researchers, e.g., Ghidey and Alberts (1999) and Drori et al. (2005), have found that the behaviors of herbicides and nutrients are related to soil properties such as organic carbon content (OC), cation exchange capacity (CEC), and soil pH. Sudduth et al. (1995) reported that in fields and plots located in claypan soil areas, there was significant spatial variability in soil nutrient concentrations, soil water holding capacity, soil pH, topsoil depth, crop growth, and yield. Therefore, more site-specific approaches are necessary to reduce runoff and nonpoint-source pollutants (Veihe, 2000; Brunner et al., 2004).

Accordingly, the primary emphasis for conservation of water quality should be to define the critical areas within fields that are generating more runoff and nonpoint-source pollutants. Milne (1936) was among the initial researchers to propose the idea that soils are uniquely related to landscape position and to introduce the concept of a catena. He suggested that the processes at one point on the landscape not only affect soil properties and processes at that position but also soil properties at downslope landscape positions. Ruhe (1960) proposed five landscape elements: summit, shoulder, backslope, footslope, and toeslope. These elements are widely used with minor modifications (Hall and Olson, 1991) for soil studies, agricultural management, and the mitigation of nonpoint-source pollutants. Since different landscape positions have different surface and subsurface geometries and soil properties, these positions affect various hydrologic and

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The authors are **Ashish Mudgal, ASABE Member Engineer,** Student, Department of Soil , Environmental, and Atmospheric Sciences, University of Missouri, Columbia, Missouri; **Claire Baffaut, ASABE Member Engineer,** Research Hydrologist, USDA-ARS Cropping Systems and Water Quality Research Unit, Columbia, Missouri; **Stephen H. Anderson,** Professor, Department of Soil, Environmental, and Atmospheric Sciences, University of Missouri, Columbia, Missouri; **Edward John Sadler, ASABE Member,** Research Leader, USDA-ARS Cropping Systems and Water Quality Research Unit, Columbia, Missouri; and **Allen Thompson, ASABE Member Engineer,** Associate Professor, Department of Biological and Agricultural Engineering, University of Missouri, Columbia, Missouri. **Corresponding author:** Claire Baffaut, USDA-ARS Cropping Systems and Water Quality Research Unit, Columbia, MO 65211; phone: 573-882-1114, ext. 315, fax: 573-882-1115; e-mail: Claire.Baffaut@ars.usda.gov.

chemical processes occurring concurrently in the field. One approach for identifying critical areas in an agricultural field is to study the behavior of various landscape elements integrated together.

Some field experimental studies have been conducted to evaluate the contribution of different landscape positions to surface runoff, sediment load, and runoff of various nutrients and herbicides. Gabbard et al. (1998) studied the influence of topographic properties and hydrologic processes on runoff and soil erosion occurring at specific landscape positions by simulating the runoff and soil loss in the laboratory. They found that there was an increased probability of more soil loss as they moved from summit to lower backslope. Naef et al. (2002) experimentally evaluated various landscape positions according to the type and characteristics of the dominant runoff processes. They then proposed cropping systems and management practices specifically adapted to each area. In order to extend these results to other landscapes, there is a need to verify that simulation models produce results that are sensitive to landscape position and to their sequence along a hillslope profile. Attention needs to be given to the processes and the amounts of runoff and pollutant loadings simulated in each landscape position.

Often, a sequence of landscape positions occurs in the order of summit, backslope, and footslope, which have correspondingly different soil properties and surface topography. Jiang et al. (2007) showed that topsoil hydraulic conductivity, bulk density, and depth to claypan were significantly affected by the landscape position. In particular, bulk density was significantly higher in the footslope area at the 10 to 20 cm depth, followed by that of the backslope and then summit positions. At the same time, hydraulic conductivity for a tilled cropping system was one order of magnitude lower at the backslope than at the summit or footslope. But natural or man-made processes can occur that disrupt the natural sequence of these landscape positions. For example, stream bank erosion can lead to a situation where the backslope drains directly into the stream because the footslope has eroded away. Similarly, structural modification of the drainage in a field (terraces or grassed waterways) can lead to a different sequence of landscape positions. It is hypothesized that significant differences in runoff and agrichemical concentrations will occur at the outlet of a landscape due to variations in the sequence of landscape positions. These effects will also be different when differential lengths of landscape positions occur.

It is difficult to experimentally investigate the above proposition in natural settings and in a controlled environment where parameters other than those associated with landscape position, i.e., management, soil type, precipitation, would be similar. Simulation models are one way to overcome these limitations. Models provide the flexibility of simulating different landscape arrangements and of comparing the output over time. In this study, the Agricultural Policy/Environmental eXtender (APEX; Williams et al., 2008) was used to simulate runoff and atrazine loss from 189 m long plots that are typical of claypan landscapes. APEX is a field/watershed scale model that provides flexibility to define weather, land use, soils, topography, and management practices such as tillage, crop rotation, and agriculture inputs. The model can also take into account the impact of different configurations of management on erosion, water quantity and quality, and soil quality while allowing for routing processes for runoff, sediments, nutrients, and herbicides/pesticides within and from fields (Saleh et al., 2004; Wang et al., 2006). APEX performs all these processes across complex landscapes through the channel to small watershed or field outlets (Srivastava et al., 2007). Gassman et al. (2010) reviewed many APEX simulation studies for different environments with various agricultural management practices to simulate runoff, herbicides, and nutrients inside and at the outlet of watersheds. In all the studies, APEX was able to simulate different agricultural processes satisfactorily.

The goal of this simulation study was to evaluate the effects of landscape position on runoff and atrazine loss on claypan soils. Specific objectives were to: (1) test whether APEX is sensitive to variations of soil properties due to landscape position, and (2) determine the effects of the sequence and size of landscape positions with their corresponding slope and soil properties on the amount and intensity of simulated runoff and dissolved atrazine losses from claypan soils.

Materials and Methodology

Study Area and Cropping Systems

The study area is located in the Goodwater Creek Experimental Watershed (GCEW), a 7250 ha agricultural area in north-central Missouri. The area is characterized by a 30-year average annual precipitation of 964 mm and average annual minimum and maximum daily temperatures of 6.3°C and 16.9°C, respectively. Thirty 189 m × 18 m research plots (fig. 1), were laid out in 1991 in the southeast part of the GCEW to evaluate the effects of cropping systems on yield and transport of agrichemicals to surface water (Ghidey et al., 2005). These plots were hydrologically separated by berms to avoid intermixing of surface flow, and vertical plastic lining was inserted along the berm length to prevent subsurface flow between plots. The plot sites are on a sloping landscape (slopes ranging between 0% and 3%) with three major landscape positions: summit, backslope, and footslope. The lengths of each landscape position varied from plot to plot. Generally, the footslope was found to be shortest in all the plots and ranged from 18 to 33 m among all plots. Summit and backslope positions were almost equivalent in length and ranged from 30 to 52 m and from 24 to 55 m, respectively, for all the plots.

