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Representation of agricultural conservation practices with SWAT

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Abstract:

Results of modelling studies for the evaluation of water quality impacts of agricultural conservation practices depend heavily on the numerical procedure used to represent the practices. Herein, a method for the representation of several agricultural conservation practices with the Soil and Water Assessment Tool (SWAT) is developed and evaluated. The representation procedure entails identifying hydrologic and water quality processes that are affected by practice implementation, selecting SWAT parameters that represent the affected processes, performing a sensitivity analysis to ascertain the sensitivity of model outputs to selected parameters, adjusting the selected parameters based on the function of conservation practices, and verifying the reasonableness of the SWAT results. This representation procedure is demonstrated for a case study of a small agricultural watershed in Indiana in the Midwestern USA. The methods developed in the present work can be applied with other watershed models that employ similar underlying equations to represent hydrologic and water quality processes. Copyright © 2007 John Wiley & Sons, Ltd.

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INTRODUCTION

Agricultural conservation practices, often called best management practices or BMPs, are widely used as effective measures for preventing or minimizing pollution from nonpoint sources within agricultural watersheds. Because their effectiveness cannot be tested in all situations, watershed managers rely on models to provide an estimate of their impact on improving water quality at the watershed scale. Many watershed management programmes (e.g. EPA, 2005) have suggested modelling strategies for development and implementation of watershed management plans. In the absence of a standard procedure for representing agricultural conservation practices with watershed models, the results of modelling studies are subject to modellers' potentially inconsistent decisions in evaluating practice performance. Establishing a standard procedure for representation of conservation practices with a selected watershed model would: (i) reduce potential modeler bias; (ii) provide a roadmap to be followed; (iii) allow others to repeat the study; and (iv) improve acceptance of model results.

The Soil and Water Assessment Tool (SWAT; Arnold and Fohrer, 2005) is often used to evaluate water quality benefits of agricultural conservation practices. Kalin and Hantush (2003) reviewed key features and capabilities of widely cited watershed scale hydrologic and water quality models with emphasis on the ability of the models to represent practices and total maximum daily load (TMDL) development. The review indicated that the SWAT model offers the greatest number of management alternatives for modelling agricultural watersheds. Additionally, the model has also been adopted as part of the USEPA Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) software package for applications including support of TMDL analyses. SWAT is also being used by many US federal and state agencies, including the US Department of Agriculture within the Conservation Effects Assessment Project (CEAP), to evaluate the effects of conservation practices.

SWAT already has an established method for modelling several agricultural practices including changes in fertilizer and pesticide application, tillage operations, crop rotation, dams, wetlands, and ponds. The model also has the capacity to represent many other commonly used practices in agricultural fields through alteration of its input parameters. A number of previous modelling studies have used SWAT to evaluate conservation practices around the globe. Vaché *et al.* (2002) used the model to evaluate the water quality benefits of crop rotation, riparian buffer strips, and strip-cropping practices in two watersheds in central Iowa (50–100 km^2). Representation of filter strips, nutrient management plans, riparian forest buffers, critical area planting, grade stabilization structures, and trees and shrub planting with SWAT was examined by Santhi *et al.* (2003) in two segments of the Big Cypress Creek watershed in Texas with a total drainage area of 1674 km^2. Chu *et al.* (2005) used SWAT

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to study water quality impacts of tillage operations in a 3·5 km^2 watershed in Maryland. However, Bracmort *et al.* (2006) is the only study, to our knowledge, that provides detailed description of the procedure used for the representation of field borders, parallel terraces, grassed waterways, and grade stabilization structures.

Lack of numerical guidelines for the representation of management practices is not limited to the SWAT model. For example, Mostaghimi *et al.* (1997) used the Agricultural Nonpoint Source Pollution (AGNPS) model to evaluate water quality benefits of several agricultural conservation practices. Although the authors specified the model parameters to be altered, no numerical procedure was presented. Nietch *et al.* (2005) developed a framework, centred on using conservation practices, for addressing critical needs for managing sediments within watersheds. The numerical representation of practice performance was identified as a vital research need. Likewise, Shields *et al.* (2006) suggested that representation methods should be developed to examine water quality effects of agricultural conservation practices with existing models.

Most previous work on the evaluation of conservation practices has been done through applying *a priori* empirical load reduction coefficients (ASCE-AWRI, 2001). Application of this approach is limited because the performances of practices are site-specific, greatly influenced by landscape characteristics and interactions between practices. Process-based approaches should be developed where water quality impacts of practices are evaluated based on their physical characteristics and spatial location. Such methodologies are important for the evaluation of management practices at the watershed scale, especially in ungauged basins with no/little monitoring data, which are commonplace.

The objective of this study is to present a stepwise procedure for the representation and evaluation of hydrologic and water quality impacts of several agricultural conservation practices with the SWAT2005 model. To this end, we have focused on representation of the practices for which SWAT does not offer an established method. These include seven practices that are installed in upland areas (contour farming, strip cropping, parallel terraces, cover crops, residue management, field borders, filter strips) and three practices that are implemented within small channels (grassed waterways, lined waterways, and grade stabilization structures). The hydrologic and water quality processes affected by each practice are reviewed, and the sensitivity of the SWAT outputs to the proposed representation is evaluated. Application of the methods for evaluation of impacts of these practices on water quality is demonstrated for a small agricultural watershed in Indiana. Given that the practices discussed in the present work have a long history of use around the world, we expect the methods will be widely applied for selection and implementation of agricultural NPS pollution control strategies at the watershed scale.

HYDROLOGIC AND WATER QUALITY PROCESSES IN SWAT2005

SWAT (Arnold *et al.*, 1998; Neitsch *et al.*, 2005) is a process-based distributed-parameter simulation model, operating on a daily time step. The model was originally developed to quantify the impact of land management practices in large, complex watersheds with varying soils, land use, and management conditions over a long period of time. SWAT uses readily available inputs and has the capability of routing runoff and chemicals through streams and reservoirs, and allows for the addition of flows and the inclusion of measured data from point sources. Moreover, SWAT has the capability to evaluate the relative effects of different management scenarios on water quality, sediment, and agricultural chemical yield in large, ungauged basins. Major components of the model include weather, surface runoff, return flow, percolation, evapotranspiration (ET), transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loads, and water transfer.

For simulation purposes, SWAT partitions the watershed into subunits including subbasins, reach/main channel segments, impoundments on the main channel network, and point sources to set up a watershed. Subbasins are divided into hydrologic response units (HRUs) that are portions of subbasins with unique land use/management/soil attributes. The geographical information system (GIS) interface of the model (AvSWAT; Di Luzio *et al.*, 2002) enables users to specify a critical source area (CSA) that controls the number of subbasins and the density of the channel network in the study area. This critical source area is the minimum area that is required for initiation of channel flow. The number of subbasins and the density of the channel network increase with decreased CSA (Di Luizo *et al.*, 2002; Arabi *et al.*, 2006).

Hydrologic component

SWAT uses a modification of the SCS curve number method (USDA Soil Conservation Service, 1972) to compute surface runoff volume for each HRU. Peak runoff rate is estimated using a modification of the Rational Method. Daily or sub-daily rainfall data is used for calculations. Flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method. In this study, SCS curve number and Muskingum routing methods along with daily climate data, were used for surface runoff and streamflow computations.

Sediment component

Sheet erosion is estimated for each HRU using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975):

$$S = 11{\cdot}8 \times (Q \times q \times A)^{0{\cdot}56} \times K \times C \times P \times LS \times F \qquad (1)$$

where S is the sheet erosion on a given day (metric tons), Q is the surface runoff volume (mm water), q is the peak runoff rate (m^3 s^{-1}), A is the area of the HRU (ha), K is the USLE soil erodibility factor, C is the USLE cover and management factor, P is the USLE support practice factor, LS is the USLE topographic factor, and F is the coarse fragment factor.

Sediment deposition and channel degradation (i.e. channel erosion) are the two dominant channel processes that affect sediment yield at the outlet of the watershed. Whether channel deposition or channel degradation occurs depends on the sediment loads from upland areas and transport capacity of the channel network. If sediment load in a channel segment is larger than its sediment transport capacity, channel deposition will be the dominant process. Otherwise, channel degradation occurs over the channel segment. SWAT estimates the transport capacity of a channel segment as a function of the peak channel velocity:

$$T_{ch} = a \times v^b \tag{2}$$

where T_{ch} (ton m^{-3}) is the maximum concentration of sediment that can be transported by streamflow (i.e., transport capacity), a and b are user-defined coefficients, and v (m s^{-1}) is the peak channel velocity. The peak velocity in a reach segment at each time step is calculated from:

$$v = \frac{\alpha}{n} \times {R_{ch}}^{2/3} \times {S_{ch}}^{1/2} \tag{3}$$

where α is the peak rate adjustment factor with a default value of unity, n is Manning's roughness coefficient, R_{ch} is the hydraulic radius (m), and S_{ch} is the channel invert slope (m m^{-1}). Channel degradation (S_{deg}) and deposition (S_{dep}) in tons are computed as:

$$S_{\text{dep}} = \begin{cases} (S_i - T_{ch}) \times V_{ch} & ; S_i > T_{ch} \\ 0 & ; S_i \le T_{ch} \end{cases} \tag{4}$$

$$S_{\text{deg}} = \begin{cases} 0 & ; S_i \ge T_{ch} \\ (T_{ch} - S_i) \times V_{ch} \times K_{ch} \times C_{ch} & ; S_i < T_{ch} \end{cases} \tag{5}$$

where S_i is the initial sediment concentration in the channel segment (ton m^{-3}), V_{ch} is the volume of water in the channel segment (m^3), K_{ch} is the channel erodibility factor (cm h^{-1} Pa^{-1}), and C_{ch} is the channel cover factor. The total amount of sediment that is transported out of the channel segment (S_{out}) in tons is computed as:

$$S_{\text{out}} = (S_i + S_{\text{deg}} - S_{\text{dep}}) \times \frac{V_{\text{out}}}{V_{ch}} \tag{6}$$

In Equation (6), V_{out} is the volume of water leaving the channel segment (m^3) at each time step.

Nutrient and pesticide components

Movement and transformation of several forms of nitrogen and phosphorus and pesticides over the watershed are accounted for within the SWAT model. Nutrients are introduced into the main channel through surface runoff and lateral subsurface flow, and transported downstream with channel flow. It is worth mentioning that in the current version of the model (SWAT2005), in-stream nutrient processes are not linked with sediment channel processes.

Pesticides loadings from land areas to streams and water bodies are simulated in soluble or sorbed forms. Transport and transformation of pesticides in the channel network is modelled with a simple mass balance analysis. The current version of the model (SWAT2005) has the capacity to route only one pesticide through the channel network.

METHODS AND MATERIAL

Ten important agricultural conservation practices were selected for representation with the SWAT2005 model, based on their relatively common use in water quality projects. These include contour farming, strip-cropping, parallel terraces, cover crops, residue management, field borders, filter strips, grassed waterways, lined waterways, and grade stabilization structures. A representation methodology for the selected practices was developed and then applied in the Smith Fry watershed in Indiana. The water quality variables of interest included sediment, total P, total N, and pesticide (i.e. atrazine) yields. All computations in this study were performed on a monthly basis for the 2001–2025 time horizon.

Study area

The Smith Fry watershed located in Allen County, north-east Indiana, is a 7·3 km^2 watershed in the Maumee River basin in the midwestern portion of the USA (Figure 1). The major soil series in the watershed is hydrologic group C with moderate to low drainage characteristics. Land use in the watershed based on NASS 2000 data (USDA-NASS, 2000) is comprised of 30% corn, 30% soybean, 29% pasture, 7% forested areas, and 4% other covers.

For computational purposes, the watershed was subdivided into 97 subwatersheds corresponding to a critical source area (CSA) of 3 ha. Major soils and land use were used to characterize each subwatershed. Thus, each subwatershed was comprised of only one hydrologic response unit (HRU). The overall land use in the watershed changed by only 2% as a result of this watershed configuration.

Baseline simulation

The baseline values for the input parameters could be selected by (i) a model calibration procedure; or (ii) a 'suggested' value obtained from the literature, previous studies in the study area, or prior experience of the analyst. In this analysis, baseline values were selected from a manual calibration exercise (Arabi *et al.*, 2004, 2006). Specific management operations used for the baseline simulation include: 10 May planting ('plant begin, beginning of the growing season') for corn and soybean, and 15

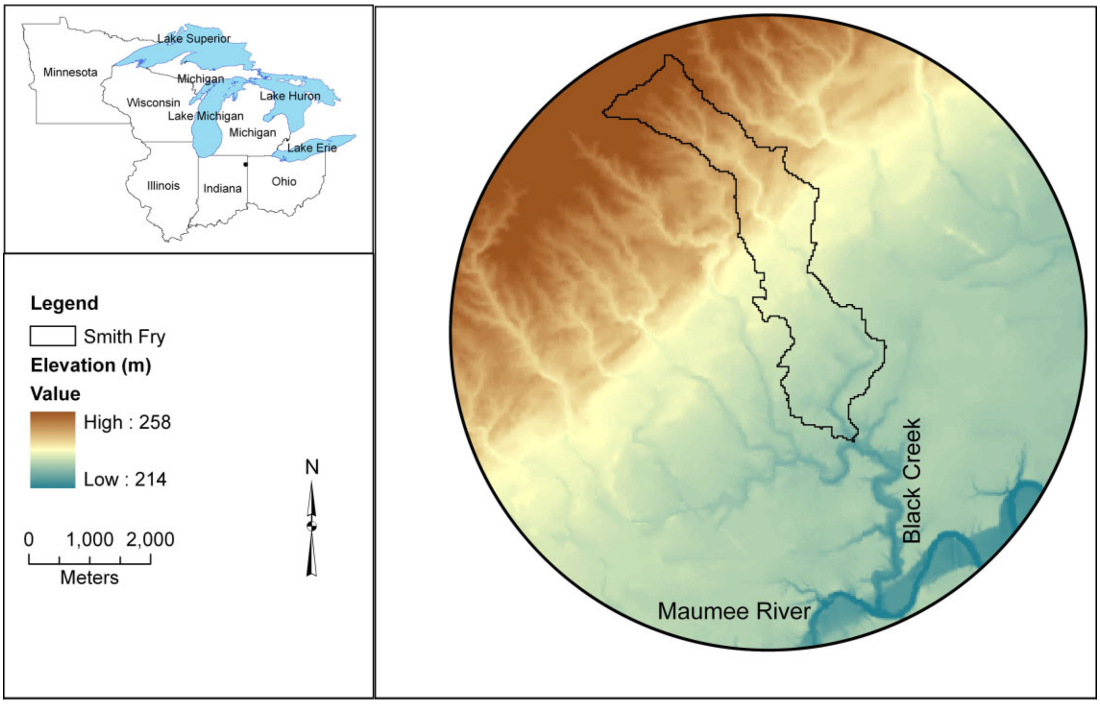

Figure 1. Location and elevation maps for the Smith Fry watershed

October for 'harvest and kill' operation for corn and soybean. A generic spring ploughing operation and fertilizer applications were scheduled 7 days and 5 days before the beginning of the growing season for crops. Pesticide (atrazine) application was scheduled 3 days after the beginning of the growing season only for corn-planted areas. No crop rotation was considered in the baseline scenario. Rates of N-fertilizer and P-fertilizer application (in kg ha^{-1}) were set, respectively, to 150 and 60 for corn, zero and 50 for soybean, 75 and 50 for winter wheat, and 50 and 35 for pasture lands. Rate of application of the pesticide atrazine in corn areas was set to 1·5 kg ha^{-1}. SWAT default values were used for other management operations.

Representation of conservation practices

Based on the function of a conservation practice, a method was suggested for representing the practice with SWAT. This included a discussion of specific parameters that need to be changed. Definition and purpose of practices were obtained from national conservation practice standards—NHPS (USDA-NRCS, 2005). Various hydrologic and water quality processes that were considered include: infiltration; surface runoff (peak and volume); upland erosion (sheet and rill erosion); gully and channel erosion; nutrient and pesticide loadings from upland areas; and within-channel processes.

Contour farming. Implementation of contour farming practices in a field will result in: (1) reduction of surface runoff by impounding water in small depressions; and (2) reduction of sheet and rill erosion by reducing erosive power of surface runoff and preventing or minimizing development of rills. SCS curve number (CN) and USLE practice factor ($USLE\_P$) were modified to simulate these impacts.

Neitsch *et al.* (2005) provide a table with recommendations for curve number in fields with different land use and soil characteristics under various hydrologic conditions adapted from Wischmeier and Smith (1978). The recommendations also include impacts of contour farming, strip-cropping, terracing, and residue management on curve number.

However, curve number is a primary parameter used for calibration of the hydrologic component of the SWAT model (Santhi *et al.*, 2001), and thus the use of these values directly from the table will not represent adequately the effect of the conservation practice. Therefore, the recommendations were used to establish a more general relationship between curve number before and after implementation of contour farming, terraces, and residue management. Figure 2 illustrates the impact of these practices on curve number, using all the values in the table in Neitsch *et al.* (2005), which recommends curve number values under various conditions. For contour farming, curve number was reduced from the default/calibrated value by 3 units. Table I presents USLE support practice factor ($USLE\_P$) for fields under contouring, strip-cropping, and terraced conditions, and these values were used to simulate the erosion reduction due to implementation of the corresponding practices.

Strip-cropping. Implementation of strip-cropping practices in a field will result in: (1) reduction of surface runoff by impounding water in small depressions; (2) reduction of peak runoff rate by increasing surface roughness and slowing surface runoff; and (3) reduction of sheet and rill erosion by preventing development of

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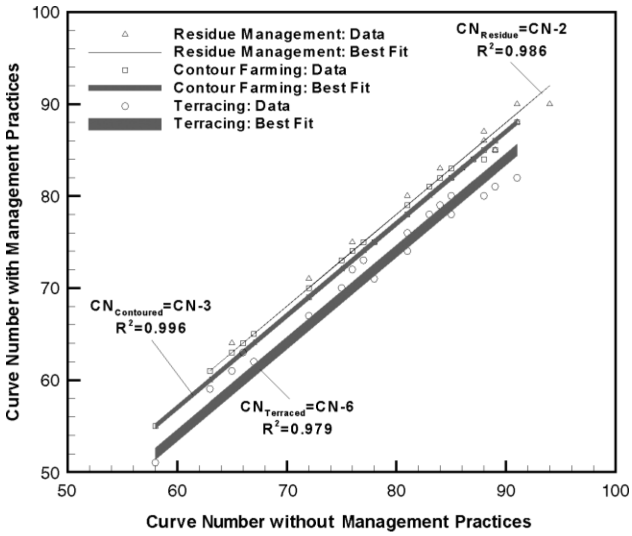

Figure 2. Effect of contouring, terracing, and residue management on curve number

Table I. *USLE_P* factor values for contouring, strip-cropping, and terracing (adapted from Wischmeier and Smith, 1978)

Land slope (%)	*USLE_P*			
	Contour farming	Strip-cropping	Terracing	
			Type1[a]	Type2[b]
1 to 2	0·60	0·30	0·12	0·05
3 to 5	0·50	0·25	0·1	0·05
6 to 8	0·50	0·25	0·1	0·05
9 to 12	0·60	0·30	0·12	0·05
13 to 16	0·70	0·35	0·14	0·05
17 to 20	0·80	0·40	0·16	0·06
21 to 25	0·90	0·45	0·18	0·06

[a] Type1: Graded channels sod outlets.
[b] Type2: Steep backslope underground outlets.
Refer to ASAE (2003) for description of these types of terracing.

rills. SCS curve number (*CN*), USLE support practice factor (*USLE_P*), USLE cover factor (*USLE_C*) and Manning's roughness coefficient for overland flow (*OV_N*) should be modified for representation of strip-cropping practices. Renard *et al.* (1997) suggest that impacts of a strip-cropping system on movement of runoff and the deposition of sediment are taken into account in the USLE practice factor. However, this does not reflect the protection given to the soil by surface cover. This impact must be represented through the USLE cover factor.

Similar to contour farming, in fields where strip-cropping is practised, curve number was reduced from the calibrated value by 3 units. Table I provides recommendations for *USLE_P* value under strip-cropping conditions. *USLE_C* and *OV_N* were adjusted based on weighted average values for the strips in the system. The weighted average can be computed based on the area of each strip in the field.

Parallel terraces. Implementation of parallel terraces in a field will result in: (1) reduction of surface runoff volume by impounding water in small depressions; (2) reduction of peak runoff rate by reducing length of the hillside; and (3) reduction of sheet and rill erosion by increased settling of sediments in surface runoff, reducing erosive power of runoff, and preventing formation of rills and gullies. SCS curve number (*CN*), USLE support practice factor (*USLE_P*), and slope length of the hillside (*SLSUBBSN*) were modified for representation of parallel terraces.

Curve number value (*CN*) was reduced by 6 units from its calibrated value to represent the impact of parallel terraces on surface runoff volume (Figure 2). Also, Table I provides recommended *USLE_P* values for terraced condition with two types of outlets. Slope length (*SLSUBBSN*) was modified to (ASAE, 2003):

$$SLSUBBSN = (x \times SLOPE + y) \times \frac{100}{SLOPE} \tag{7}$$

where x (dimensionless) is a variable with values from 0·12–0·24, y (dimensionless) is a variable influenced by soil erodibility, cropping systems, and crop management practices, and *SLOPE* is average slope of the field. Variable x can be determined from ASAE standard S268·4 FEB03 (ASAE, 2003) based on its geographical location in the USA. Variable y can take values of 0·3, 0·6, 0·9, or 1·2. The low value (i.e. 0·3) is used for highly erodible soils with conventional tillage and little residue, while the high value (i.e. 1·2) is used for soils with very low erodibility and no-till/residue (residue more than 3·3 t ha^{-1}) management condition.

The USLE topographic factor (*LS*) in the MUSLE Equation (1) is determined as a function of slope (*SLOPE*) and slope length (*SLSUBBSN*) of the field:

$$\begin{aligned} LS &= \left(\frac{SLSUBBSN}{22{\cdot}1}\right)^{m} \\ &\quad \times (65{\cdot}41 \times \sin^2\alpha + 4{\cdot}56 \times \sin\alpha + 0{\cdot}065); \\ m &= 0{\cdot}6[1 - \exp(-35{\cdot}835 \times SLOPE)]; \\ \alpha &= \tan^{-1}(SLOPE) \end{aligned} \tag{8}$$

As evident in Equation (8), slope length (*SLSUBBSN*) has a more significant impact on the *LS* factor in subbasins with higher slope (*SLOPE*).

Peak runoff rate is also affected by changing slope length. SWAT uses the modified Rational Method for computing the peak flow rate for each HRU:

$$q = \frac{\alpha_{tc} \times Q \times A}{3{\cdot}6 \times t_c} \tag{9}$$

where t_c is time of concentration, and α_{tc} reflects the fraction of daily rainfall that occurs during the time of concentration. Time of concentration is computed as:

$$t_c = \frac{SLSUBBSN^{0{\cdot}6} \times OV\_N^{0{\cdot}6}}{18 \times SLOPE} \tag{10}$$

where *OV_N* is the overland Manning's roughness coefficient. Thus, the total impact of slope length on upland

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erosion can be estimated as:

$$S \propto SLSUBBSN^{(m-0\cdot336)} \tag{11}$$

where S is the sheet erosion computed for the HRU (Equation (1)). In fields where m is less than 0·336 or slope is less than 0·023, SWAT-estimated upland erosion is inversely correlated to slope length (Figure 3). Thus, reducing slope length to represent parallel terraces will result in higher erosion estimates for these conditions. For such areas, adjustment of slope length ($SLSUBBSN$) for the representation of parallel terraces with SWAT should be skipped.

Residue management. Implementation of residue management practices in a field will result in: (1) slowing down surface runoff and peak runoff by increasing land cover and surface roughness; (2) increasing infiltration/reducing surface runoff by decreasing surface sealing and slowing down the overland flow; and (3) reducing sheet and rill erosion by reducing surface flow volume, overland flow rate, raindrop impact, providing more surface cover, and preventing development of rills. SCS curve number (CN), Manning's roughness coefficient for overland flow (OV_N), and USLE cover factor ($USLE\_C$) were modified for the representation of residue management practices with SWAT.

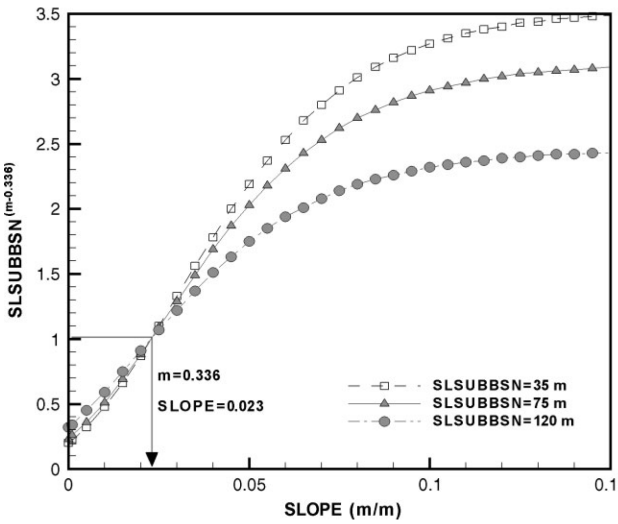

Figure 3. Impact of interplay between slope and slope length on SWAT upland erosion estimation

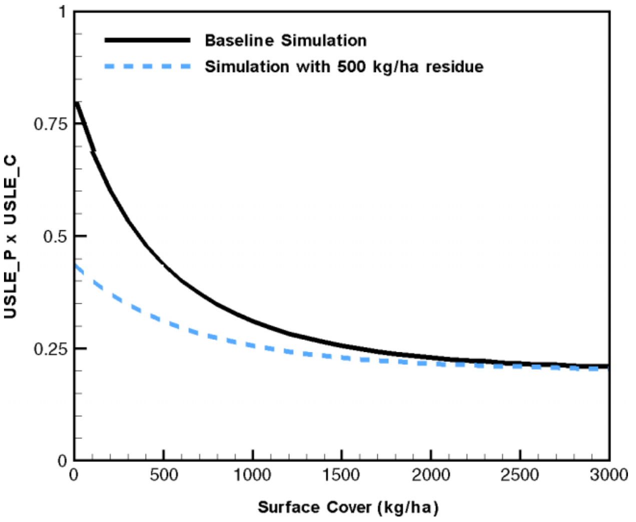

Figure 4. $USLE\_C \times USLE\_P$ before and after representation of residue management with $USLE\_C0_{orig} = 0\cdot2$, and $rsd = 500$ kg ha^{-1}

In fields with residue management practices, curve number value was reduced by 2 units from its default/calibrated value, as demonstrated in Figure 2. The direct impact of surface residue on erosion estimates is reflected in computation of USLE cover factor. SWAT updates USLE cover factor for each field on a daily basis as a function of residue cover (SOL_COV) on the surface:

$$USLE\_C = 0\cdot8^{k} \times USLE\_C0^{(1-k)};$$
$$k = \exp(-0\cdot00115 \times SOL\_COV) \tag{12}$$

where $USLE\_C0$ is the original minimum of the USLE cover factor that is typically obtained from calibration. $USLE\_C$ decreases as plant residue increases during the growing season.

Users can define a harvest efficiency value for each HRU that specifies the amount of residue biomass that is removed from the HRU in the harvest operation. The current version of the SWAT model does not incorporate the impact of residue biomass on sheet erosion and transport of nutrients from upland fields. Thus, an alternative procedure for representation of the impact of residue biomass on sheet erosion was applied. The alternative procedure included a manipulation of factors in the MUSLE equation as follows:

(i) Adjust USLE practice factor ($USLE\_P$) for the field:

$$USLE\_P = \frac{USLE\_C}{USLE\_C0} = 0\cdot8^{(k'-1)} \times USLE\_C0^{(1-k')};$$
$$k' = \exp(-0\cdot00115 \times rsd) \tag{13}$$

where rsd reflects the residue biomass left on the surface. For $rsd = 500$ kg ha^{-1} and $USLE\_C0 = 0\cdot2$, $USLE\_P$ would be 0·55.

(ii) Adjust minimum USLE cover factor ($USLE\_C0$): since users can define only one USLE practice factor ($USLE\_P$) for a given field, minimum USLE cover factor ($USLE\_C$) were altered such that the product of $USLE\_C$ and $USLE\_P$ for the growing season remains the same. This is because residue biomass is left on the surface to reduce upland erosion when there is no crop growing. The $USLE\_C0$ was adjusted as:

$$USLE\_C0_{\mathrm{mod}} = \frac{USLE\_C0_{\mathrm{orig}}}{USLE\_P} \tag{14}$$

where $USLE\_C0_{\mathrm{orig}}$ and $USLE\_C0_{\mathrm{mod}}$ are the original and modified minimum USLE cover factor, respectively. The original minimum USLE cover factor is either the SWAT default value or obtained from calibration.

Table II. Values of Manning's roughness coefficient for overland flow (Neitsch *et al.*, 2005)

Characteristics of land surface	*OV_N*
No till, no residue	0·14
No till, 0·5–1 t ha^{-1} residue	0·20
No till, 2–9 t ha^{-1} residue	0·30

Table III. An example of a corn–soybean rotation practice

Year	Operation	Crop	Date	
			month	day
1	Tillage	CORN	May	3
1	N-fertilizer	CORN	May	5
1	P-fertilizer	CORN	May	5
1	**Plant begin**	**CORN**	**May**	**10**
1	Pesticide application	CORN	May	13
1	**Harvest and kill**	**CORN**	**October**	**15**
1	Tillage	SOYB	May	3
2	N-fertilizer	SOYB	May	5
2	P-fertilizer	SOYB	May	5
2	**Plant begin**	**SOYB**	**May**	**10**
2	**Harvest and kill**	**SOYB**	**October**	**15**

Figure 4 shows how the representation procedure works. For the period of the year when no crop is growing, the residue biomass is effective in reducing the upland erosion (left asymptotic behaviour). The impact diminishes as crop biomass increases during the growing season (right asymptotic behaviour).

Residue management influences surface roughness of the field. Recommended *OV_N* values for crop lands with residue are provided in Table II.

Conservation crop rotation. SWAT contains a management feature for representation of crop rotation practices. The management input files (.mgt) for HRUs accommodate crop rotation in successive years. An example of a corn–soybean rotation is provided in Table III. Operations in bold are required management operations.

Cover crops. Cover crops were represented with SWAT by scheduling a crop rotation within a single year. An example of management operations for a winter wheat (WWHT) cover in a corn field is provided in Table IV. Operations in bold are required management operations. Notice that SWAT does not allow growing of two crops in a single HRU simultaneously. Therefore, 'plant begin, beginning of the growing season' and 'harvest and kill' operations were scheduled for the cover crop both in spring and winter covering the time the main crop is not growing.

Table IV. An example of a winter wheat-cover in a corn field

Year	Operation	Crop	Date	
			month	day
1	**Plant begin**	**WWHT**	**March**	**1**
1	**Harvest and kill**	**WWHT**	**May**	**2**
1	Tillage		May	3
1	N-fertilizer		May	5
1	P-fertilizer		May	5
1	**Plant begin**	**CORN**	**May**	**10**
1	Pesticide application	CORN	May	13
1	**Harvest and kill**	**CORN**	**October**	**15**
1	**Plant begin**	**WWHT**	**October**	**20**
1	**Harvest and kill**	**WWHT**	**December**	**31**

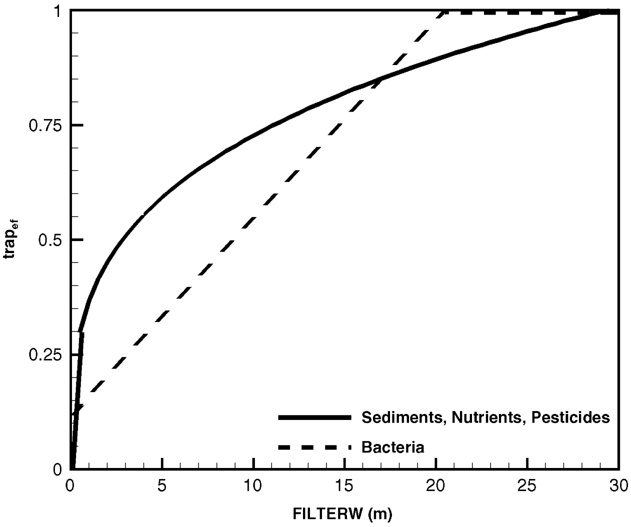

Figure 5. Effect of strip width on trapping efficiency of vegetative strips

Field borders. Field borders are installed along the perimeter of a field to reduce sediment, nutrients, pesticides, and bacteria in surface runoff as it passes through the edge-of-the-field vegetative strip. Pollutant loads in surface runoff are trapped in the strip of vegetation. SWAT provides a specific method to incorporate edge-of-field filter strips through the *FILTERW* parameter that reflects the width of the strip. The trapping efficiency for sediment, nutrients and pesticides ($trap_{ef\_sed}$) is calculated from:

$$trap_{ef\_sed} = 0{\cdot}367 \times FILTERW^{0{\cdot}2967} \tag{15}$$

Equation (15) implicitly incorporates the higher efficiency of the front portion of the strips in trapping sediments, nutrients, and pesticides (Figure 5). For bacteria, the trapping efficiency ($trap_{ef\_bac}$) is calculated:

$$trap_{ef\_bac} = \frac{(11{\cdot}8 + 4{\cdot}3 \times FILTERW)}{100} \tag{16}$$

While SWAT uses the same trapping efficiency (Equation (15)) for sediments, nutrients, and pesticides, users can manipulate the *FILTERW* parameter in order to modify both linear and exponential coefficients in the equation. For example, if the desired form of Equation (15) for phosphorus is $trap_{ef\_p} = c \times FILTERW^k$, a modified width of the field border can be computed as $FILTERW_{\mathrm{mod}} = c^k(0{\cdot}367 \times FILTERW^{0{\cdot}2967})^{-k}$, where *FILTERW* reflects the actual width.

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Filter strips. The function of filter strips is similar to the field borders except filter strips are installed along the edge of a channel segment. Therefore, pollutant loads from the area that drains into the channel segment are trapped in the vegetative strip. For representation of filter strips, the parameter *FILTERW* in Equations (15) and (16) for the fields that constitute the drainage area for the channel segment was adjusted.

Grassed waterways. Grassed waterways will increase sediment trapping in a channel segment by reducing flow velocity. Also, peak flow rate/flow velocity in the channel segment will be reduced by increasing roughness of flow in the channel segment. Moreover, gully erosion in the channel segment will be reduced by establishing channel cover in streambed/banks. Channel width (*CH_W2*), channel depth (*CH_D*), channel Manning's roughness coefficient (*CH_N2*) and channel cover factor (*CH_COV*) were adjusted in channel segments where grassed waterways are installed.

Manning's roughness coefficient for flow in the channel segment (*CH_N2*) was adjusted based on the type and density of vegetation used in the grassed waterway. Fiener and Auerswald (2006) assumed *CH_N2* ranges between 0·3 and 0·4 over the year. A *CH_N2* value of 0·1 was suggested for grassed waterways under poor conditions. These values are typical in the case of dense grasses and herbs under non-submerged conditions (Jin *et al.*, 2000; Abu Zreig, 2001). Channel cover factor (*CH_COV*) was adjusted to 0·001 (fully covered). Note that 0·001 is an arbitrary very low value that is used instead of zero. If this value is set to zero, the default value will be used in SWAT simulations. Channel width and depth are typically defined by the design specifications.

Lined waterways/stream channel stabilization. The function of lined waterways and stream channel stabilization practices is to cover a channel segment with erosion resistant material to reduce gully erosion. Representation of these practices was achieved by adjusting channel width (*CH_W2*), channel depth (*CH_D*), channel Manning's roughness coefficient (*CH_N2*), and channel erodibility factor (*CH_EROD*).

Channel width and depth are typically defined by the design specifications. Channel erodibility factor was adjusted to 0·001 (non-erodible). Again, a very small number (i.e. 0·001) was used instead of zero to avoid the use of default values. Channel Manning's roughness coefficient was adjusted according to values in Table V.

Grade stabilization structures. Grade stabilization structures (GSS) are used to control the grade and head cutting in natural or artificial channels. Implementation of grade stabilization structures will increase sediment trapping by reducing flow velocity in the channel segment. Peak flow rate/flow velocity in the channel segment will be decreased by reducing the slope of the channel segment. Gully erosion will be reduced in the channel segment by reducing channel erodibility and flow velocity. Slope of the channel segment (*CH_S2*) and channel erodibility factor (*CH_EROD*) were adjusted for the representation of grade stabilization structures.

Table V. Manning's roughness coefficient for lined channels (adapted from USDA-NRCS, 2005)

Lining		*CH_N2*
Concrete	Trowel finish	0·012–0·014
	Float finish	0·013–0·017
	Shotcrete	0·016–0·022
	Flagstone	0·020–0·025
1/ Riprap - (angular rock)		$0{\cdot}027(D_{50}CH\_S2)^{0{\cdot}147}$
Synthetic turf reinforcement Fabrics and grid pavers		Manufacturer's recommendations

1/ Applies on slopes between 2 and 40% with a rock mantle thickness of $0{\cdot}05 \times D_{50}$ where:
D_{50} = median rock diameter (m), CH_S2 = lined section slope (m m^{-1}) ($0{\cdot}02 \leq CH\_S2 \leq 0{\cdot}4$)

The slope of the upstream channel segment (*CH_S2*) was adjusted as follows:

$$CH\_S2 = CH\_S2_{pre} - \frac{h}{CH\_L2} \tag{17}$$

where *CH_S2* is the slope of the upstream channel after implementation of the GSS, CH_S2_{pre} is the slope of the upstream channel before implementation of the GSS, *h* (m) reflects the height of the GSS, and *CH_L2* (m) is the length of upstream channel segment. Channel erodibility factor (*CH_EROD*) was adjusted to 0·001 (non-erodible).

Sensitivity analysis

Representation of conservation practices with the method presented in this paper is based on altering appropriate model parameters. The methodology would be handicapped if the model was not sensitive to the selected parameters. The SWAT model is a distributed-parameter model that has hundreds of parameters. Some of these parameters represent initial or boundary conditions while others are forcing factors. Selection of a parameter that is an insensitive parameter under any given temporal and spatial condition would not be appropriate for representation of practices. Therefore, a sensitivity analysis was conducted to check that parameters selected for representation of practices are not insensitive parameters.

The Morris One-At-a-Time (OAT) (Morris, 1991) procedure was used for sensitivity analysis of the SWAT model. Morris OAT is a sensitivity analysis technique that falls under the category of screening methods (Saltelli *et al.*, 2000). Each model run involves perturbation of only one parameter in turn. In this way, the variation of model output can be unambiguously attributed to perturbation of the corresponding factor. For each input parameter, local sensitivities are computed at different points of the parameter space, and then the global (main) effect is obtained by taking their average. The elementary effect of a small perturbation Δ of the *i*th component of the *p*-dimensional parameter vector (α_i) at a given point in the parameter space $\alpha = (\alpha_1, \ldots, \alpha_{i-1}, \alpha_i, \alpha_{i+1}, \ldots, \alpha_p)$) is (Morris, 1991):

$$d(\alpha_i|\alpha) = \frac{[y(\alpha_1, \ldots, \alpha_{i-1}, \alpha_i + \Delta, \alpha_{i+1}, \ldots, \alpha_p) - y(\alpha)]}{\Delta} \tag{18}$$

where $y(\alpha)$ corresponds to model output. The results are quantitative, elementary, and exclusive to the parameter α_i. However, the elementary effect computed from Equation (18), i.e. $d(\alpha_i|\alpha)$, is only a partial effect and depends on the values chosen for the other elements of the parameter vector (α_j). A finite distribution (F_i) of elementary effects of parameter α_i is obtained by sampling at different points of the space, i.e. different choices of parameter set α. The mean of the distributions is indicative of the overall influence of the parameter on the output, while the variance demonstrates interactions with other parameters and nonlinearity effects.

Sensitivity of each model parameter from Equation (18) was estimated at 10 different points of the parameter space. Therefore, a total of 20 model simulations were performed for each parameter in the sensitivity analysis. Table VI provides a list of parameters that were considered in the analysis, their definitions, units, and suggested ranges (lower and upper bounds). The suggested range of model parameters were obtained from the SWAT users' manual (Neitsch *et al*., 2005) and our previous experience in the same study watershed. The analysis was conducted for both daily and monthly simulations.

Evaluation of conservation practices

The water quality impacts of the conservation practices described previously were evaluated at the outlet of the Smith Fry watershed. In general, these practices can be classified into two groups: (1) practices that are installed on upland areas, including conservation crop rotation,

Table VI. SWAT parameters included in the sensitivity analysis with their lower bound (LB) and upper bound (UB). Parameters specified by * were altered as a percentage of the default values

NO	SWAT Symbol	Definition	Units	LB	UB
1	*ALPHA_BF*	baseflow alpha factor for recession constant	days	0	1
2	*BIOMIX*	biological mixing efficiency		0·01	1
3	*CH_COV*	channel cover factor		0·001	0·6
4	*CH_K1**	effective hydraulic conductivity in tributary channels	mm/hr	−0·5	1
5	*CH_K2*	effective hydraulic conductivity in the main channel	mm/hr	0·1	150
6	*CH_N1*	Manning's roughness coefficient for tributary channels		0·008	0·065
7	*CH_N2*	Manning's roughness coefficient for the main channel		0·01	0·3
8	*CH_S1**	average slope for tributary channels		−0·5	1
9	*CH_S2**	average slope for the main channels		−0·5	1
10	*CMN*	rate factor for mineralization of active organic nutrients		0·001	0·003
11	*CN**	SCS runoff curve number		−0·5	0·15
12	*DAY_CORN*	day of 'planting/beginning of growing season' for corn		1	30
13	*DAY_SOYB*	day of 'planting/beginning of growing season' for soybean		1	30
14	*DAY_WWHT*	day of 'planting/beginning of growing season' for winter wheat		1	30
15	*DDRAIN*	depth of tile drains	mm	0	5000
16	*ESCO*	soil evaporation compensation factor		0·001	1
17	*FILTERW*	width of edge-of-field filter strip	m	0	5
18	*GW_DELAY*	groundwater delay	day	0	500
19	*GW_REVAP*	groundwater 'revap' coefficient		0·02	0·2
20	*GWQMN*	threshold depth of water in the shallow aquifer for return flow	mm	0	5000
21	*HARVEFF*	harvest efficiency			
22	*LABP*	initial soluble P in soils	mg/kg	1	50
23	*NPERCO*	nitrogen percolation coefficient		0·001	1
24	*ORGN*	initial organic N in soils	mg/kg	1	10 000
25	*ORGP*	initial organic P in soils	mg/kg	1	4000
26	*OV_N*	Manning's roughness coefficient for overland flow		0·1	0·3
27	*PERCOP*	pesticide percolation coefficient		0·001	1
28	*PPERCO*	phosphorus percolation coefficient	10 m^3/Mg	10	17·5
29	*RSDCO*	residue decomposition coefficient		0·02	1
30	*SFTMP*	snowfall temperature	^{o}C	−5	5
31	*SLOPE**	average slope steepness		−0·5	1
32	*SLSUBBSN**	average slope length	m	−0·5	1
33	*SOL_AWC**	available soil water capacity	m/m	−0·5	1
34	*SOL_K**	saturated hydraulic conductivity	mm/hr	−0·5	1
35	*SOLN*	initial NO_3 in soils		0·1	5
36	*SPCON*	linear coefficient for in-stream channel routing		0·0001	0·01
37	*SURLAG*	surface runoff lag time	day	1	12
38	*USLE_C**	minimum value of USLE equation cover factor		−0·5	1
39	*USLE_K**	USLE equation soil erodibility factor		−0·5	1
40	*USLE_P*	USLE equation support practice factor		0·2	1

cover crop, contour farming, strip-cropping, parallel terracing, residue management, field border and vegetative filter strip; (2) practices that are installed within the channel network, including grassed waterway, lined waterway, and grade stabilization structure. It should be noted that although filter strips are implemented along the edge of streams, they do not impact within-channel processes. Therefore, filter strips were evaluated with the group of upland practices. The upland practices were evaluated when implemented in areas with corn land use. Fields with corn land use cover nearly 30% of the total watershed area.

Impacts of within-channel practices were evaluated when installed within streams with different geomorphologic characteristics. The channels in the watershed were classified based on the Strahler Scheme (Smart, 1972) that is often used for ranking the geomorphologic order of channel segments:

1. Channels that originate at upland areas are defined as class 1 streams. Class 1 streams do not have any upstream channels.
2. A stream of class $j + 1$ is generated when two streams of class j meet.
3. When two streams of classes i and j meet, the class of the immediately downstream channel segment is max (i, j).
4. The class of the watershed is the highest stream class.

The Smith Fry watershed with the subdivision scheme shown in Figure 6 is of class 4. Table VII provides information regarding the class of streams in the study watershed. The impacts of within-channel practices were evaluated when they were considered for implementation in streams of class 1, streams of classes 2 and lower, streams of classes 3 and lower, and streams of classes 4 and lower. The latter case covers the entire channel network.

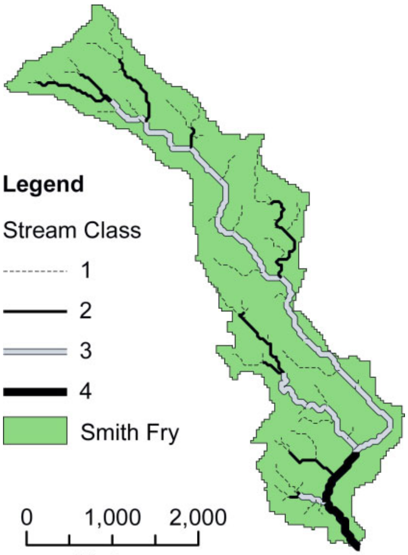

Figure 6. Class of streams in the computational setup for the Smith Fry watershed with CSA = 3 ha

Table VII. Fraction of stream classes in the Smith Fry watershed

Stream class	Number of segments	Length (m)	Fraction of total drainage network (%)
1	47	13 240	45
2	22	6333	21
3	25	8570	29
4	3	1457	5
Total	97	29 600	100

The extent of the channel network derived with the GIS interface of the SWAT model based on a Digital Elevation Model (DEM) varies with the choice of the user-specified critical source area (CSA). Selection of smaller values for the CSA will result in a larger number of class 1 channel segments with smaller drainage areas. Thus, the class of channel segments based on the Strahler Scheme in a modelling effort is a function of the selected CSA.

One limitation of the SWAT model is that nutrient channel processes are not linked with sediment channel processes. Therefore, evaluation of the impacts of within-channel practices on transport of sediment-bound nutrients, especially phosphorus, with the method discussed previously will not be meaningful. Here, evaluation of within-channel practices was limited to impacts of sediment yield at the outlet of the study watershed.

RESULTS AND DISCUSSION

The results of SWAT simulations for the baseline scenario showed that daily streamflows would range between 0 and $6{\cdot}06\ \mathrm{m}^3\ \mathrm{s}^{-1}$ over the 2001–2025 simulation period. The average daily streamflow was estimated at $0{\cdot}084\ \mathrm{m}^3\ \mathrm{s}^{-1}$ with a standard deviation of $0{\cdot}24\ \mathrm{m}^3\ \mathrm{s}^{-1}$. Baseflow, on average, contributed nearly 75% of the daily streamflow, while this contribution ranged from 0·1% to 100%.

