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WEPP Model Application in CEAP Watersheds in NE Indiana

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Abstract. The Conservation Effects Assessment Project (CEAP) of the United States Department of Agriculture (USDA) is targeted at determining the impacts of conservation practices on off-site losses of sediment, nutrients, and pesticides. One of the Agricultural Research Service (ARS) benchmark CEAP watersheds is the St. Joseph River Watershed, located in northeastern Indiana, northwestern Ohio, and southern Michigan. The USDA-ARS National Soil Erosion Research Laboratory (NSERL) in West Lafayette, Indiana, has been conducting field and watershed monitoring in sub-basins of the St. Joseph River watershed since 2002. The area is largely agricultural, with major crops of corn and soybeans. Soils are moderately to poorly drained, and the topography is flat to gently rolling, with large numbers of closed surface depressional areas (potholes). While a number of hydrology and pesticide simulations have been conducted for this location with larger scale watershed models, no detailed modeling of sediment loss has been done up to this point. This paper will describe application of the Water Erosion Prediction Project (WEPP) model to small fields (~2 ha) where detailed measurements of climate, soil properties, topography, management, and storm runoff and sediment loss are available. Adequacy of WEPP model predictions will be evaluated, and model calibration and validation results presented. WEPP was also applied to the next larger scale of watersheds (~250 ha) to determine potential effects of land management practices there on runoff and sediment loss. Some typical alternative management practices evaluated were conservation tillage, buffer strips, and conversion of critically eroding regions to forest or grass.

Keywords. CEAP, WEPP, runoff, erosion, modeling, soil loss, sediment, calibration, validation

Introduction

Soil erosion of agricultural land continues to be a problem, both within the United States, as well as throughout the world. Soil detached by raindrops and flowing water carries with it precious organic matter and nutrients as it is transported from field to channels to streams. Sediment remains the largest water pollutant by volume, and billions of dollars are spent each year to dredge channels, rivers and harbors to maintain water flow and navigation. The nutrients (Nitrogen and Phosphorus) in the water and attached to the sediment contribute to water quality problems, such as eutrophication in lakes, and hypoxia in water bodies such as the Gulf of Mexico.

Soil conservation practices are frequently applied to control soil erosion and reduce sediment movement from fields. The Conservation Effects Assessment Project (CEAP) is a multi-agency USDA project aimed at determining the effects that these conservation practices have on off-site water quality (Mausbach and Dedrick, 2004). Both the Natural Resources Conservation Service (NRCS) and the Agricultural Research Service (ARS) are conducting research, modeling, and watershed assessment studies to estimate how soil conservation practices impact sediment, nutrient, and pesticide levels in streams, rivers, and lakes.

ARS research scientists have been examining fourteen benchmark watersheds throughout the U.S. One of these is the 281,000 ha St. Joseph River Watershed (SJRW), located in northeastern Indiana, southern Michigan, and northwestern Ohio (Figures 1 and 2). The SJRW is the source of drinking water for the city of Fort Wayne, Indiana (population ~250,000), and significant concerns there are related to nutrient and pesticide contamination of agricultural runoff water that ultimately reaches the water treatment plant (Flanagan et al., 2003; Flanagan et al., 2008). The ARS National Soil Erosion Research Laboratory (NSERL) has been conducting extensive monitoring of several nested watersheds there since 2002, focusing efforts within the Cedar Creek subcatchment (Figures 2 and 3). Cedar Creek is the largest tributary to the St. Joseph River, and contains soils and agricultural management systems typical of the entire SJRW. The region is largely agricultural land (~79%) that is predominantly used for production of corn and soybeans. Topography is generally flat to gently rolling with morainal hills composed of till or sand and gravel, with local relief ranging from 30 to 60 meters and many depressional areas that hold water after large rainfall events (SJRWI, 2005; Greeman, 1994).

Figure 1. Location of the St. Joseph River Watershed in the midwestern United States.

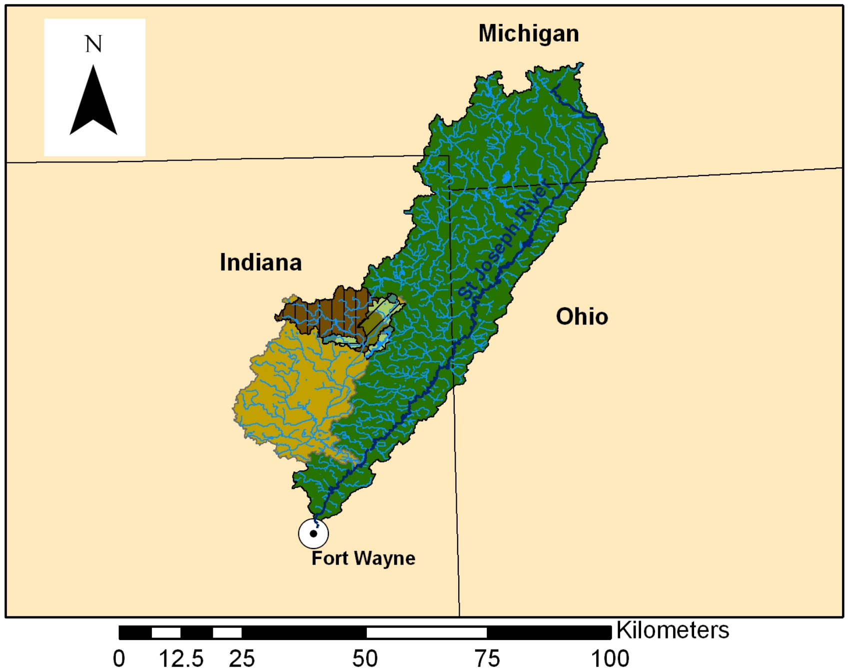

Figure 2. The St. Joseph River Watershed is the source of drinking water for the city of Fort Wayne, Indiana. The Cedar Creek subcatchment is shown in shades of tan and brown.

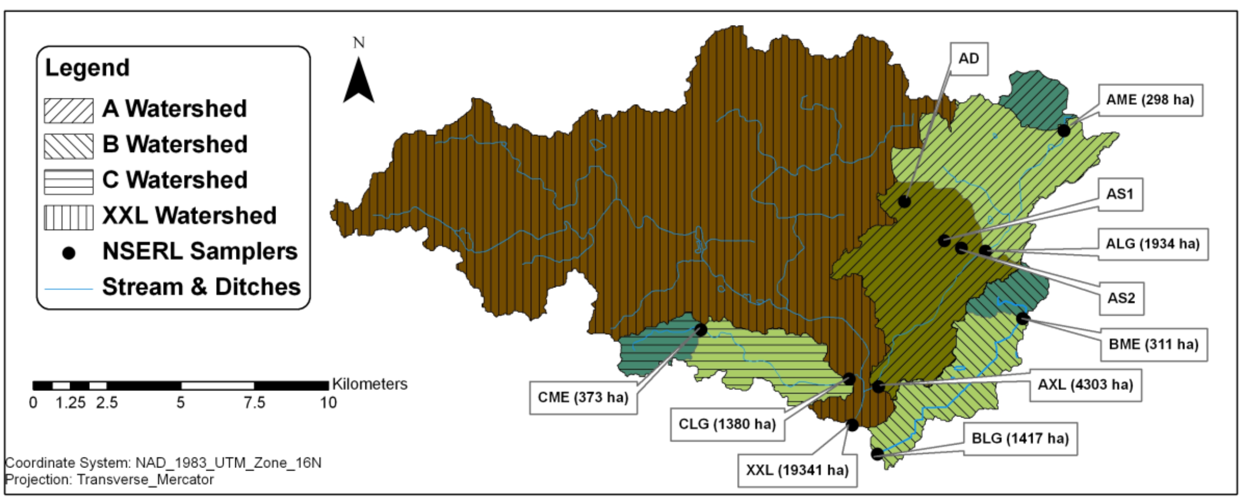

Figure 3. Portion of Upper Cedar Creek, with NSERL watersheds and water quality monitoring sites shown.

There are currently 12 catchments being monitored by the NSERL, ranging in size from 2 to 19,300 ha. The smallest 4 sites are field catchments: AS1 (2.0 ha), AS2 (2.5 ha), ADW (4.0 ha), and ADE (4.5 ha). At these locations runoff is measured and samples collected for the determination of both chemicals in the runoff as well as sediment loss, from individual storm events. The other monitoring sites are larger ditch locations, where flow is measured and runoff samples collected for chemical analyses.

In this paper, we will discuss application of the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) to estimate runoff and soil losses occurring from the AS1 and AS2 small field watersheds. Additionally, results of WEPP applications to a larger (BME) watershed to assess the potential impacts of various conservation practices on runoff and sediment losses are also presented.

Materials and Methods

WEPP Model

The Water Erosion Prediction Project (WEPP) model is a process-based, spatially distributed erosion prediction computer program, implemented for use on personal computers (Flanagan and Nearing, 1995; