Evaluation of APEX for Daily Runoff and Sediment Yield from Three Plots in the Middle Huaihe River Watershed, China

L. Yin, X. Wang, J. Pan, P. W. Gassman

Abstract. *This study was conducted to evaluate the performance of APEX using daily runoff and sediment yield (1982-1986) collected from three plots located in the middle Huaihe River watershed, China. A sensitivity analysis was conducted using an extended Fourier amplitude sensitivity test, followed by an automatic calibration procedure to calibrate the curve number for moisture condition 2 (CN_2), curve number index coefficient (CNIC), conservation practice factor (PEC), and peak runoff rate - rainfall energy adjustment factor (APM). The percent errors of mean (PE) were within 20%, with Nash-Sutcliffe efficiency (EF) and R^2 values all above 0.45 and 0.55 for both daily runoff and sediment yield for the three plots during the calibration period. For the validation period, the PE values were within 25%, and the EF and R^2 values ranged from 0.41 to 0.84 and from 0.55 to 0.85, respectively. Scenario analyses were conducted for a 24-year period for (1) fallow (baseline), (2) mixed wood-grass with horizontal terraces (scenario 1), and (3) woodland with horizontal-level ditches (scenario 2). The long-term benefits of scenario 1 over the baseline were quantified as minimum surface runoff and sediment yield reductions of 37 mm year^{-1} (35%) and 22 Mg ha^{-1} year^{-1} (84%), respectively. The benefits of scenario 2 over the baseline were reductions of 37% surface runoff and 89% sediment yield. The results suggest that APEX is a useful tool for evaluating soil and water loss for different management practices in the middle Huaihe River watershed, China, and that construction of horizontal-level ditches and horizontal terraces, and enhancing vegetation, are efficient strategies for controlling runoff and sediment in the region.*

Keywords. *APEX model, Middle Huaihe River watershed, Model calibration, Model validation, Runoff, Sediment yield.*

The Huaihe River watershed covers a total land area of 269,800 km^2 and is one of the seven major river watersheds in China (Tang et al., 2004). Cropland (120,542 km^2), woodland (42,652 km^2), grassland(3,362 km^2), and unmanaged ("wild") land (13,585 km^2) cover the watershed, with cropland characterized by extreme slopes covering 10,413 km^2 of the overall cropland area. Soil erosion rates as high as 35 Mg ha^{-1} year^{-1} occur across nearly 22% of the watershed area (Tang et al., 2004). Inappropriate land use practices such as extensive cultivation, cultivating on steep slopes (over 27%), and deforestation, in combination with a lack of conservation practices and mismanaged construction projects, aggravate water-induced erosion from this region (Tang et al., 2004). Significant amounts of nutrients are also lost from cropland soils, resulting in soil quality degradation and threatening food security.

The Chinese government has placed significant importance on, and financed accordingly, soil and water conservation in the Huaihe River watershed since 1950. For example, the Converting Farmland to Forestland Project has been providing support since 2000 to reduce soil and water loss, resulting in the conversion of cropland with slopes over 27% to woodland in the Huaihe River watershed. In this program, farmers can receive economic and food compensation by converting cropland to woodland in order to reduce soil and water loss. In total, 35,000 km^2 in the Huaihe River watershed have been treated with some forms of best management practices (BMPs) since 1950 through investments provided by the local governments. These BMPs include building horizontal terraces on 6,000 km^2 of cropland, installing 600,000 ponds and 250,000 check dams, and planting of forest and grass on 22,000 km^2 of land for soil and water conservation. The overall benefits of these practices were quantified to be an increase of approximately 2,000 million m^3 year^{-1} of water storage capacity and sediment yield reductions of roughly 100 million Mg year^{-1} (Zhang, 2007).

Properly tested hydrologic and water quality models are useful tools that can be used to explore and evaluate management options for sustainable agricultural productivity and environment benefits. It is urgent that reliable hydrologic/water quality simulation models be established to evaluate soil erosion impacts for the Huaihe River watershed region, where long-term and detailed rainfall data, and soil and water loss monitoring data, are generally not available. The required

Submitted for review in October 2007 as manuscript number SW 7212; approved for publication by the Soil & Water Division of ASABE in October 2009.

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  ISSN 2151-0032

model characteristics include: (1) watershed-based, (2) continuous simulation, (3) able to predict the impact of future natural or man-made changes, such as BMP scenarios, (4) required inputs generally available, and (5) able to consider both point-source and nonpoint-source pollutants.

The Agricultural Policy/Environmental eXtender (APEX) model (Williams and Izaurralde, 2006; Williams et al., 2006; Williams et al., 2008; Gassman et al., 2009) is a flexible and dynamic tool that is capable of simulating management and land use impacts for whole farms and small watersheds. APEX is essentially a multi-field version of the predecessor Environmental Policy Impact Climate (EPIC) model (Williams, 1990; Izaurralde et al., 2006), which has been extensively tested and applied for a wide variety conditions in the U.S. and other regions (Gassman et al., 2005). The APEX model was chosen for this study due to the following reasons: (1) the essential functions of EPIC are included in APEX, and (2) APEX provides additional multi-subarea capabilities advantages. Establishing the validity of APEX in studies such as this provides a foundation for analyzing conservation practices and cropping systems with the model in whole farm or small watershed contexts in China. APEX functions on a daily time step, can perform long-term continuous simulations, and can be used for simulating the impacts of different nutrient management practices, tillage operations, conservation practices, alternative cropping systems, and other management practices on surface runoff and losses of sediment, nutrient, and other pollutant indicators. The model can also be configured for novel land management strategies such as filter strip impacts on pollutant losses from upslope crop fields, intensive grazing scenarios, and land application of manure removal from livestock feedlots.

APEX has been tested and applied at the field or watershed level in several different cropland-, pasture-, or forest-based studies, primarily in the U.S., as chronicled by Gassman et al. (2009). Wang et al. (2006d) also conducted an extensive sensitivity test of 15 APEX parameters for 159 sites representative of agricultural conditions across the U.S. However, ongoing testing of APEX is needed to further improve its accuracy and to expand the overall climatic, management, landscape, and vegetation conditions that the model can be applied to in both the U.S. and other regions (Gassman et al., 2009). In China, APEX erosion tests have only been reported for the Loess Plateau region (Wang et al., 2006a), which is characterized by much different conditions as compared to the Huaihe River watershed. Thomson et al. (2005) reported the impacts of assessing two climate change scenarios on soil carbon levels with EPIC for conditions representative of the Huang-Hai Plain region in northeast China, which partially overlaps the Huaihe River watershed; however, they did not perform any erosion assessments.Thus, there is a need to perform additional testing of the APEX erosion subcomponent and other routines for the unique conditions of the Huaihe River watershed, where cropland slopes can often exceed 30% as opposed to more typical maximum slopes of 15% in the U.S. (Wang et al., 2006a; Tang et al., 2004).

Therefore, a key goal of this study was to evaluate the applicability and performance of APEX for simulating daily runoff and sediment yield from three small plots at a research site in the middle Huaihe River watershed in Henan Province, east central China, where the three plots represent three different treatments: (1) fallow (control plot), (2) mixed wood-grass with horizontal terraces, and (3) woodland with horizontal-level ditches. The landscape, cropping system, and conservation practice characteristics of these plots are representative of the much larger Huaihe River watershed, especially those areas that are dominated by steep slopes, which are highly vulnerable to erosion. Long-term evaluation of different BMPs with APEX is also important to provide better insight regarding the potential benefits of using such practices in the region. Thus, the specific objectives of the study were as follows: (1) conduct a sensitivity analysis to identify which APEX parameters are the most sensitive in predictions of surface runoff and sediment yield, (2) calibrate and validate APEX using observed values of surface runoff and sediment yield for the three research plots, and (3) conduct scenario analyses using the calibrated model to estimate long-term effects of land use and conservation practice changes on runoff and sediment yield.

Materials and Methods

Description of Plots

The data used for this study were collected from Lushan Soil and Water Conservation Experimental Station (33.90° N, 112.73° E) in Henan Province, east central China, which is located in the middle Huaihe River watershed (fig. 1). The average annual precipitation is 728 mm, the average monthly daily maximum temperature of the warmest month (June) is 31°C, and the average monthly daily minimum temperature of the coldest month (January) is –3°C. The average elevation at the experimental station site is 270 m. The study site was not cultivated until 1981 and consisted of unmanaged land dominated by weeds prior to the establishment of the research plots.

Three experiment plots were constructed with different land uses and conservation practices (table 1) in 1981 to evaluate the response of surface runoff and sediment yield to conservation practice and land use changes. The three plots, denoted EHC1, EHC2, and EHC4, are located next to each other and isolated with concrete borders. The plots range in size from 610 to 1390 m^2 and in slope from 19% to 29%. The soil properties of the three research plots are listed by layer in table 2. The soil belongs to hydrologic group A (X. He, 2008, personal communication, Lushan Soil and Water Conservation Experimental Station, China). EHC1 was cropped with pine trees and summer pasture during the time of the study, while EHC2 and EHC4 were managed with poplar trees and fallow, respectively. The row spacing and plant spacing were 2.5 and 1.5 m for EHC1 and 1.5 and 1.5 m for EHC2, respectively.

Horizontal terraces and horizontal-level ditches were installed in 1982 as conservation practices on EHC1 and EHC2, respectively, to control soil erosion.The terraces installed on EHC1 were 2.5 m in length. The terraces were stabilized with stones, and the field was connected to the sumps using side ditches. Level ditches are a common practice used in China to control soil erosion, as described by He et al. (2007). They are installed prior to cropping, are spaced at regular intervals based on field slope, can be vegetated or unvegetated, and are designed to capture excess surface runoff and reduce soil erosion. The EHC2 level ditches were installed at 3 m intervals and were 0.7 m in depth and width. Further description of a typical system including a diagram and photo is provided by He et al. (2007).

Figure 1. Location of the Huaihe River watershed in China (incomplete map of China) and location of the study site within the middle Huaihe River watershed.

Table 1. Characteristics and management practices of the three plots.

Plot	Slope (%)	Upland Slope Length (m)	Area (ha)	Land Use	Conservation Practice	Length (m)	Width (m)	Management Practices
EHC1	29	16.5	0.10	Mixed wood-grass	Horizontal terraces	50	20	(1) Pine tree transplanting followed by watering (2) Grass planting followed by watering (3) Mowing
EHC2	19	25.0	0.14	Woodland	Horizontal level ditches	55	25	Poplar transplanting followed by watering
EHC4	27	19.0	0.06	Fallow	None	30	20	Weeding

Table 2. Soil properties used in the simulation for the study site.

Property	Soil Layer 1	Soil Layer 2	Source
Depth (m)	0.05	0.65	Lab
Bulk density (Mg m^{-3})	1.49	1.55	Lab
Sand (%)	73.6	73.6	Lab
Silt (%)	6.4	6.4	Lab
Soil PH	6.7	6.7	Lab
Coarse fragment (%)	11.3	11.3	Lab
Organic carbon (%)	0.5	0.4	Lab
Wilting point (m m^{-1})	0.05	0.05	Rawls and Brakensiek (1985)
Field capacity (m m^{-1})	0.2	0.2	Rawls and Brakensiek (1985)
Saturated conductivity (mm h^{-1})	9.4	9.4	Estimated in APEX[a]

[a] Saturated conductivity = $12.7 \times XC / (XC + \exp(11.45 - 0.097 \times XC)) + 1$ where XC = 100 - clay (%) (Williams et al., 2008).

Surface runoff and sediment yield were measured on a daily basis for the three experimental plots for storm events that occurred at the study site during 1982-1986. Three sumps and a tank were installed at the downslope end of each plot, similar to the system shown in figure 2. The three sumps and the tank were 0.5, 0.14, 0.14 and 1.8 m^3 in volume, respectively. The surface runoff was channeled into the first collecting sump, followed by the second sump, then the third sump, and finally into the tank. The overflow from the first sump was passed through a splitter, which divided the flow into four equal parts and directed one part into the second sump. The overflows from the second and third sumps were also passed through splitters, which divided the flows into five equal parts. Only one part of the flow from the second sump was directed into the third sump. And only one part of the flow from the third sump was directed into the tank. The volume in the collecting tank was multiplied by the splitter calibration factor (which was calibrated by running a known volume of water through the splitter), together with the volume in the three collecting sumps, to calculate the total amount of runoff. For sediment sampling, water in the sump or tank was first agitated using a shovel to mix the fine and coarse sediments. Sediment samples were taken from three different depths (bottom, middle, and surface) of each sump or tank and then

Figure 2. Photos of runoff collection system below an experiment plot (the system shown here was not located at the site described for this study, but is similar to the system that was used).

mixed such that the volume of the mixed sediment samples for a given sump or tank exceeded 1000 cm^3 (no mixing was performed between sumps or the tank). The mixed sediment samples were agitated once again and then resampled to keep at least half for drying and weighing.

Unfortunately, several of the surface runoff and sediment samples were inadvertently lost following collection of the data. This resulted in an uneven number of samples available for model testing between the three plots. The remaining samples are listed by total number per year in table 3. These were further subgrouped into calibration and validation periods as discussed below in the Model Calibration and Validation section.

Description of APEX

The APEX model can be subdivided into nine separate components defined as weather, hydrology, soil erosion, nutrients, soil temperature, plant growth, tillage, plant environment control, and economics (Williams and Izaurralde, 2006; Williams et al., 2008). Routing of flow and pollutants can be simulated between different subareas for whole farm, watershed, or other configurations requiring multiple subareas. Current versions of APEX also feature an improved soil carbon cycling routine that was initially developed for EPIC, as described by Izaurralde et al. (2006). A wide variety of management practices can be simulated in APEX, including tillage, irrigation, subsurface drainage, buffer strips, terraces, grassed waterways, lagoons, feedlots, and fertilizer, manure, and pesticide applications. The APEX plant growth and plant competition capabilities provide a very flexible basis for simulating crop rotations and other cropping/vegetation systems, such as cover crops, double cropping, plant-weed competition, pastures, and tree production. Five different options are provided in the model for simulating evapotranspiration (ET), and seven different equations are available to simulate water-induced soil erosion. A broad range of edge-of-field environmental indicators can be output from APEX, including water and wind erosion losses, soil carbon sequestration rates, surface losses of soluble and sediment-bound nitrogen, phosphorus, and pesticides, nitrate losses in lateral subsurface flow, subsurface tile drainage and percolation, and ammonia volatilization. Descriptions are provided here regarding the daily runoff volume and soil erosion calculations that were used in this study, as given by Williams et al. (2008) unless otherwise noted. Further description of other model components is provided by Williams et al. (2008) and Williams and Izaurralde (2006).

Table 3. Numbers of samples collected for each plot in each year for runoff and sediment yield during 1982-1986.

		1982	1983	1984	1985	1986	Total
Runoff	EHC1	10	1	4	1	3	19
	EHC2	10	1	3	2	1	17
	EHC4	11	1	2	1	1	16
Sediment yield	EHC1	7	1	1	1	3	13
	EHC2	10	1	3	1	3	18
	EHC4	9	1	3	1	1	15

The hydrology component simulates daily runoff volume, peak runoff rate, subsurface flow, percolation below the soil profile, evapotranspiration, and snowmelt. The daily runoff volume is calculated using a modification of the NRCS curve number method (Mockus, 1969; USDA-NRCS, 2004). Two methods are provided in APEX for calculating the retention parameter S of the curve number method. The first method is based on the traditional approach of calculating the retention parameter as a function of soil moisture content, as described by Mockus (1969) and USDA-NRCS (2004). The alternative approach, which was used in this study, calculates the retention parameter as a function of plant evapotranspiration (Kannan et al., 2008) as follows:

$$S = S_{prev} + PET \times \exp\left(-CNIC \times \frac{S_{prev}}{S_{\max}}\right) - P_{prev} + Q_{prev} \tag{1}$$

where PET is the potential evapotranspiration for the day (mm d^{-1}); $CNIC$ is the curve number index coefficient; S_{prev} is the retention parameter on the previous day (mm); S_{max} is the maximum value that the retention parameter can achieve (mm), which is associated with CN_1 for moisture condition 1 (dry); P_{prev} is the rainfall after plant interception on the previous day (mm); and Q_{prev} is the runoff on the previous day (mm). The basic effect of the alternative approach is that S increases as the hydrologic system becomes more "ET dominated", resulting in a lower CN and thus increased infiltration of rainfall. The reverse effect occurs as rainfall begins to dominate ET in the hydrologic regime. This approach tends to more realistically capture the water balance effects of gradual soil recharge processes, which happens in many regions during the transition from ET-dominated summer periods into fall periods characterized by increased rainfall and subsequent soil water recharge (J. R. Williams, 2008, personal communication, Blackland Research and Extension Center, AgriLife Research and Extension, Texas A&M System, Temple, Texas).

Water-induced soil erosion was simulated in this study using the APEX MUST option, which is a variant of the Modified Universal Soil Loss Equation (MUSLE) developed by Williams and Berndt (1977). The MUST equation uses runoff variables to simulate erosion and sediment yield for individual storm events and is defined as follows:

$$Y = 2.5 \times (Q \times q_p)^{0.5} \times EK \times CVF \times PEC \times SL \times ROKF \quad (2)$$

where Y is the sediment yield (Mg ha^{-1}), Q is the runoff volume (mm), q_p is the peak runoff rate (mm h^{-1}), EK is the soil erodibility factor, CVF is the crop management factor, PEC is the erosion control practice factor, SL is the slope length and steepness factor, and $ROKF$ is the coarse fragment factor.

The soil erodibility factor (EK) is calculated for the topsoil layer each year with the following equations:

$$EK = X1 \times X2 \times \left(\frac{SIL}{CLA + SIL}\right)^{0.3} \times \left(1 - \frac{0.25 \times WOC}{WOC + \exp(3.72 - 2.95 \times WOC)}\right) \quad (3)$$

$$X1 = 0.2 + 0.3 \times \exp[-0.026 \times SAN \times (1 - 0.01 \times SIL)] \quad (4)$$

$$X2 = 1 - [0.7 \times (1 - 0.01 \times SAN)] \div [1 - 0.01 \times SAN + \exp(-5.51 + 22.9 \times (1 - 0.01 \times SAN))] \quad (5)$$

where SAN, SIL, CLA, and WOC are the sand, silt, clay, and organic carbon contents, respectively, of the soil (%).

An enhanced CVF factor is used in APEX. Because the plant cover varies during the growth cycle, the CVF factor is internally updated for all days when runoff occurs (Wang et al., 2008). It is calculated as a function of crop residue, crop height, standing live biomass of the crop, and soil surface random roughness using the following equation:

$$CVF = \exp(-0.026 \times (RRUF - 6.1)) \times FRSD \times FBIO \quad (6)$$

where $RRUF$ is the soil surface random roughness (mm), $FRSD$ is the crop residue factor, and $FBIO$ is the growing biomass factor. The $FRSD$ and $FBIO$ factors are calculated using the following equations:

$$FRSD = \exp(-RCFC \times CVRS) \quad (7)$$

$$FBIO = 1.0 - \exp(-RFC \times CPHT) \times \frac{STL}{STL + \exp(1.175 - 1.748 \times STL)} \quad (8)$$

where $CVRS$ is the aboveground crop residue (Mg ha^{-1}), $RCFC$ and RFC are coefficients in the exponential functions, $CPHT$ is the crop height (m), and STL is the standing live biomass of the crop (Mg ha^{-1}). The effect of crop residue on the CVF factor is governed by the exponential coefficient $RCFC$. The effect of crop residue on the CVF factor would be reduced with an increased value of $RCFC$, which would lead to reduced sediment yield in responding to a reduced CVF factor. The influence of $RCFC$ was analyzed in the sensitivity analysis conducted by Wang et al. (2006b). The effect of crop height on the CVF factor is governed by the exponential coefficient RFC. An increased value of RFC would lead to an increase value of CVF and therefore increased sediment yield.

Input Data

APEX requires the user to input weather, soil, site information, and field management information. The input dataset for the model testing phase of this study was developed for a 6-year (1981-1986) continuous simulation period for each experimental plot. Daily total precipitation, maximum and minimum temperatures, and relative humidity that were measured at the field experiment station were input for the 6-year prediction period. The first year (1981) served as an initialization year, and model testing was performed during the remaining years.

Up to 45 different soil properties can be entered in APEX for each layer of the soil profile (Williams et al., 2006). The minimum set of soil layer data required by APEX includes layer depth (m), bulk density (Mg m^{-3}), organic carbon (%), sand (%), silt (%), and pH. The soil properties by layer are listed in table 2. The EHC1 pine trees and pasture and the EHC2 poplar trees (table 1) were simulated using pre-existing plant characteristics contained in the APEX crop parameter file. Planting of the trees and pasture were simulated to occur on 15 March 1982, and continuous growth was modeled for the remainder of the simulation period. No fertilizer was applied for the trees or the pasture. Simulated mowing of the pasture was performed in September of each year for EHC1. The fallow condition for EHC4 (table 1) was simulated as simply bare soil without any management practices. The Hargreaves evapotranspiration routine was used for simulation of all three plots.

The effects of the conservation practices, i.e., horizontal terraces for EHC1 and horizontal-level ditches for EHC2 (table 1), were accounted for primarily by calibrating the Universal Soil Loss Equation (USLE) erosion control practice (PEC) factor. Calibration of the PEC was also performed for the EHC4 fallow conditions. The slope and slope length factors used in the USLE calculations were based on the percent slope and upland slope length values reported for each plot in table 1.

Sensitivity Analysis

A previous sensitivity analysis of APEX was performed by Wang et al. (2006d) for different U.S. conditions. However, van Griensven et al. (2006) pointed out that sensitivity analysis results are not readily transferable, and thus a sensitivity analysis should be performed for each unique study region investigated with a model. Moriasi et al. (2007) further stressed that a sensitivity analysis is an essential step in determining which parameters need to be calibrated. Therefore, a sensitivity analysis was performed in this study that was focused on surface runoff and sediment yield. These two model components consist of many parameters, of which 13 key parameters were selected (table 4) that were known to be potentially the most sensitive based on model documentation and previous simulation expertise. This suite of parameters provided the ability to conduct a more thorough sensitivity analysis of the surface runoff and erosion components in APEX as compared to the study performed by Wang et al. (2006d),

Table 4. APEX input parameters and their ranges considered in the sensitivity analysis.