The predominant soils in the GCEW watershed are claypan soils (93%) of the Central Claypan Soil Major Land Resource Area (MLRA 113), an area of about 3 million ha in Missouri and Illinois (USDA-NRCS, 2006; Lerch et al., 2005). Claypan soils have a dense and very slowly permeable layer generally occurring 15 to 45 cm below the surface and having much higher clay content than the overlying material. Claypan soils impart a unique hydrology by impeding the vertical flow of water and thus increasing surface runoff (Kitchen et al., 1999; Jung et al., 2005). The soils within the plots for this study are primarily classified as Mexico (fine, smectitic, mesic Aeric Vertic Epiaqualfs) and Adco (fine, smectitic, mesic Vertic Albaqualfs), which have the characteristic argillic horizon with clay content >500 g kg^{-1} and have a considerable quantity of smectitic clay minerals with high shrink-swell potential. These claypan soils can have crack volumes ranging around 0.06 m^3 m^{-3} due to high shrinkage during dry summers (Baer and Anderson, 1997; Jung et al., 2005).

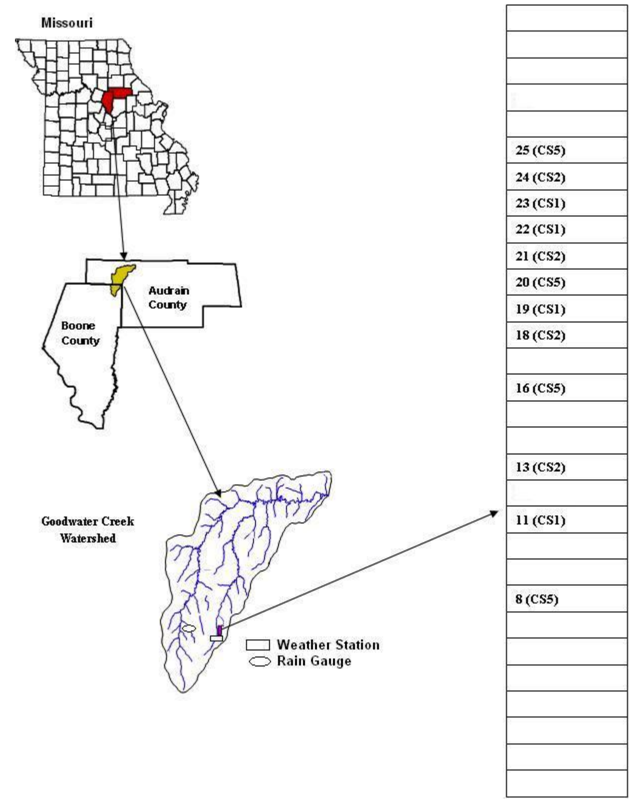


Figure 1. Location of the twelve research plots, rain gauge, and weather station with plot numbers and treatments used for the present study: CS1 = mulch tillage corn/soybean rotation, CS2 = no-till corn/soybean rotation, and CS5 = no-till corn/soybean/wheat rotation (adapted from Ghidey et al., 2005).

Out of the thirty plots, six plots per year with three different tillage and herbicide management sequences were selected for measurement of surface runoff during the corn year of the rotation from 1997 to 2002. Overall, twelve plots were selected for the present simulation study: four plots under cropping system 1 (CS1), a mulch tillage corn/soybean rotation system; four plots under cropping system 2 (CS2), a no-till corn/soybean rotation; and four plots under cropping system 3 (CS5), a no-till corn/soybean/wheat rotation. For the third cropping system (CS5), an adaptive weed management practice was followed for which the herbicide type, rate, and timing were specific to weed intensity and species (Ghidey et al., 2005). Since the corn year of these plots was monitored from 1997 to 2002, runoff and dissolved herbicide data were available for each plot only for two to three years depending on the length of the rotation (table 1).

The twelve plots represented the three cropping systems with four plots in each. For each cropping system, two plots had the corn crop one year and the other two plots the next year. These plots with similar cropping system and similar cropping years were treated as replicates during the statistical analysis. Thus, for each cropping system, there were two sets of replicates.

Runoff Measurement and Sample Analysis

In 1996, the outlets of the selected plots were instrumented with ASTM-standard Parshall flumes (Culverts and Industrial Supply Co., Mills, Wyo.) with nominal 0.154 m throat to measure the runoff amount on an event basis. Head was measured by a pressure sensor (America Sigma, Inc., New York, N.Y.) for the calculation of total discharge for each event. A flow-proportioning sampler (Sigma 900MAX, America Sigma, Inc., New York, N.Y.) with an eight-bottle rack was installed near the stilling well and connected to the sensor. Each bottle sampled up to 6.35 mm of runoff, which enabled the sampling of a maximum 50 mm total runoff depth. Collected runoff samples were analyzed for atrazine concentrations (Ghidey et al., 2005).

Table 1. Research plots under corn management with respective treatments, by year: CS1 = mulch tillage corn/soybean rotation, CS2 = no-till corn/soybean rotation, and CS5 = no-till corn/soybean/wheat rotation.

Year	Plots	Cropping System
1997	19, 22	CS1
	13, 24	CS2
	8, 16	CS5
1998	11, 23	CS1
	18, 21	CS2
	20, 25	CS5
1999	19, 22	CS1
	13, 24	CS2
2000	11, 23	CS1
	18, 21	CS2
	8, 16	CS5
2001	19, 22	CS1
	13, 24	CS2
	20, 25	CS5
2002	11, 23	CS1
	18, 21	CS2

APEX Model Setup and Input Parameters

Due to the presence of a shallow claypan in the study area and low permeability of the soils, surface runoff was the major component of the hydrology. APEX includes two possible methods for estimating runoff volume: a modification of the Natural Resources Conservation Service (NRCS) curve number technique (USDA-NRCS, 2004), and the Green and Ampt infiltration equation (Green and Ampt, 1911). The curve number method was used because it easily relates runoff to soil type, land use, and management practices (Williams et al., 2006).

The model was set up for each plot from 1997 to 2002, the period during which runoff was monitored and samples were collected and analyzed. The major inputs required for the model were soil parameters, weather, site conditions, cropping systems, and field management. An automated weather station was installed near the plots in 1991 (fig. 1), from which sub-daily rainfall (mm), temperature (°C), average solar radiation (MJ m^{-2}), and wind speed (mm h^{-1}) data were collected, recorded, and maintained in a server database managed by the Cropping Systems and Water Quality Research Unit (CSWQRU) at the University of Missouri-Columbia (Sadler et al., 2006).

Each plot's cropping and management system was outlined by Ghidey et al. (2005). Protocols were developed each year by the USDA-ARS-CSWQRU in Columbia, Missouri. Soil data measured on the plots were obtained from Dr. N. R. Kitchen (soil scientist, ARS-CSWQRU, March 2007, personal communication) for the soil samples collected from four landscape positions in nine plots out of thirty. The landscape positions included summit, backslope, footslope, and the shoulder, which is the transition between the summit and the backslope. Properties measured included texture, cation exchange capacity, organic carbon content, sum of bases, and pH for four to six horizons in each profile. Plots with missing soil data were assigned the data of plots having similar management and located nearest to the plot of interest. Soil physical parameters, i.e., vertical saturated hydraulic conductivity (K_{sat}), field capacity, and bulk density, were measured by Jiang et al. (2007). They collected soil samples for three depths at 10 cm intervals for all landscape positions per plot except for the footslope where an additional depth of 30 to 40 cm was also included. To minimize the variability in soil physical parameters, average values were used for the same management, landscape position, and depth. For more details on soil properties, see Jiang et al. (2007).

The measured values of K_{sat} by Jiang et al. (2007) were the vertical K_{sat}, but in the present simulation study these values were also considered as horizontal K_{sat}. In a study in a similar area, Mudgal et al. (2010) found that the horizontal and vertical K_{sat} values were almost equivalent. In another study with similar soils, Blanco-Canqui et al. (2002) also found non-significant differences between horizontal and vertical K_{sat} values.

A detailed elevation contour map of the study area is available in Kitchen et al. (1998). Elevation difference between the summit and plot outlet was about 2 m, with maximum slope at the backslope position, for all of the plots. Between summit and backslope, a transition zone was also delineated, i.e., a slight convex shoulder (Myers et al., 2007). Similarly, a transition between backslope and footslope was also delineated, with 0% to 2% slope.

Once data sets were established, separate files for each plot were created. Each plot was divided into five landscape positions: summit, transition between summit and backslope, backslope, transition between backslope and footslope, and footslope. The lengths of three main landscape positions ranged as follows: summit, 31 to 52 m; backslope, 25 to 55 m; and footslope, 18 to 33 m. For most plots, the backslope was the longest and the footslope the shortest.

Model Calibration

A manual sensitivity analysis was conducted for three plots, one from each cropping system, to identify sensitive parameters. Most of the APEX parameters incorporated in this sensitivity analysis were previously analyzed by Wang et al. (2006). A few other parameters were also considered: the selection of the method to estimate the curve number out of four possible choices and their corresponding parameters, the selection of potential evapotranspiration (PET) estimation method out of five different methods provided in APEX and the corresponding parameters, and all control parameters related to soil moisture content and pesticide movement. Main soil parameters were not considered during calibration because measured values were available, but some of them were tested for sensitivity analysis. In a study at the same site, Jiang et al. (2007) found significant differences in depth to claypan, K_{sat}, and bulk density for different landscapes. Therefore, it was speculated these properties could explain the variations in runoff generation and atrazine loss from different landscape positions. Hence, model sensitivity for these soil parameters was also tested. As stated before, no difference was considered between horizontal and vertical K_{sat} values; therefore, during the sensitivity analysis, both parameters were tested by varying them together. Single-parameter sensitivity analysis was done by varying one parameter at a time from its maximum to minimum values and recording the subsequent changes in runoff and atrazine concentrations at the plot outlets.

The APEX model was calibrated and validated separately for each of the twelve plots. Since each plot was calibrated separately, values of some parameters were slightly different among plots. The parameters were adjusted to calibrate surface runoff, crop yield, and then atrazine concentrations in runoff. Other than soil, management, weather, and topographic data, the model was started with the default values of the parameters provided in the model.

Calibration of the model was done on an event basis for runoff and dissolved atrazine concentrations. The calibration and validation periods were selected to have a comparable number of events in each: 1997 to 1999 for calibration and 2000 to 2002 for validation. The model's goodness of fit was evaluated through the linear regression (r^2) method and the Nash and Sutcliffe (1970) efficiency equation:

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(Q_m - Q_s)^2}{\sum_{i=1}^{n}(Q_m - Q_a)^2} \quad (1)$$

where NSE is the efficiency of the model, Q_m are measured values, Q_s are simulated values, Q_a is the average measured value, and n is the number of events. The r^2 method measures the correlation between measured and simulated values. The Nash-Sutcliffe equation measures how simulated values match the observed data. If NSE is close to 0.0, then the model simulation is no more accurate than the mean of the observed data; if it is 1, the simulation is considered perfect. Moriasi et al. (2007) recommended that NSE be greater than 0.5 and 0.7 for satisfactory and good calibration, respectively, at a monthly time step and noted that it may need to be relaxed for daily time step calibrations. These authors also indicated that values of r^2 greater than 0.5 are often considered acceptable. However, they cautioned the use of r^2 because of its sensitivity to high values. Krause et al. (2005) suggested that when the r^2 efficiency criteria is considered, one should additionally use the slope and intercept values of the line of fit, and the slope's value should be close to 1 for a good agreement between simulated and measured values. Slopes greater and lower than 1 indicate over- and underestimation, respectively, only when the intercept is close to zero.

Many researchers have considered various acceptable ranges for r^2 and NSE based upon the amount of available measured data, output time interval, and purpose of the study. Ramanarayanan et al. (1997) have taken $r^2 > 0.5$ and NSE > 0.40 as satisfactory values for the APEX model while studying surface water quality for daily events. Wang et al. (2007) suggested values of $r^2 > 0.5$ and NSE > 0.40 as acceptable for monthly outputs of streamflow, nutrient concentrations, and runoff using the APEX model. In addition, Santhi et al. (2001) found $r^2 > 0.5$ and NSE > 0.5 as acceptable values for monthly calibration values using the Soil and Water Assessment Tool (SWAT), a watershed-scale model that is very similar to APEX. In this study, $r^2 > 0.5$ and NSE > 0.45 were

Table 2. Theoretical sequence of landscape positions with abbreviations.

	Landscape Sequence	Upper Position	Transition Zone (TZ)	Middle Position	Transition Zone (TZ)	Lower Position
Theoretical sequence	SFB	Summit		Footslope		Backslope
	FSB	Footslope		Summit		Backslope
	FBS	Footslope		Backslope		Summit
	BFS	Backslope		Footslope		Summit
	BSF	Backslope		Summit		Footslope
Original sequence	SBF	Summit		Backslope		Footslope

selected as thresholds for satisfactory calibration and validation, with regression between measured and simulated values having slope and intercept close to 1 and 0, respectively.

Landscape Sequence and Size

After the calibration and validation of the model, simulations were conducted to predict the effects on runoff and dissolved atrazine concentrations for two different types of landscape variations: (1) varying the sequence of landscape positions; and (2) varying the size of landscape positions. For the first type of landscape variation, six permutations of the sequence of landscape positions were considered. The natural sequence (summit-backslope-footslope) was the baseline sequence to which others were compared. Five theoretical sequences were developed and are shown in table 2. For the purpose of evaluating the sensitivity of the model to these permutations, we considered all the theoretical sequences independently of their likelihood of occurrence. The profiles and soil properties of the transition zones were adapted to fit each theoretical sequence. Simulations were performed with the calibrated model separately for each plot and each sequence with measured weather data from 1978 to 2007. The collection of measured climate data at the research plot site was initiated in 1993. Therefore, rainfall data measured at the nearest available rain gauge (fig. 1) was used for the 1978 to 1992 precipitation inputs to the model, while the remaining climate data inputs were generated in APEX during that period. There were six simulations per plot, which were compared for seasonal runoff and atrazine loads from May to October at the plot outlet as affected by landscape sequence.

For the second type of landscape variation, three scenarios were planned using the natural sequence of landscape positions. In each scenario, the length of one out of three landscape positions was increased by 20% while maintaining the lengths of the others. The percent slope for all the landscape positions was left unchanged. Three simulations were conducted with the calibrated model independently for each plot, one for each size of landscape position, from 1978 to 2007, using measured weather data. The three simulations were then compared for seasonal runoff and atrazine loads during the cropping season at the plot outlet as affected by the size of each landscape position for the three cropping systems.

Percent change in runoff and atrazine load relative to the natural landscape sequence or size was calculated for the five theoretical sequences and the three sizes. Statistical comparisons were made among the sequences or sizes using SAS (SAS, 1999) with the PROC GLM procedure. The sequence and size of the landscape positions were tested for significant effects on runoff and atrazine loads at the 95% confidence level ($p < 0.05$).

Result and Discussion

Sensitivity Analysis

The most suitable method for runoff calculation was determined to be the nonlinear curve number estimation method weighted by soil water content. This method calculates the curve number based on water content in the soil profile. The Hargreaves equation was used to estimate potential evapotranspiration. These methods were selected because they gave the best results as compared to measured data.

The two soil parameters found to be significantly different across landscape positions by Jiang et al. (2007), the hydraulic conductivity (K_{sat}) and the depth to claypan, were also found to significantly affect the results of the APEX model. Thus, there was strong indication that the APEX model would be able to discriminate these landscape positions based on their potential to generate runoff and herbicide losses. Higher K_{sat} values and deeper clay pan reduced the amount of runoff generated and the atrazine loss. The model was not found to be sensitive for the measured range of values of bulk density.

Parameters found sensitive for estimating atrazine loads are presented in table 3. The pesticide leaching ratio and pes–

Table 3. Parameters considered for calibration of the model (for detailed description of parameters, see Williams et al., 2008).

Input File	Parameter	Abbreviation	Description	Range	Calibrated Values[a]
PARM	PARM3	WSHI	Water stress harvest index	0.0 - 1.0	0.7
	PARM5	SWLL	Soil water lower limit in the top 0.5 m soil depth	0.0 - 1.0	0.7 - 0.8
	PARM16	ECRP	Expands CN retention parameter (1.0 - 1.5)	1.0 - 1.5	1.1 - 1.3
	PARM17	SEPC	Soil evaporation plant cover factor	.01 - 0.5	0.3
	PARM24	PLR	Pesticide leaching ratio	0.1 - 1.0	0.1 - 0.2
	PARM34	HPETE	Hargreaves PET equation exponent	0.5 - 0.6	0.6
	PARM38	WSEC	Water stress weighting coefficient	0.0 - 1.0	0.5 - 0.6
	PARM42	CNIC	NRCS curve number index coefficient	0.3 - 2.5	0.8 -1.2
	PARM44	UCNRP	Upper limit of CN retention parameter	1.0 - 2.0	1.3 - 1.6
	PARM63	PLC	Pesticide loss coefficient	0.1 - 1.0	0.15 - 0.25
Pest.Dat		PHLS	Pesticide half-life in soils (days)	10 - 100	30

[a] Range of values is provided if different values were used for different plots.

Table 4. Range of r^2 and NSE values and total number of runoff events recorded during calibration and validation periods for all the plots under different cropping systems: CS1 = mulch tillage corn/soybean rotation, CS2 = no-till corn/soybean rotation, and CS5 = no-till corn/soybean/wheat rotation.

Cropping System	Runoff			Atrazine Loads			Runoff Events[a]
	r^2	NSE	BIAS	r^2	NSE	BIAS	
Calibration (1997 to 1999)							
CS1	0.58 - 0.93	0.49 - 0.61	-51% to -24%	0.52 - 0.89	0.46 - 0.65	-53% to -3%	7 - 8
CS2	0.60 - 0.90	0.47 - 0.65	-49% to -18%	0.52 - 0.92	0.46 - 0.68	-51% to -15%	5 - 7
CS5	0.76 - 0.92	0.46 - 0.67	-59% to -32%	0.53 - 0.89	0.48 - 0.73	-25% to -13%	5 - 8
Validation (2000 to 2002)							
CS1	0.65 - 0.98	0.59 - 0.94	-39% to -12%	0.60 - 0.97	0.49 - 0.86	-26% to -6%	13 - 19
CS2	0.71 - 0.92	0.52 - 0.89	-34% to -12%	0.52 - 0.86	0.46 - 0.77	-41% to -2%	6 - 16
CS5	0.65 - 0.95	0.58 - 0.92	-51% to -13%	0.58 - 0.93	0.42 - 0.80	-34% to -4%	12 - 19

[a] Number of runoff events recorded during the corn phase.

ticide loss coefficient are related to soil properties and partition the atrazine loss between that moving downwards with percolating water in the soil profile and what is moving with surface runoff. During calibration, these two parameters were allowed to be different among the plots based on the management, whereas the atrazine half-life in soil was considered similar for all plots. Its calibrated final value was found to be 30 days. The other parameters listed in table 3 were adjusted during the calibration of the model within the ranges recommended in the APEX manual (Steglich and Williams, 2008).

Model Calibration and Validation

The coefficient of determination (r^2) and NSE value ranges for each cropping system are shown in table 4, along with the range of number of events recorded on each plot during the corn phase and used for calibration and validation. These events are daily events and the number varied by plot based on which year the plots were under corn (table 1). In all cases, the r^2 and NSE values were greater than 0.5 and 0.42, respectively. The r^2 varied more than expected, ranging from 0.5 to 0.9 for different plots of the same cropping system. This may be due to the fact that the years of the corn phase were different for different plots.

The criterion determined by Moriasi et al. (2007) for flow calibration at the monthly time step is a minimum NSE of 0.5 and a maximum percent bias of 25%. These daily time step results for a small number of events on each plot are therefore quite strong. In all cases, the goodness of fit was lower when there were fewer events recorded, a possible indication that the model performed better under normal or wet conditions. This may explain why the r^2 and NSE values were slightly lower during the drier calibration period for which there were 5 to 8 events recorded on each plot compared to the wetter validation period for which there were 8 to 19 events.

As suggested by Krause et al. (2005), the slope of the line of fit value is indicative of the bias of simulated output relative to measured values. Figure 2 illustrates some linear regression results, better and worse, between measured and simulated values. In figure 2a, which illustrates runoff validation results from plot 11, the slope is 1.11 and the intercept is 1.1. With a slope close to 1 and an intercept close to zero, these values indicate no strong bias. In comparison, figure 2b shows the worst-case scenario. It illustrates the calibration results for daily atrazine load from plot 18. In this case, r^2 and NSE were 0.57 and 0.48, respectively, percent bias was -51%, and the line of fit slope (0.63) and intercept (7.15) indicate a bias and an overestimation of the loads.

Overall, average NSE values for each cropping system varied from 0.55 to 0.77 for runoff and from 0.53 to 0.64 for atrazine loads. Average percent bias for each cropping system varied from -24% to -36% for runoff with an exception of -50% for CS1. For atrazine loads, percent bias varied from -17% to -38%. In spite of some poorer results on some of the plots, these results were quite satisfactory in comparison to other APEX studies compiled by Gassman et al. (2010). Saleh et al. (2004) found NSE values in the range of 0.74 to 0.88 for daily runoff measured over 35 to 108 events in nine forested watersheds in eastern Texas; no validation results were reported. Wang et al. (2009) calibrated and validated the APEX model for the 22.5 km^2 Shoal Creek watershed, Fort Hood, Texas, and achieved r^2 and NSE values in the range of

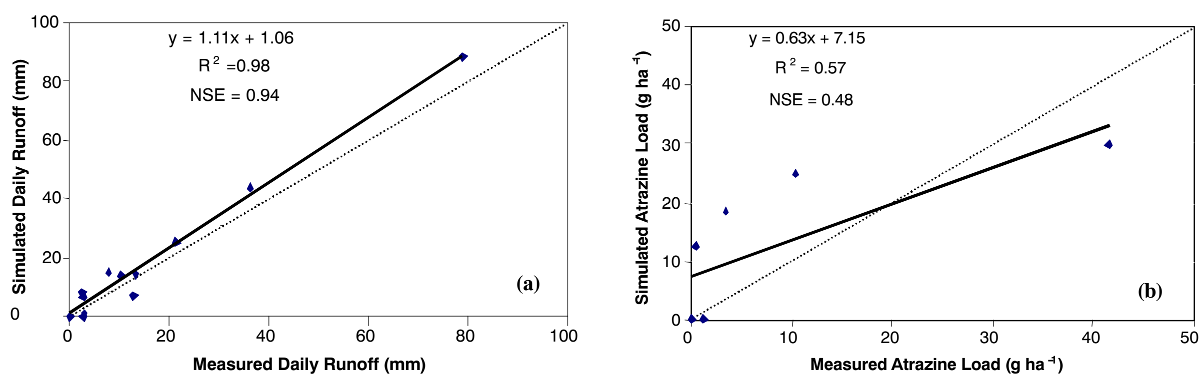


Figure 2. Examples of linear regressions of measured vs. simulated values: (a) daily runoff during validation period at plot 11, management CS1 (mulch tillage corn/soybean rotation system), and (b) daily atrazine load during calibration period at plot 18, management CS2 (no-till corn/soybean rotation system).

Table 5. Effects of landscape sequence on 30-year average annual runoff on plots with different management: CS1 = mulch tillage corn/soybean rotation, CS2 = no-till corn/soybean rotation, and CS5 = no-till corn/soybean/wheat rotation.

Landscape Sequence[b]	Simulated Average Annual Runoff (mm)[a]					
	CS1		CS2		CS5	
	I[c]	II[c]	I	II	I	II
SBF	176 c	177 b	178 b	178 b	183 b	187 b
FSB	250 a	246 a	251 a	254 a	262 a	269 a
SFB	229 ab	229 a	234 a	236 a	241 a	245 a
FBS	216 abc	213 ab	215 ab	215 ab	221 ab	225 ab
BFS	183 c	181 b	182 b	183 b	189 b	194 b
BSF	172 c	168 b	168 b	168 b	177 b	179 b

[a] Within a column, sequences with the same letter are not significantly different at the 95% confidence level.
[b] S = summit, B = backslope, and F = footslope.
[c] Plots under corn during same year are grouped together to calculate the means, giving two different groups in each treatment, I and II.

Table 6. Effects of landscape sequence on 30-year average annual area unit atrazine loss on plots with different management: CS1 = mulch tillage corn/soybean rotation, CS2 = no-till corn/soybean rotation, and CS5 = no-till corn/soybean/wheat rotation.

Landscape Sequence[b]	Simulated Average Annual Atrazine Loss (g ha^{-1})[a]					
	CS1		CS2		CS5	
	I[c]	II[c]	I	II	I	II
SBF	38 bc	32 c	46 d	47 bc	52 b	65 c
FSB	56 a	52 a	70 a	69 a	77 a	96 a
SFB	48 ab	44 b	62 ab	63 a	71 a	90 ab
FBS	45 bc	42 b	57 bc	59 ab	66 a	82 abc
BFS	39 bc	34 c	48 cd	48 bc	55 b	67 bc
BSF	35 c	30 c	44 d	44 c	51 b	63 c

[a] Within a column, sequences with same letter are not significantly different at the 95% confidence level.
[b] S = summit, B = backslope, and F = footslope.
[c] Plots under corn during the same year are grouped to calculate the means, giving two different groups in each treatment, I and II.

0.60 to 0.80 and 0.33 to 0.77, respectively, for daily stream flow. Williams et al. (2006) obtained r^2 values of 0.72 to 0.73 for surface runoff in a study at a Bison feedlot in North Dakota.

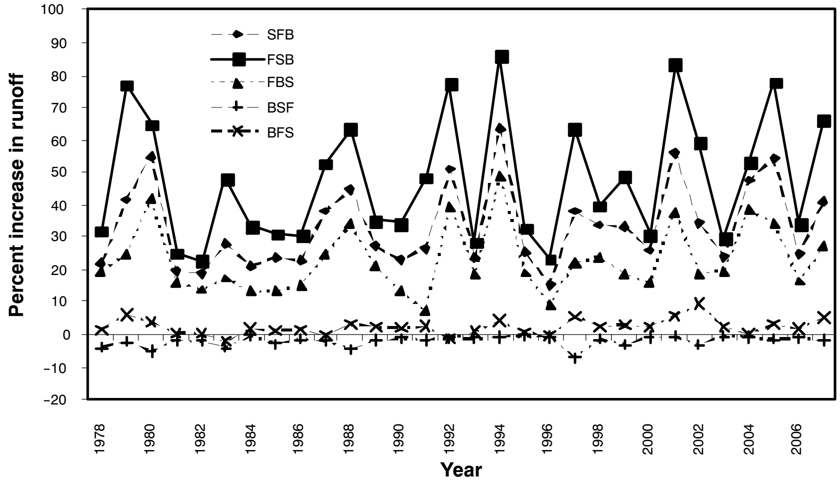
Landscape Sequence and Size

The effect of varying the landscape sequence from its natural order was very similar for all three cropping systems, as shown in tables 5 and 6 for runoff and area unit atrazine loss, respectively. The maximum runoff and atrazine loss occurred at the plot outlet when backslope conditions were found just before the outlet (i.e., FSB and SFB sequences, table 2) and were significantly different ($p < 0.0001$) from the natural sequence (i.e., SBF sequence, table 2). Any of the other sequences in which either the footslope or the summit positions were positioned just before the outlet did not consistently produce significantly different runoff or atrazine loss compared to the natural sequence. However, the sequence FBS, the complete reversal of the natural sequence, did produce significantly higher area unit atrazine loss than the natural sequence (SBF) for half of the plots in each treatment. The runoff values, although always higher for FBS than for SBF, were not significantly higher compared to any of the other sequences.

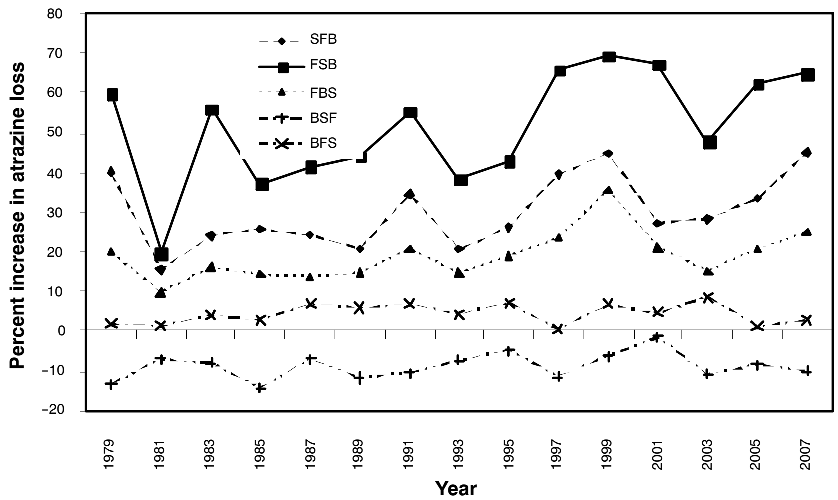
The relative difference between each sequence and the natural sequence is visualized for plot 19 of CS1 in figure 3, which shows that the sequence that generates more runoff and atrazine load remains higher for all the years, and the sequence generating the least also remained lowest for all years. The magnitude of the differences varies from year to year because of the corn-soybean rotation and the weather variability. Atrazine loss is shown only for alternate years as it was applied only during the corn cropping years. Increase in runoff when backslope conditions occurred near the outlet ranged from 20% to 80%. Increase in atrazine loss ranged from 20% to 70%, as depicted in figure 3. This trend was similar for all other cropping systems, and the maximum increase in runoff and atrazine loss among all plots was 86% and 80%, respectively.

These results could be attributed to the fact that during sensitivity analysis of the model the runoff generated was found to be sensitive to the saturated hydraulic conductivity (K_{sat}) of the soil and the depth to claypan. Both parameters varied significantly with landscape position. In a previous study, the variation in vertical K_{sat} with landscape position was found significant in all the plots (Jiang et al., 2007), with the highest surface K_{sat} at the footslope and lowest at the backslope. K_{sat} values of the surface layer were on average 5 mm h^{-1} for the footslope positions while they were only 0.43 mm h^{-1} for the backslope. In addition, the depth to claypan was least at the backslope (7 to 17 cm) and largest at the footslope (21 to 70 cm) (Kitchen et al., 1998). Thus, the backslope was where runoff was first generated due to the lower permeability of the surface layer and the smaller water holding capacity caused by a shallow depth to claypan. The lower conductivity of the surface layer also impacted the ability of that layer to drain through lateral subsurface flow. This lower permeability resulted in higher values of the curve number, which increased the occurrence and magnitude of simulated runoff. It also decreased the percolation out of that surface layer, which together with a shallow depth to claypan, increased the surface layer water content and caused an increase in the daily value of the curve number and in runoff. During a rainfall event, when the backslope was at the end of the sequence, water coming from the upper part of the landscape flowed directly out of the plot and hence increased runoff and dissolved atrazine loss. But when the footslope was at the end, its thicker and more permeable silt loam layer above the claypan acted as a buffer by allowing runoff and dissolved atrazine to infiltrate rather than to flow laterally. In that case, the runoff and atrazine load at the outlet of the landscape were lower. When the summit was located at the outlet, the runoff and atrazine load generated were between the two extremes. These results were expected, as the claypan thickness and K_{sat} values of the summit position were also between those of the footslope and backslope positions.

Significant changes in the frequency of runoff occurrence for the landscape sequences were also found. The percentage of runoff days occurring relative to the occurrence of precipitation days (% RO) during a season was calculated by dividing the total number of runoff days by the total number of rainfall days during one season. As figure 4 shows, the highest % RO was for the FSB sequence almost for every year, and the lowest % RO was for the BSF sequence. An increase in runoff events means more vulnerability to atrazine transport with runoff from the plots. There were 10% more runoff-causing precipitation events for the sequence that produced the most runoff events compared to the sequence that pro-



(a)



(b)

Figure 3. Seasonal percent increase in (a) runoff (mm) and (b) atrazine loss (g ha^{-1}, only during corn cropping years) for the theoretical landscape sequences relative to the natural sequence (SBF), for crop management CS1 (mulch tillage corn/soybean rotation), plot 19.

Table 7. Effects of the size of landscape position on 30-year average annual runoff on plots with different management: CS1 = mulch tillage corn/soybean rotation, CS2 = no-till corn/soybean rotation, and CS5 = no-till corn/soybean/wheat rotation.