Sensitivity analysis

The results of the sensitivity analysis indicated that parameters selected for representation of conservation practices were sensitive parameters. Table VIII summarizes the Morris' OAT sensitivity indices from Equation (18) for SWAT parameters in Table VI. A negative sensitivity index indicates that the parameter and the output variable are inversely correlated.

Curve number was the most sensitive parameter for all output variables but baseflow by a large margin. Channel process parameters were among the most sensitive parameters for sediment computations. These parameters included the parameters that influence transport capacity of the channel network, such as *CH_N2* and *SPCON*. Moreover, sediment computations were not sensitive to the channel cover factor (*CH_COV*). Channel cover is used for estimation of channel erosion as described in Equation (5). These indicated that channel deposition was the dominant channel process in the study watershed for the simulation period. It is worthwhile to re-emphasize

Table VIII. Sensitivity of SWAT parameters in Table VI. Top five parameters in each category are highlighted

Parameter	Stream Flow	Sediment	Total P	Total N	Pesticide
ALPHA_BF	0·03	0·25	0·21	0·21	**0.35**
BIOMIX	−0·03	0·07	0·09	0·07	0·06
CH_COV	0·00	0·00	0·00	0·00	0·00
CH_K1	−0·01	−0·01	−0·01	0·00	0·00
CH_K2	−0·01	−0·16	−0·12	−0·12	−0·14
CH_N1	0·00	−0·08	−0·12	−0·09	0·00
CH_N2	−0·01	**−0.75**	−0·14	−0·13	−0·19
CH_S1	0·00	0·10	0·13	0·08	−0·01
CH_S2	0·00	0·20	0·04	0·03	0·04
CMN	0·02	0·03	0·04	0·11	0·00
CN	**2.39**	**4.28**	**4.16**	**3.26**	**6.78**
DAY_CORN	0·00	0·00	0·01	0·03	**0.45**
DAY_SOYB	0·00	0·00	0·01	0·00	0·00
DAY_WWHT	0·00	0·00	0·00	0·00	0·00
DDRAIN	**0.15**	0·20	0·37	0·32	0·35
ESCO	**0.27**	0·20	0·22	0·35	**0.68**
FILTERW	0·00	0·30	**0.74**	**0.60**	**0.60**
GW_DELAY	−0·04	0·00	0·00	−0·08	−0·01
GW_REVAP	−0·07	0·00	0·00	−0·09	0·00
GWQMN	**−0.24**	−0·04	−0·01	−0·21	−0·03
HARVEFF	−0·01	−0·01	−0·12	−0·13	−0·01
LABP	0·00	0·00	0·14	0·00	0·00
NPERCO	0·00	0·00	−0·01	0·09	0·00
ORGN	0·01	0·03	0·05	**0.81**	−0·01
ORGP	0·00	0·00	**0.85**	0·00	0·00
OV_N	−0·01	−0·10	−0·16	−0·11	−0·01
PERCOP	0·00	0·00	0·03	0·01	0·81
PPERCO	0·00	0·00	0·00	0·00	0·00
RSDCO	0·00	0·00	0·00	0·00	0·00
SFTMP	−0·01	−0·04	−0·03	−0·02	−0·02
SLOPE	0·07	0·40	0·68	0·54	0·21
SLSUBBSN	−0·08	0·00	0·01	0·00	−0·02
SOL_AWC	**−0.31**	−0·29	−0·33	−0·50	−1·01
SOL_K	−0·03	−0·07	−0·07	−0·06	−0·38
SOLN	0·00	0·00	0·00	0·00	0·00
SPCON	0·00	**0.67**	0·00	0·00	0·00
SURLAG	0·01	0·10	0·12	0·08	−0·03
USLE_C	0·00	0·21	0·35	0·26	0·00
USLE_K	0·00	**0.50**	**0.83**	**0.65**	0·01
USLE_P	0·00	**0.49**	**0.80**	**0.60**	0·01

that sediment and nutrient channel processes of the SWAT model are not linked. This explains why sediment channel process parameters are not as sensitive for total P and total N computations.

SWAT uses the user-defined harvest efficiency (*HARVEFF*) parameter to update USLE cover factor for the period after the harvest operation. Interestingly, the results in Table VIII indicated that harvest efficiency (*HARVEFF*) had marginal impacts on flow and sediment computations of the SWAT model. Therefore, adjusting *HARVEFF* would not be adequate for representation of residue management practices. In this study an alternative approach based on manipulation of parameters in the MUSLE equation (Equation (1)) was suggested and applied to evaluate residue management practices.

Table IX. Estimated effectiveness (r) of upland practices implemented within areas with corn land use using the proposed representation procedures

Management practice	r (%)			
	Sediment	Total P	Total N	Pesticide
Corn–soybean rotation in Table III	0	0	0	40
Cover crop (winter wheat cover crop in Table IV)	3	10	14	2
Contouring	5	18	24	16
Strip-cropping (50% oat strips)	10	20	29	16
Residue management ($rsd = 2000$ kg ha^{-1})	15	23	35	17
Parallel terracing (steep backslope underground outlet)	15	27	36	27
Field border ($FILTERW = 5$ m)	3	21	24	32

Demonstration of methods in the Smith Fry Watershed in Indiana, USA

Upland conservation practices. Effectiveness of conservation practices that are implemented within agricultural fields was evaluated by comparing model simulations with no practice and simulations with the practice implemented in fields under corn land use. Areas with corn land use cover nearly 30% of the total area of the Smith Fry watershed based on the NASS 2000 land use. Effectiveness of each practice (r) was computed as:

$$r = \frac{y_1 - y_2}{y_1} \times 100 \qquad (19)$$

where y_1 and y_2 reflect model outputs before and after implementation of the practice, respectively.

Table IX provides a summary of results on the effect of upland practices on water quality of the study watershed. Corn–soybean rotation for corn, as described in Table III, did not impact sediment and nutrient yields compared with continuous corn, but reduced atrazine use by nearly 40% over the 25-year simulation period. This was mainly because atrazine was applied only in years when corn was planted. Among all other upland practices, parallel terraces were the most effective for reducing sediments and nutrients. Filter strips were considered an upland practice because they impact pollutant loads from upland areas and not within-channel processes. Although water quality benefits of field borders and filter strips are the same in this analysis, filter strips have significantly higher effectiveness per unit area than field borders.

Effectiveness of residue management/no till practices were evaluated for various residue biomasses left on the soil surface after the harvest operation. Results in Table X indicate that effectiveness of residue management practices increased with higher residue biomass (rsd) left on the soil surface.

Figure 7 shows the effectiveness of filter strips with various widths. As width of the vegetative strip increased,

Table X. Estimated effectiveness (r) of residue biomass (rsd) in the residue management/no till practice implemented within areas with corn land use in the Smith Fry watershed

rsd (kg ha^{-1})	*r* (%)			
	Sediment	Total P	Total N	Pesticide
500	7	16	28	13
1000	10	20	32	14
2000	15	23	35	17

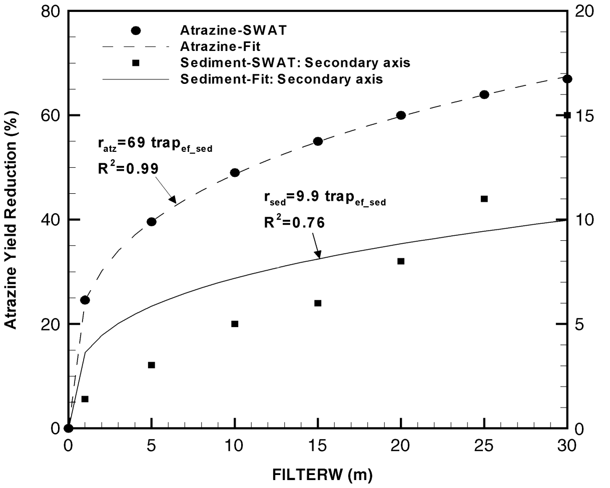

Figure 7. Estimated effect of width of edge-of-the-field filter strips implemented within areas with corn land use on sediment and atrazine yields in the Smith Fry watershed. Variable *trapef_sed* is defined in Equation (15)

higher pollutant load reduction was achieved. The circles and squares in this figure show the effectiveness of filter strips computed based on SWAT simulations. The lines were computed based on the best fit between the trapping efficiency in Equation (15) and the effectiveness based on SWAT simulations, shown in circles and squares. Interestingly, it is evident that the estimated reduction of atrazine load based on SWAT simulations was linearly proportional to the trapping efficiency of filter strips for sediments, nutrients, and pesticides in Equation (15). The proportionality constant is 69. The SWAT model assumes 75% application efficiency for pesticide application. Moreover, the calibrated value for the pesticide percolation coefficient was 5%. Thus, considering channel degradation and erosion do not affect atrazine transport, *a priori* estimate of the proportionality constant between atrazine load reduction and the trapping efficiency in Equation (15) would also be nearly 70. Similar trends with different proportionality constants were observed for total P and total N. These indicated that comparison of impacts of filter strips with different widths on nutrient and atrazine yields could be simply achieved without SWAT simulations, using only Equation (15).

The results for sediment yield, however, were different. Sediment reductions estimated by SWAT were not linearly proportional to the trapping efficiency given by Equation (15). As the results of sensitivity indicated, channel deposition was the dominant channel process in the study watershed. Therefore, sediment transport in the watershed channels behaved nonlinearly with the edge-of-the-field vegetative filter strips. Thus, more accurate estimates of the impacts of filter strips on sediment yield were achieved by SWAT simulations.

Table XI. Estimated effects of within-channel practices installed within channels of various classes

Stream class	Sediment reduction r (%)		
	Grassed waterway[1]	Lined waterway[2]	Grade stab. structure[3]
1	1	0	1
1 to 2	—	−4	2
1 to 3	—	−3	9
1 to 4	—	−302	74

[1] Manning's roughness coefficient: $CH\_N2 = 0{\cdot}3$.
[2] Concrete-trowel finish: $CH\_N2 = 0{\cdot}014$.
[3] Height of the structure: $h = 1{\cdot}2$ m.

Within-channel conservation practices. Grassed waterways are typically installed to prevent gully erosion due to concentrated flow. Thus, the performance of grassed waterways was evaluated when implemented within class 1 streams with drainage areas less than 15 ha. Lined waterways and grade stabilization structures implemented within various stream classes in Table XI were evaluated. The class of the streams reflects the location of the practices within the watershed shown in Figure 6.

The results indicated that implementation of grassed waterways and grade stabilization structures within class 1 channels would not reduce sediment yield at the outlet significantly. The highest water quality benefits from grade stabilization structures would be achieved when implemented within class 4 streams that are located at the very downstream part of the watershed, and constitute less than 5% of the channel network (Table VII). Conversely, implementation of lined waterways would increase sediment at the outlet. The calibrated value of Manning's roughness coefficient for a channel segment (*CH_N2*) was 0·04, which is a typical value for natural streams. Lining the channels with concrete finish would decrease *CH_N2* to 0·014. As a result, flow velocity in the channel segments and consequently their transport capacity would increase. Increasing the transport capacity of channel segments, especially class 4 streams at the downstream part of the watershed, would reduce sediment deposition in the channel network. Thus, more sediment would be carried to and out of the watershed outlet.

Additional analysis was performed to evaluate the sensitivity of the suggested representation method for grade stabilization structures to the height of the structure. The results depicted in Figure 8 indicate insensitivity of the procedure to values higher than 1·25 m in the Smith Fry watershed. The SWAT model provides a specific option for modelling reservoirs installed within the channel network. Stabilization structures should be

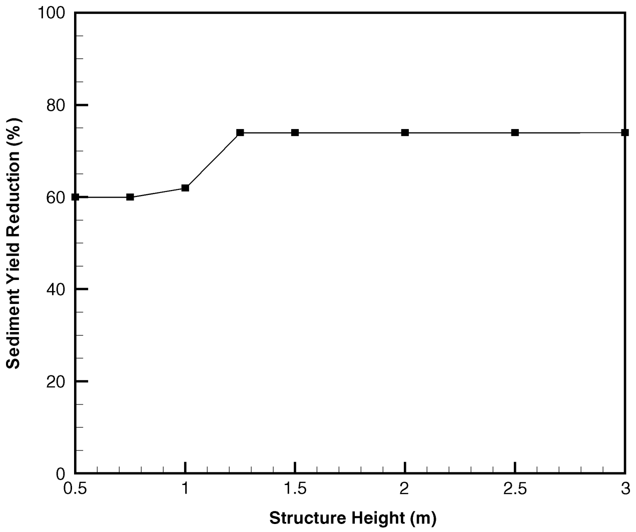

Figure 8. Sensitivity of estimated sediment reduction in the Smith Fry watershed to height of grade stabilization structure *h*

modelled as a reservoir when they function as small dams.

The water quality benefits of conservation practices evaluated in this study are site specific and are likely to vary in other watersheds with different characteristics. However, the representation methodology could be used in other studies. A standard procedure as recommended herein could reduce the subjectivity of results to potential modellers' bias and would help watershed managers endorse and apply the results in the decision making process.

Of importance is that evaluation of the effectiveness of management actions, such as agricultural conservation practices, may be affected by the watershed subdivision schemes used for parameterization of the watershed. For example, a watershed is divided into subwatersheds and channel segments in SWAT. Arabi *et al.* (2006) showed that the estimated effectiveness of practices clearly varied with the number of subwatersheds. While the methods in the current study will allow users to model the impacts of practices for a given watershed subdivision scheme, additional analysis similar to the approach by Arabi *et al.* (2006) would provide complimentary information for practice evaluation.

Finally, the methods developed in the present study are based on assessment of impacts of conservation practices on hydrologic and erosion processes represented in SWAT primarily by the SCS curve number method and the Modified Universal Soil Loss Equation. Because these two methods are the most widely used methods in mathematical representation of watershed models (Nietch *et al.*, 2005), they can be applied with many other watershed models besides SWAT at various spatial scales.

CONCLUSIONS

A standard procedure was suggested for the representation of 10 agricultural conservation practices using the SWAT model. The representation method is based on hydrologic and water quality processes that are modified by the practice. Appropriate process parameters were identified and altered to mimic the functionality of the practices. A global sensitivity analysis was conducted to investigate the sensitivity of model outputs to the selected process parameters. The analysis provided herein can be used by (i) watershed modellers and managers to evaluate water quality impacts of the selected conservation practices at the watershed scale, and (ii) SWAT model developers to increase the capacity of the model for representation of these practices. For example, it became evident that flow and sheet erosion computations of the model are not sensitive to the harvest efficiency coefficient, which could potentially, be used to represent residue management practices.

The applicability of the recommended procedure was demonstrated in a small, primarily agricultural, watershed in Indiana. The results indicated that SWAT simulations were sensitive to the methods applied for representation of the selected conservation practices. The demonstration study revealed that practices installed within upland areas could potentially reduce sediment, nutrient, and pesticide loadings from agricultural nonpoint sources. Moreover, within-channel practices could reduce the transport of pollutant loads to the watershed outlet.

The process outlined in this paper could be used to develop practice representation methods within other watershed models, particularly those that employ the SCS curve number method for representation of runoff processes and the Universal Soil Loss Equation for erosion estimation. However, care should be taken when dealing with representation of pollution prevention strategies at various spatial and temporal scales. The performance of management actions is likely to vary under different flow regimes. In this paper, the discussion focused on the impacts of practices on average monthly pollutant loads based on daily SWAT simulations over a long-term (25 years) simulation period. Similar approaches could be employed to investigate whether these conclusions would be different under varying sub-daily flow conditions. Future studies should focus on identification of appropriate spatial and temporal scales for representation of practices, and assessment of the impacts of model uncertainty on the evaluation of practices.

ACKNOWLEDGEMENTS

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