Parameter (parm in APEX)	Description	Range	Source of Range	Ranking of Influence		Final Chosen Values
				Runoff	Sediment	
SEC (parm12)	Soil evaporation coefficient	1.5 - 2.5	Williams et al. (2006)	11	13	1.5
PCF (parm17)	Soil evaporation - plant cover factor	0.0 - 0.5		13	11	0.1
RCNIA (parm20)	Runoff curve number initial abstraction	0.05 - 0.4		4	6	0.2
HPETE (parm34)	Hargreaves PET equation exponent	0.5 - 0.6		12	9	0.5
CNIC (parm42)	Curve number index coefficient	0.5 - 5.0		2	4	1.5[a]
RCFC (parm46)	RUSLE C factor exponential residue coefficient	0.5 - 5.0		3	5	1.5
RCF (parm47)	RUSLE C factor exponential crop height coefficient	0.01 - 3.0		7	8	0.01
RIC (parm50)	Rainfall interception coefficient	0.05 - 0.3		5	10	0.1
APM	Peak runoff rate-rainfall energy adjustment factor	0.1 - 1.0		10	3	0.1[a]
PEC	Erosion control practice factor	0.1 - 1.0	Bracmort et al. (2006)	9	1	0.29[a] (EHC1) 0.21[a] (EHC2) 0.72[a] (EHC4)
CN_2	Initial input of condition 2 curve number	20 - 90		1	2	21[a],[b] (EHC1, EHC2) 65[a],[b] (EHC4)
SATC	Saturated conductivity (mm h^{-1})	8 - 50	J. R. Williams (personal communication)	6	12	9.4
DIFFW	Difference of soil water contents at field capacity and wilting point (m m^{-1})	0.03 - 0.16		8	7	0.15

[a] Values were calibrated. The rest of parameter values are APEX defaults.
[b] CN_2 values for EHC1, EHC2, and EHC4 were further adjusted internally in APEX while accounting for slope effects to 25, 24, and 69, respectively.

who investigated 15 parameters that influenced a broader range of APEX components. The ranges of the 13 selected parameters were based on the values recommended in the APEX user's guide (Williams et al., 2006) and possible ranges reported and used for sensitivity analysis in previously reported studies, as listed in table 4. These parameters were assumed to be uniformly distributed for the purpose of the sensitivity analysis.

In this study, the extended Fourier amplitude sensitivity test (FAST) was used. The FAST is a variance-based sensitivity analysis method based on analyzing the output variance in relation to the variation of the input quantities (Schwieger, 2004). Both the first-order sensitivity index and the total-order sensitivity index can be computed using the extended FAST. The first-order sensitivity index represents the sensitivity of prediction to single parameters, while the total-order sensitivity index represents the overall impact of a parameter on the model prediction, including the parameter main effect and interaction effects. SIMLAB software (SIMLAB, 2004) was used to conduct the extended FAST sampling and perform the FAST sensitivity analyses. A procedure was also developed to use parameter estimation software (PEST, 2004) for automatically updating APEX input files with generated parameters and transforming APEX outputs into the SIMLAB-required format. The procedure also automated APEX runs after each updating of input files. A total of 2,509 APEX runs were conducted for the sensitivity analysis.

Model Calibration and Validation

Calibration and validation has been established by a vast body of scientific literature as a vital step in establishing the effectiveness of water quality models (e.g., Gassman et al., 2007, 2009; Moriasi et al., 2007; Engel et al., 2007). The automatic calibration procedure described by Wang et al. (2006c) was used in this study, which relies on a combination of Monte Carlo simulation and multi-objective function techniques. The multi-objective function consisted of two specific objective functions: the Nash-Sutcliffe modeling efficiency (EF) (Nash and Sutcliffe, 1970) and percent error of mean (PE), with two transformation constants 1 and 0.5 to compensate for the differences in the magnitudes of the different measures. The multi-objective function equation is defined as follows:

$$F_{agg} = \left[\left(1 - EF(\theta)\right)^2 + \left(\left|PE(\theta)\right| + 0.5\right)^2 \right]^{1/2} \quad (9)$$

where F_{agg} is a scalar value that aggregates the two objective functions into one aggregated function and is used for comparison, and θ = 1, 2, 3, ..., m, where m is the number of sets of model parameters. CN_2, CNIC, APM, and PEC were chosen for calibration, based on the sensitivity results obtained for this study. The smallest F_{agg} was identified automatically, and the corresponding set parameter values were regarded as the optimization parameter results.

The samples in 1982 encompass both the smallest and largest storm events recorded for each plot; therefore, the model calibration was performed using the samples collected from each plot in 1982 (table 3), which included 10 to 11 runoff storms and 7 to 10 sediment events. This is similar to the procedure reported by Chung et al. (1999), who incorporated the driest and wettest years of the total simulation period in the calibration period, to test the EPIC model with the annual climatic extremes. The validation was performed for the remaining four years with 5 to 9 runoff storms and 6 to 8 sediment events collected in 1983-1986 (table 3), without any further adjustments to the model parameters. Although the data for the validation period were taken across four years, the runoff and sediment yield events were generally smaller than those in 1982. The calibration and validation tests focused on daily comparisons, which differs from many of the previously reported EPIC and APEX evaluations that relied on testing at monthly, annual, or average storm event time scales (e.g., Chung et al., 1999, 2001, 2002; Gassman et al., 2007, 2009; Wang et al., 2007).

The EF, PE, and R^2 statistics were used to evaluate the performance of APEX. Explicit standards for evaluating model performance using statistics such as the R^2 and EF have not been established. Moriasi et al. (2007) proposed several statistical criteria for establishing satisfactory water quality model performance, including an EF value greater than 0.5 for monthly comparisons, with appropriate relaxing or tightening of the criteria for shorter or longer time steps. Other criteria for satisfactory model performance have been reported in the literature, including values of $R^2 > 0.5$ and $EF > 0.3$ as reported by Chung et al. (1999, 2001, 2002). Based on the guidelines suggested by these previous studies, criteria of $R^2 \geq 0.5$, $EF \geq 0.4$, and PE within 25% of observed values were established to assess if the model results were satisfactory for the daily comparisons performed in this study. These criteria are consistent with those discussed above, especially considering the fact that the comparisons between the predicted and measured values were performed on a daily basis. The model performance was also evaluated using the paired t-test to determine if the difference between the measured and predicted values was significantly different from zero, similar to the approach reported by Wang et al. (2006b).

Scenario Analyses

The calibrated model was used for long-term (1982-2005) scenario analyses to estimate the effects of land use and conservation practice changes on runoff and sediment yield over a 24-year period. The scenario analyses were performed by initially conducting a baseline simulation for EHC4, and then replicating the land use and conservation practices implemented in EHC1 and EHC2 for EHC4 in two separate simulations. Historical climate data were used for all of the scenario simulations.

Results and Discussion

Sensitivity Analysis

The extended FAST method provides both first-order and total-order sensitivity indices. The total-order sensitivity index is generally greater than the first-order sensitivity index (fig. 3) because the total-order sensitivity index reveals an overall parameter influence. In this study, both the first-order and total-order sensitivity indices were considered during the ranking of the importance of the tested parameters (table 4). The CN_2 and CNIC (eq. 1) input parameters were both found to strongly influence surface runoff, and correspondingly affected water-induced sediment yield (table 4 and fig. 3). In addition to CN_2 and CNIC, sediment yield was also very sensitive to the choice of PEC and APM parameters (table 4 and fig. 3). The CNIC value regulates the effect of PET in driving the NRCS curve number retention parameter, as shown in equation 1. The impact of CNIC on runoff and sediment yield

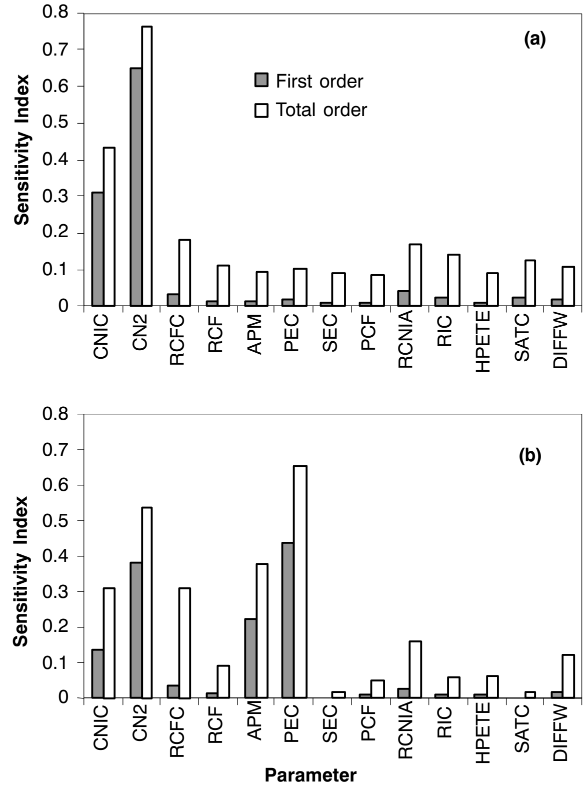

Figure 3. Total-order and first-order sensitivity indices for (a) runoff and (b) sediment yield based on average values of three plots.

was also identified by Wang et al. (2006d) for APEX. However, several other sensitive parameters reported by Wang et al. (2006d) were not found to be sensitive for the conditions simulated in this study, including the Hargreaves PET equation exponent (HPETE) for runoff and the RUSLE C factor coefficient (RCFC) for sediment yield. The parameters that were found to be the most sensitive in influencing the surface runoff and sediment yield estimates, respectively, were selected for calibrating APEX (table 4), i.e., CN_2 and CNIC for surface runoff and CN_2, CNIC, PEC, APM for sediment yield. These results are consistent with previous modeling studies that have reported the need to calibrate either the CN_2 value (e.g., Green et al., 2006; Jha et al., 2007; Stewart et al., 2006) or the PEC value (Bracmort et al., 2006). The model output was found to be effectively insensitive to the remaining parameters; thus, default values were chosen for those inputs, and no further calibration was performed.

Model Calibration

The CN_2 and CNIC values were initially adjusted for the runoff calibration, because runoff is the driving factor for the MUST sediment yield estimates (Williams and Izaurralde, 2006). Then the APM and PEC were calibrated for sediment yield. The model was first calibrated for EHC2, and then subsequent calibration was performed for EHC1 and EHC4. The EHC2 calibration resulted in CNIC, CN_2, APM, and PEC values of 1.5, 21, 0.1, and 0.21, respectively (table 4). The calibrated values of CNIC and APM were both within the recommended range (Williams et al., 2006) and were also used for the other two plots because they are climate related. Further runoff and sediment yield calibration resulted in CN_2 values of 21 for EHC1 and 65 for EHC4 (table 4) and PEC values of 0.29 for EHC1 and 0.72 for EHC4 (table 4). The PEC values for EHC1 and EHC2 were reduced approximately 60% and 71%, respectively, compared with the PEC value for EHC4. The EHC1 and EHC2 PEC values were also consistent with previously determined PEC values for similar conservation practices, as reported by Pan and Dong (2006) and Bracmort et al. (2006). The EHC4 fallow plot was simulated as bare soil in APEX; however, weed growth likely developed over the course of the field study, in spite of efforts to maintain the fallow conditions using manual weeding practices (table 1). Thus, the calibrated PEC and CN_2 values for the fallow condition (EHC4) were both lower than the standard tabulated values, to reflect partially vegetated conditions for the plot. Similar results have been reported for other studies, including a calibrated PEC value of 0.3 for cropland conditions in northeast Indiana that were not treated with any conservation practices (Bracmort et al., 2006).

The calibrated CN_2 values of 21 for EHC1 and EHC2 and 65 for EHC4 are both roughly 16% below the corresponding standard CN_2 values of 25 for woodland and 77 for fallow, as reported by Mockus (1969), for fallow conditions for a soil classified as hydrologic group A in good hydrologic condition. These calibrated CN_2 reductions are similar to reductions reported in some previous studies. A CN_2 reduction of about 19% was reported for a ridge-till system by Chung et al. (1999). They stated that such a reduction could be expected due to the mini-terracing effects of the ridges, based on cited expert opinion. Wang et al. (2005) further reported a maximum CN_2 reduction of 24% based on a storm-level runoff experiment (1993-1994) for fallow plots. The CN_2 adjustments performed here are also consistent with the viewpoints expressed by Jha et al. (2007), who discussed the need to adjust tabulated CN_2 values based on recommendations and results published by several other studies. It is useful to note that the calibrated CN_2 values of 21, 21, and 65 for EHC1, EHC2, and EHC4 are transformed to values of 25, 24, and 69 in APEX due to the slope adjustment effect, which are consistent with or closer to the standard table values reported by Mockus (1969). However, the slope effect is not incorporated within the original tabulated CN_2 values.

The summary statistics for the daily runoff and sediment yield comparisons that were computed for the 1982 calibration period are listed in table 5. The predicted average daily runoff was within 15% of observed values, and the predicted average daily sediment yield was within 20% of observed values. The EF values were all above 0.45, while the R^2 values exceeded 0.55. The majority of the daily variability was captured by APEX, as indicated by the average R^2 being over 0.7. The statistical results reported here meet the criteria established in this study based on the criteria described above and the guidelines suggested by Moriasi et al. (2007) and Chung et al. (1999). These statistical results also compare favorably with previous studies, including average storm event statistics reported by Saleh et al. (2004) for APEX, monthly and annual statistics reported by Chung et al. (1999, 2001, 2002) for EPIC, and daily statistics reported for several studies by Gassman et al. (2007) for the Soil and Water Assessment Tool (SWAT) model. The paired t-test for runoff and sediment had P-values above 0.4 (table 5), indicating that the predicted values agree well with observed values. Thus, the null hypothesis, that the difference between predicted and observed values are not significantly different from zero, was accepted at the significance level of $\alpha = 0.05$.

Daily time series of observed and predicted surface runoff and sediment yield are plotted in figures 4 and 5, respectively. The simulated surface runoff underpredicted the observed runoff values for the major storm event that occurred on 30 July 1982 for both EHC1 and EHC2 (fig. 4). This was especially true for EHC1, where the runoff was underpredicted by over a factor of 2. Conversely, the smaller surface events that occurred on later dates were overpredicted by APEX for the same two plots. However, the surface runoff estimates for EHC4 were in general much closer to the measured counterparts, as shown in fig. 4c, and are reflected in the statistics reported in table 5. Similar patterns occurred for the predicted sediment estimates, relative to the observed sediment loss measurements, for EHC1 and EHC2 (fig. 5). The predicted sediment estimates for EHC4 (fig. 5c) were not as accurate as the surface runoff estimates, which again are reinforced by the statistics listed in table 5.

Model Validation

The daily summary statistics that were computed for the 1983-1986 validation period are shown in table 6. The PE, EF, and R^2 values (table 6) were all found to be satisfactory, based on the previously established criteria. The predicted average daily runoff and sediment yield were within 20% and 25%, respectively, of the corresponding observed values. The EF values all exceeded 0.4, and the R^2 values were greater than 0.5 for all three plots. The daily time series of observed versus predicted surface runoff and sediment yield are plotted in figures 6 and 7, respectively. APEX tracked the daily level of observed surface runoff well for most of the events that occurred during the validation period, which is particularly no–

Table 5. Summary statistics for observed and predicted daily runoff and sediment yield for the 1982 calibration period.[a]

	Plot	Samples	Observed Mean	Observed SD	Predicted Mean	Predicted SD	PE (%)	EF	R^2	P-value[b]
Runoff			(mm day^{-1})							
	EHC1	10	19.7	51.2	22.5	27.9	14.2	0.52	0.56	0.81
	EHC2	10	11.1	29.4	12.7	23.7	14.4	0.70	0.71	0.76
	EHC4	11	31.7	49.2	35.6	62.7	12.0	0.89	0.98	0.45
Sediment yield			(kg ha^{-1} day^{-1})							
	EHC1	7	1719.2	3295.6	2045.5	2425.3	19.0	0.83	0.88	0.54
	EHC2	10	517.1	1172.9	606.8	873.2	17.3	0.67	0.68	0.68
	EHC4	9	1792.1	2264.9	2013.2	2777.2	12.3	0.48	0.66	0.69

[a] The statistics were computed on the basis of the days that storm event samples were collected (table 3).
[b] Hypothesis H_0: the difference between the paired predicted and observed values is not significantly different from zero. H_0 is rejected if the P-value is less than the level of significance ($\alpha/2 = 0.025$).

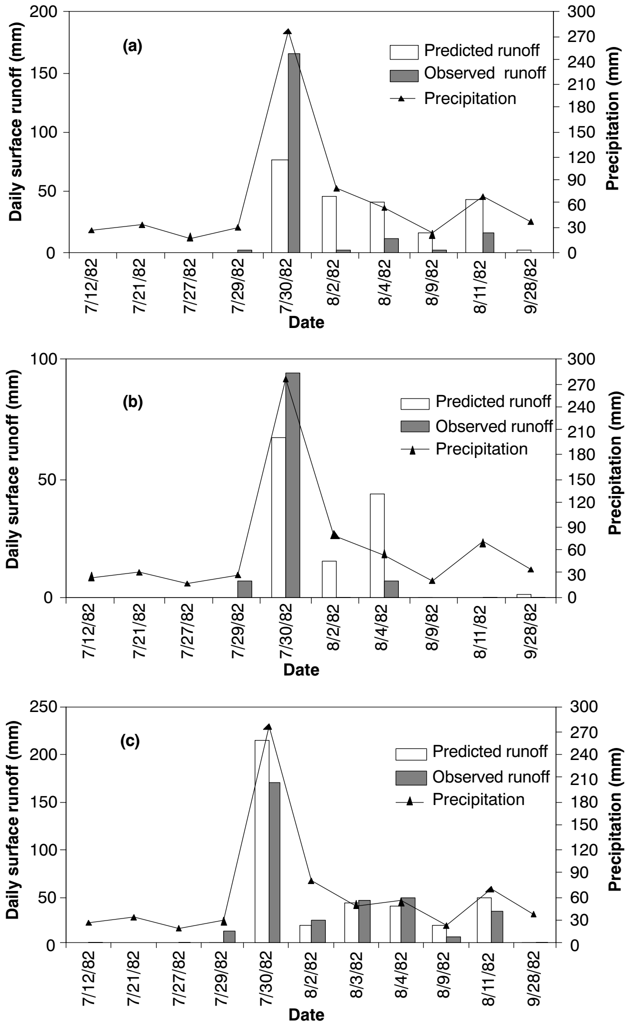

Figure 4. Precipitation vs. observed and predicted daily runoff for the calibration period for (a) EHC1 (10 events), (b) EHC2 (10 events), and (c) EHC4 (11 events). Precipitation values are on the right vertical axis.

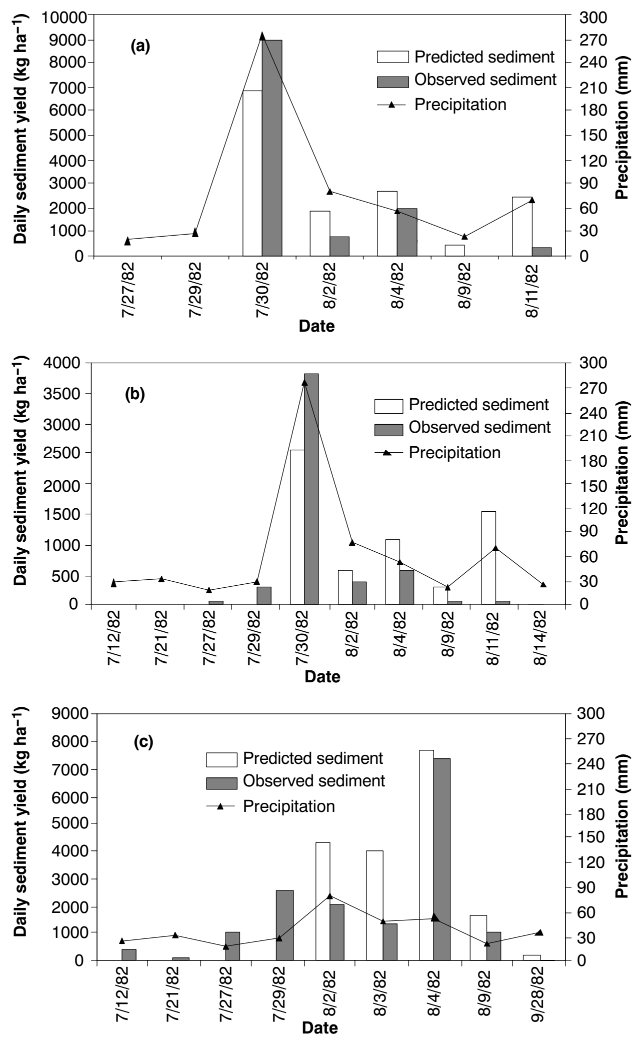

Figure 5. Precipitation vs. observed and predicted daily sediment yield for the calibration period for (a) EHC1 (7 events), (b) EHC2 (10 events), and (c) EHC4 (9 events). Precipitation values are on the right vertical axis.

table considering the small amounts of surface runoff that occurred. Both overprediction and underprediction occurred for some of the measured sediment loads, but the magnitudes of the predicted sediment yields were very consistent with the measured values, which is further underscored by the statistics reported in table 6. The P-values of the paired t-test indicated that the predicted surface runoff and sediment yield agree well with observed values for all plots (table 6).

The average value of the ratio of predicted daily runoff versus precipitation was 1.6%, 1.1%, and 20.6% for EHC1, EHC2, and EHC4, respectively, which are comparable with the corresponding observed values of 2.1%, 1.6%, and 22.2% for the three plots. Higher runoff and sediment yields were always estimated for the simulated and measured EHC4 values as compared to EHC1 and EHC2 during the same daily rain–

Table 6. Model evaluation statistics for observed and predicted daily runoff and sediment yield for the 1983-1986 validation period.[a]

			Observed		Predicted		PE			
	Plot	Samples	Mean	SD	Mean	SD	(%)	EF	R^2	P-value[b]
Runoff			(mm day^{-1})							
	EHC1	9	0.9	0.5	0.7	0.7	-16.4	0.41	0.77	0.23
	EHC2	7	0.7	0.5	0.6	0.6	-18.7	0.52	0.72	0.34
	EHC4	5	6.9	5.2	6.5	2.0	-5.5	0.50	0.72	0.83
Sediment yield			(kg ha^{-1} day^{-1})							
	EHC1	6	82.5	151.8	62.0	100.2	-24.9	0.73	0.81	0.54
	EHC2	8	15.8	28.7	15.5	30.0	-1.6	0.84	0.85	0.95
	EHC4	6	362.7	535.1	440.0	486.3	21.3	0.49	0.55	0.63

[a] The statistics were computed on the basis of the days that storm event samples were collected (table 3)
[b] Hypothesis H_0: the difference between the paired predicted and observed values is not significantly different from zero.
H_0 is rejected if the P-value is less than the level of significance ($\alpha/2 = 0.025$).