	Simulated Average Annual Runoff (mm)[a]					
	CS1		CS2		CS5	
Scenario	I[b]	II[b]	I	II	I	II
Increase in backslope	245 a	240 a	250 a	249 a	257 a	262 a
Increase in summit	221 ab	221 a	223 ab	230 a	226 a	231 ab
Control	176 b	177 b	178 b	178 b	183 b	187 b
Increase in footslope	172 b	175 b	176 b	175 b	179 b	183 b

[a] Within a column, sequences with same letter are not significantly different at the 95% confidence level.
[b] Plots under corn during the same year are grouped to calculate the means.

Table 8. Effects of the size of landscape position on 30-year average annual area unit atrazine loss on plots with different management: CS1 = mulch tillage corn/soybean rotation, CS2 = no-till corn/soybean rotation, and CS5 = no-till corn/soybean/wheat rotation.

	Simulated Average Annual Runoff (mm)[a]					
	CS1		CS2		CS5	
Scenario	I[b]	II[b]	I	II	I	II
Increase in backslope	54 a	48 a	68 a	66 a	76 a	93 a
Increase in summit	47 ab	41 a	58 ab	57 a	65 a	81 ab
Control	39 b	34 b	48 bc	47 b	52 b	65 b
Increase in footslope	36 b	31 b	44 c	43 b	50 b	63 b

[a] Within a column, sequences with same letter are not significantly different at the 95% confidence level.
[b] Plots under corn during the same year are grouped to calculate the means.

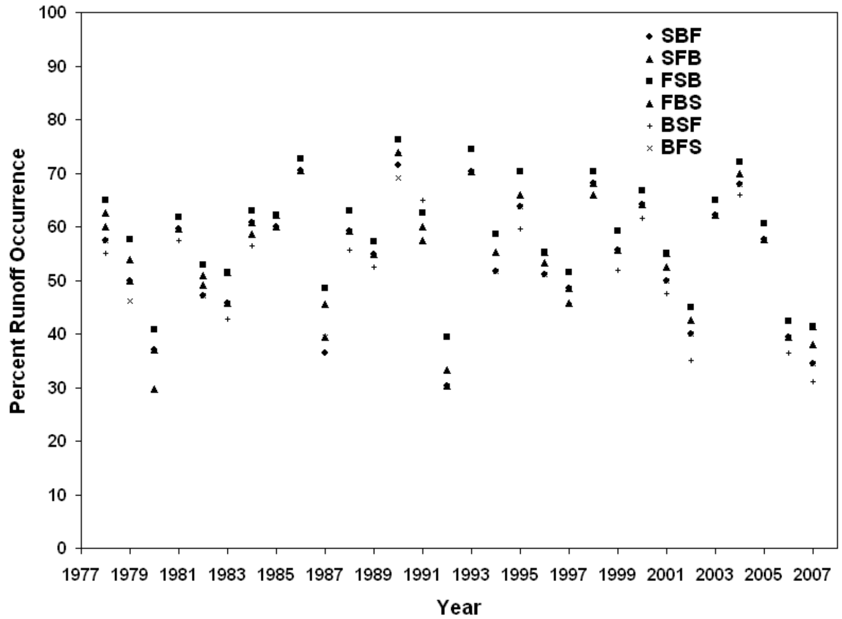
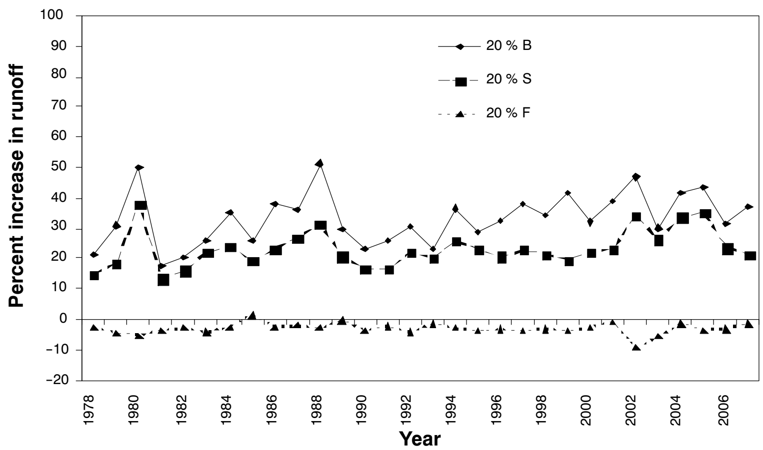
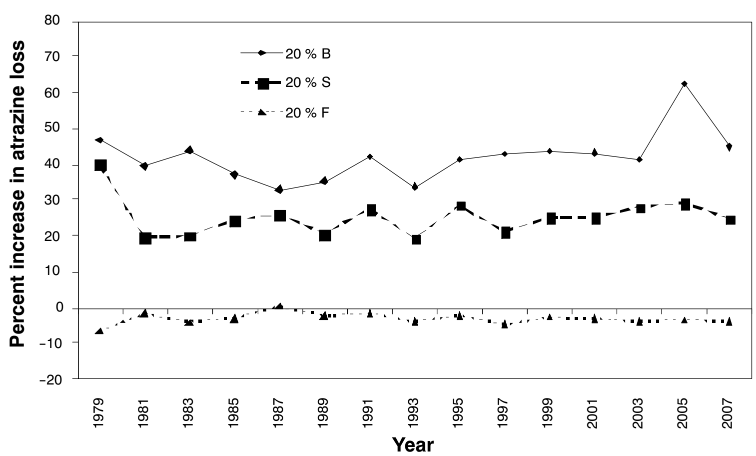


Figure 4. Frequency of seasonal runoff occurrence (% RO) for five theoretical landscape sequences and one natural sequence from 1978 to 2007.



(a)



(b)

Figure 5. Seasonal percent increase in (a) runoff (mm) and (b) atrazine loss (g ha^{-1}, only during corn cropping years) as influenced by increases in the length of specific landscape positions, for crop management CS1 (mulch tillage corn/soybean rotation), plot 19.

duced the least for the annual average of the total simulation period.

Tables 7 and 8 show the seasonal percent change in runoff and atrazine load with modified lengths of the landscape positions. The general trend was found to be similar within each cropping system during all the years (fig. 5). The highest increase in runoff and atrazine load at the plot outlet occurred when the backslope position was increased by 20%. No difference occurred in runoff when the footslope position was lengthened.

Statistical analysis showed that runoff and atrazine loss at the plot outlet were significantly increased with the increase in the backslope lengths. The reduction in runoff and atrazine loss observed with an increase in the footslope was not statistically significant. The increase in the length of the summit position showed a different trend; in each treatment, two plots had a significant increase in runoff and atrazine loss in comparison to the control, and two had a non-significant increase.