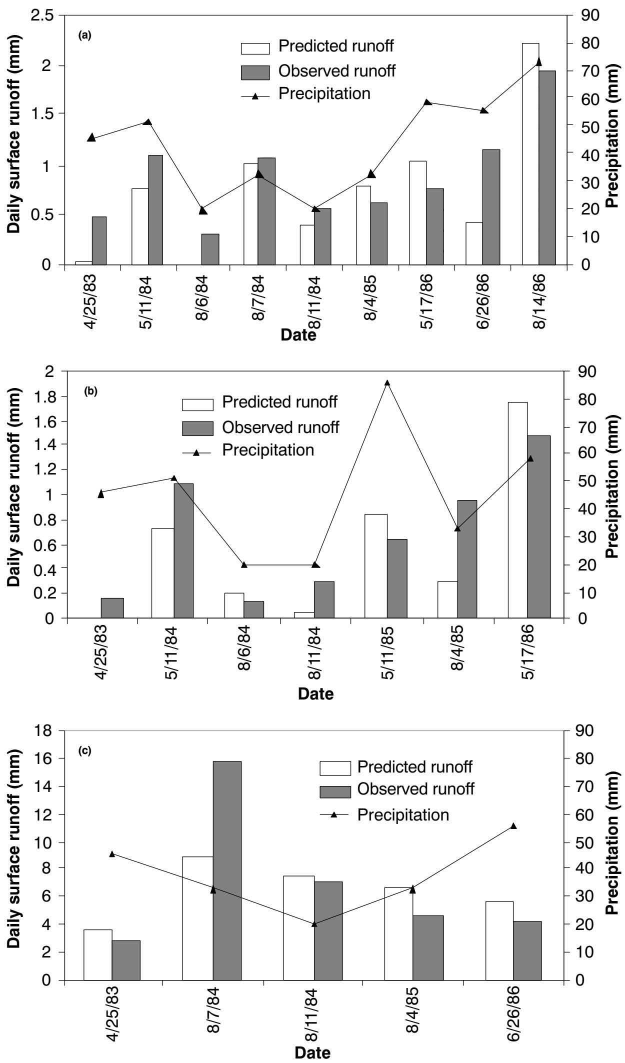

Figure 6. Precipitation vs. observed and predicted daily runoff for the validation period for (a) EHC1, (b) EHC2, and (c) EHC4. Precipitation values are on the right vertical axis.

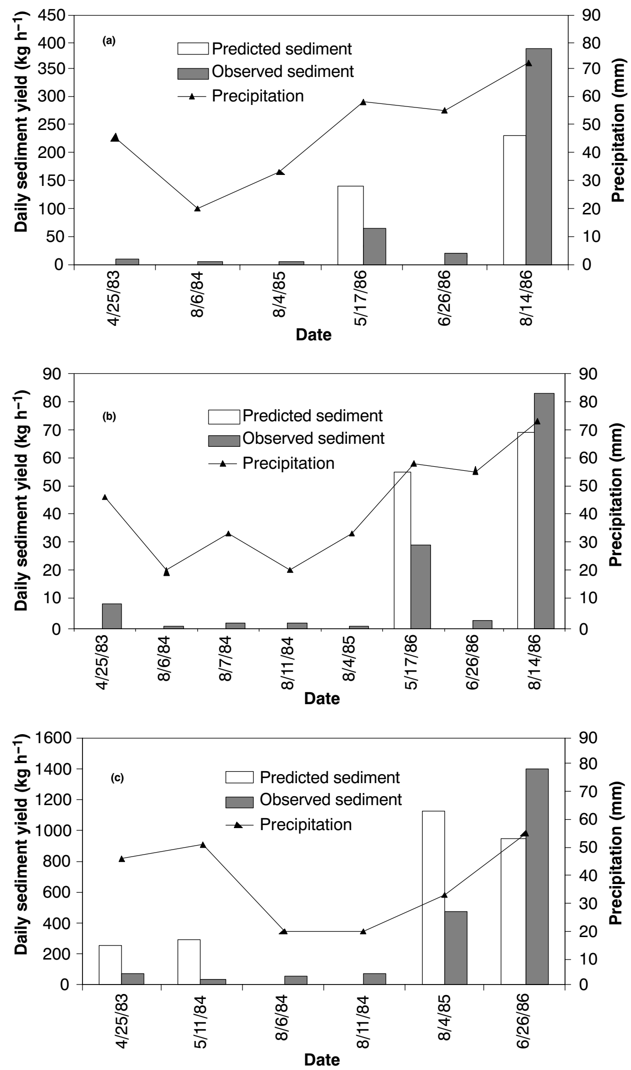

Figure 7. Precipitation vs. observed and predicted daily sediment yield for the validation period for (a) EHC1, (b) EHC2, and (c) EHC4. Precipitation values are on the right vertical axis.

fall events. Increased evapotranspiration and infiltration due to vegetative land cover contributed to the reduction in storm runoff from the EHC1 and EHC2 plots. The reduction in storm runoff and the conservation practices applied in EHC1 and EHC2 clearly further contributed to the reduction in sediment yield from the two plots.

Benefits of Conservation Practices

The long-term (1982-2005) benefits of mixed wood-grass in combination with horizontal terraces (scenario 1) and woodland with horizontal-level ditches (scenario 2) were compared versus baseline fallow conditions (table 7), following completion of the model testing phase. The previously

Table 7. Predicted runoff and sediment yield based on annual values (1982-2005).

		Predicted Runoff (mm year^{-1})			Predicted Sediment Yield (Mg ha^{-1} year^{-1})		
		Mean	Benefit[a]		Mean	Benefit[a]	
Plot	Scenario	(SD)	Amount	(%)	(SD)	Amount	(%)
EHC4	Baseline: Fallow	107.9 (110.7)	--	--	26.5 (26.0)	--	--
	Scenario 1, originally applied to EHC1: Mixed wood-grass with horizontal terraces	70.6 (100.3)	37.3	35	4.1 (7.5)	22.4	84
	Scenario 2, originally applied to EHC2: Woodland with horizontal-level ditches	67.9 (96.6)	39.9	37	2.8 (4.9)	23.7	89

[a] Model output differences between the baseline and scenarios 1 and 2.

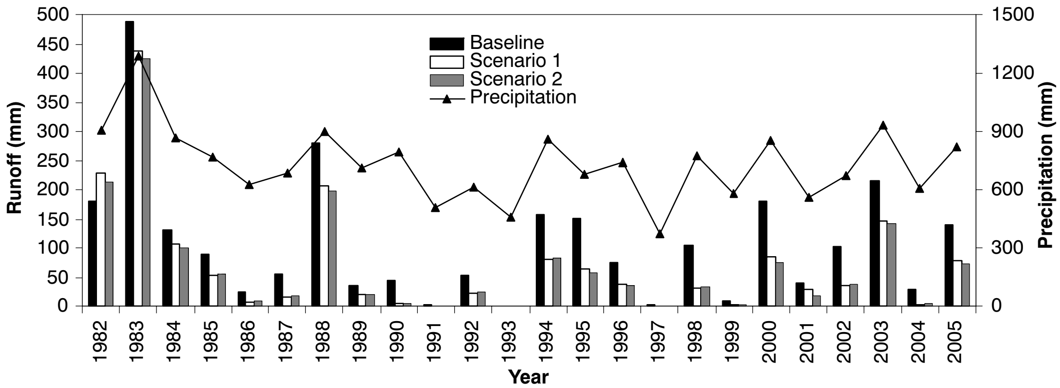

Figure 8. Precipitation and predicted annual surface runoff from EHC4 for the baseline (fallow with no conservation practice), scenario 1 (mixed wood-grass with horizontal terraces), and scenario 2 (woodland with horizontal-level ditches). Precipitation values are on the right vertical axis.

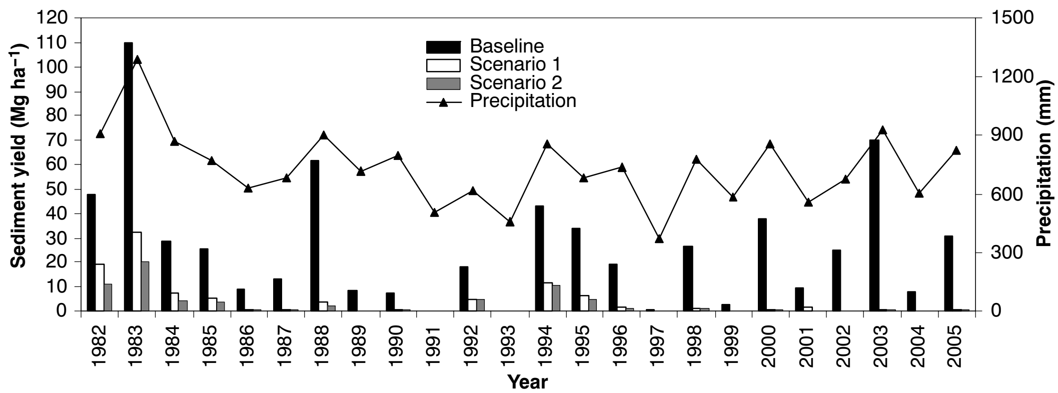

Figure 9. Precipitation and predicted annual sediment yield from EHC4 for the baseline (fallow with no conservation practice), scenario 1 (mixed wood-grass with horizontal terraces), and scenario 2 (woodland with horizontal-level ditches). Precipitation values are on the right vertical axis.

described calibrated parameters were used for the long-term simulations of each of the respective systems. Each scenario run was performed using the EHC4 landscape and area characteristics.

The long-term benefits of scenarios 1 and 2 over the baseline were quantified as reductions of surface runoff ranging from 35% to 37% and sediment yield reductions that ranged from 84% to 89% (table 7). The two vegetation-conservation practice scenarios were predicted to be very effective for surface runoff and sediment yield control at the field/plot level at the study site. The orientation of terraces or level ditches along the contour encouraged rainfall to infiltrate into the soil, which contributed to surface runoff reduction. The increased land cover of trees and mixed wood-grass also contributed to the reduction of surface runoff via canopy interception, increased water use, and the effects of surface roughness and cover. Water-induced soil erosion was reduced due to both surface runoff reduction and the conservation practices, as discussed previously for the model testing phase of the study.

The annual time-series surface runoff and sediment yield for the scenario simulations are plotted in figures 8 and 9, respectively. The runoff reduction benefit was about 4% for EHC1 and 8% for EHC2 during the vegetation/land cover establishment period (1982-1984). The sediment yield was reduced about 70% and 80% during 1982-1984 due to the establishment of the conservation practices in scenarios 1 and 2, respectively, as compared to the baseline. The horizontal terraces and horizontal-level ditches reduced surface runoff accumulation along the slope length, and in turn the water erosion power, and encouraged sediment deposition. The highest annual runoff equaled 489 mm for the fallow condition, 437 mm for scenario 1, and 424 mm for scenario 2, in response to 1285 mm of precipitation in 1983 (fig. 8). The highest sediment yield took place in 1983 because highly concentrated rainfall and runoff events occurred during that year. The baseline (fallow) scenario produced the highest level of sediment yield (110 Mg ha^{-1}), followed by scenario 1 (32 Mg ha^{-1}) and then scenario 2 (20 Mg ha^{-1}) in 1983 (fig. 9).

Scenarios 1 and 2 generated very similar results (figs. 8 and 9), which is not surprising because the same initial calibrated CN_2 values were used for the two practices, which were installed in plots with the same slope. However, different combinations of land use and conservation practices may produce similar effects for runoff and sediment control. Both cost-efficiency and what fits within the capacity and farming system of the local farmers might need to be considered when choosing alternative strategies for soil and water conservation purposes. The APEX model has an economic component for calculating cost; however, an economic analysis was beyond the scope of this study.

CONCLUSIONS

The sensitivity analysis conducted during 1982-1986 for the APEX runoff and sediment components included the same 13 input parameters for the three different plots located at the Lushan Soil and Water Conservation Experimental Station in Henan Province, east central China. SIMLAB software was used to conduct the extended FAST sampling and sensitivity analysis. The condition 2 curve number (CN_2), curve number index coefficient (CNIC), conservation practice factor (PEC), and peak runoff rate – rainfall energy adjustment factor (APM) were identified as being very influential at the study site.

These parameters were selected to calibrate the APEX model using the observed daily runoff and sediment yield samples collected for each plot in 1982. The automatic calibration procedure described by Wang et al. (2006c) was used for this study, which utilized Monte Carlo simulation and multi-objective function techniques. The predicted average daily runoff and sediment yield were within 15% and 20% of the associated observed values, respectively, for the 1982 calibration period. The EF values ranged from 0.48 to 0.89 and R^2 ranged from 0.56 to 0.98 for the calibration period. The predicted average daily runoff and sediment yield were within 20% and 25% of the corresponding observed values for the 1983-1986 validation period. The calibrated APEX model tracked the variability of daily runoff and sediment yield well for the validation period, with EF values ranging from 0.41 to 0.84 and R^2 ranging from 0.55 to 0.85. The goodness-of-fit measures revealed that the individual variations in the observed values were reasonably explained by the APEX model.

The calibration and validation results suggest that APEX is a useful tool for evaluating surface runoff and soil loss for different management practices in the middle Huaihe River watershed, China. The modeling approach was applied for scenario analyses to estimate the long-term (1982-2005) effects of alternative land use and conservation practice scenarios on surface runoff and sediment yield. Modeling outputs from EHC4 (fallow with no conservation practice) were used as a baseline to estimate the reductions from scenario 1 (mixed wood-grass with horizontal terraces) and scenario 2 (woodland with horizontal-level ditches). The results indicate that construction of horizontal terraces and horizontal-level ditches, and reforestation or revegetation, can be very effective in controlling surface runoff and sediment yield in the region. The woodland with horizontal-level ditches resulted in a 37% reduction of surface runoff and 89% of reduction sediment yield over the baseline condition. Construction of horizontal terraces with mixed wood-grass vegetation resulted in a 35% reduction of surface runoff and 84% reduction of sediment yield over the 24-year simulation period.

The results found here indicate that suitable agricultural management practices are beneficial for reducing soil and water loss, and for maintaining sustainable environmental development in the middle Huaihe River watershed. However, further research with additional data sets is needed to evaluate the applicability of APEX for other cropping and conservation practice conditions in the region, including expanded soil sampling and surface runoff measurements. It is particularly vital to test the model with data collected during storm events that generate high surface runoff, due to the limited number of runoff samples available for this study that were collected during precipitation events that typically resulted in low levels of runoff. Additional testing of sensitive parameters such as the CN_2 values will also be an important component of future research, including in-depth assessment of variations in cropping systems, conservation practices, differences in slope steepness, and scale effects. This could lead to more refined CN_2 choices for different combinations of vegetations and management systems, such as improved CN_2 values to depict differences between the EHC1 and EHC2 systems described here, and the best choice of CN_2 values for plots and fields versus larger watersheds.

It will also be important to incorporate future improved versions of APEX in applications for the middle Huaihe River watershed and other regions of China, which among other enhancements will include revised algorithms for estimating hydraulic conductivity, field capacity, and wilting point computed as a function of soil texture and other standard soil layer inputs. Initial testing of these functions indicates that they provide more accurate estimates of key APEX soil water parameters versus the routines used in currently available versions of the model (J. R. Williams, 2008, personal communication, Blackland Research and Extension Center, AgriLife Research and Extension, Texas A&M System, Temple, Texas).

Finally, the limitations of this study also point to a need for strengthening conservation practice research programs in China, which should incorporate interfaces between modeling and field data collection programs as opposed to traditional standalone efforts. A model can provide feedback to a data collection program, which can be used to enhance the experimental design, eliminate ineffective BMPs, expand temporal and spatial scales, and ultimately advance research in a more efficient manner. BMPs that are identified as being ineffective, or that have high establishment or maintenance costs, can be eliminated from studies to focus resources on more promising BMPs. This process would also support more efficient selection of optimal parameters for simulating conservation practices in APEX and other models. This could include adopting semi-automated (automatic plus manual) calibration procedures, which would facilitate adjustment of key input parameters, such as the initial CN_2 values, by first conducting automatic calibration followed by manual calibration for final refinement of selected input parameters.

Acknowledgements

This work was supported by Huaihe River Water Resources Commission through the Process and Evaluation of Remote Sensing Data of Soil and Water Loss in Huaihe River Watershed Project. Appreciation is expressed to Dr. J. R. Williams and Dr. X. S. Jiang for their support and help during the study.

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