Figure 5 shows the relative increase in runoff and atrazine load with the change in different landscape sizes for plot 19 of cropping system 1, and the trend is similar for all the plots under all cropping systems. The largest increases in runoff and atrazine area unit loss were obtained when the length of the backslope was increased by 20%. This indicates that a longer backslope, even when buffered by a footslope, could have damaging effects in terms of increased runoff and atrazine load. Therefore, priority has to be given to treat the longer backslope first. The maximum relative increase in runoff and atrazine load among all the plots due to backslope increase was 83% and 72%, respectively, and the average relative increases were 33% and 42%, respectively.

The difference in runoff and atrazine load due to landscape size increase could also be attributed to the fact that the lengths of the landscape positions were increased by 20% of the original length. With the backslope being the longest for all the plots and the footslope position the shortest, the 20% increase in the length resulted in a larger lengthening of the backslope than the footslope position. An alternate explanation may be that the length of the footslope does not significantly affect the runoff or atrazine load. To test these possible explanations, the model was run from 1997 to 2002 and the footslope length was increased by increments of 3, 5, and 10 m; the original footslope lengths for all the plots ranged from 18 to 33 m. No significant difference was found for runoff and atrazine load between control and landscape with increased footslope length. While this supports the possibility that lengthening the footslope does not significantly change runoff and atrazine loadings as long as there is a footslope, further investigations need to confirm this.

Implications

Conclusively, all the results from the present study point out that in the claypan region a landscape sequence with shallower clay depth (as in backslope position) near the outlet would generate more runoff and atrazine load. Similarly, a longer landscape with shallower claypan depth would be prone to generate more runoff and atrazine load. On the other hand, if clay was deeper in the profile near the outlet, it would reduce the runoff and atrazine load at the outlet. These results have significant implications for management. Instead of treating and managing fields uniformly, the areas with shallower clay depth could be treated as critical areas and could be managed separately to minimize ill impacts on downstream regions.

These results have implications regarding the impacts of natural or man-made changes that occur in the landscape. For example, stream bank erosion can impact water quality in more than one way. While the direct consequence is the loss of large amounts of soil into the stream, secondary effects are expected if erosion is severe enough to affect the footslope of the landscape sequence. In that case, the resulting sequence would be one with a reduced footslope length. In the extreme case of total disappearance of the footslope, the resulting landscape sequence would end with a backslope. In this case, runoff and chemical losses from the agricultural landscape would increase and could be significantly larger. The severity of the increase in losses will depend on the length of the backslope and summit. Similarly, while the construction of terraces is an effective way to reduce soil erosion on steep slopes, it could have additional effects on runoff and the transport of atrazine because the length of the back slope is reduced, thus decreasing runoff and atrazine losses. On the other hand, terraces are placed in the middle of the landscape, usually within the backslope position. Thus, water and pollutants drain directly into these structures without going through and getting the benefit of a footslope with deeper depth to clay. In addition, the broad-based terraces that are frequently found in this region are built by removing some top soil, excavating the uphill area of the terrace to build the berm, and placing the topsoil back on top of the berm and excavated area. Thus, the area of farmed land directly uphill of the berm ends up having a steeper slope and lower depth to clay than the original backslope. Hydraulic conductivity would depend on the final compaction of the soil. Consequently, this area may temporarily become more sensitive than the original landscape profile, especially in very shallow soils and when the slope is steep.

In this study, we benefited from a very detailed description of the landscape topography, soil properties, and the depth to claypan. While GIS and soil information are tools frequently used by researchers, this level of information is normally out of reach for farmers. Nevertheless, topographic information and SSURGO soil maps are available to delineate the critical areas based on landscape type. Additional research is needed to test whether similar results could be obtained based on readily available data in this region. If so, one can envision a landscape position dependent management in which these critical areas would benefit from crop rotations and management practices that would take the shallow depth to claypan into account.

Simulation models are important tools not only for research purposes but are also extensively needed to develop specific management principles applicable on targeted locations. There are many models available at various scales, but each comes with its own limitations (Singh, 1995). In the present study, we showed that APEX, a daily time step model, could be used at the landscape scale and was detailed enough to detect the effect of the different landscape positions. In particular, soil parameters specific to the backslope position, i.e., hydraulic conductivity, slope, and depth to claypan, significantly affected simulated runoff and atrazine loss at the outlet. On the other hand, we did not find that APEX was sensitive to the soil bulk density in the range of values that distinguish the different positions of a claypan landscape. The theoretical landscape sequences generated were an effort to stretch the limits of the APEX model to test whether simulated runoff and atrazine loss were sensitive to the differences in slope and soil properties inherent to different positions along the landscape. We recognize that these sequences are theoretical, and some of them are unlikely to occur. Results indicate that this model is indeed sensitive to landscape positions and their associated soil properties and thus can be used to define and test management scenarios (cropping systems, crop rotations, tillage, and inputs) adapted to each position.

Conclusion

This study was conducted to evaluate variations in simulated runoff and dissolved atrazine load at the plot outlet of a claypan landscape due to different landscape sequences and sizes for claypan soils. This research demonstrated that the calibrated and validated model APEX was able to produce the differences in simulated runoff and atrazine load associated with different sequences of landscape positions and with different lengths of landscape positions.

APEX was able to simulate runoff and atrazine loss from agricultural plots in a claypan area, as indicated by the selected goodness of fit criteria. For daily runoff, r^2 and NSE varied from 0.55 to 0.98 and from 0.46 to 0.94, respectively; for daily atrazine loads, r^2 and NSE values ranged from 0.52 to 0.97 and from 0.45 to 0.86, respectively. The slopes of the regression between measured and simulated values varied between 0.70 and 1.38.

Landscape sequence analysis showed that the sequences ending with a backslope produced the most runoff and atrazine loss. The footslope-summit-backslope (FSB) sequence produced the highest amount of seasonal runoff and atrazine loads, 86% and 82% more, respectively, than the natural summit-backslope-footslope (SBF) sequence. Seasonal runoff and atrazine loads were highest and increased significantly, by 83% and 72%, respectively, when the backslope length was increased by 20% relative to its original length. These findings may be helpful in delineating critical areas for conservation management within fields. These theoretical landscape sequences may not occur naturally, but these results can be useful to take landscape characteristics into account for management decisions. For example, if a crop field is large enough to accommodate different management systems, then the areas that have longer backslope positions need extra effort to reduce runoff and atrazine loads. Efforts are especially needed when these landscape characteristics occur near the outlet, channel, or any subsurface drainage system.

In this study, the critical characteristics that separated the summit, backslope, and footslope positions from each other were the landscape geometries (slope and length), depth to claypan, and hydraulic conductivity above the claypan. The latter two parameters were also found sensitive in the APEX model for runoff and atrazine load estimation. These findings could allow land managers and conservationists to delineate critical areas based on depth to claypan and saturated hydraulic conductivity and to test alternative management systems for these areas with the APEX model.

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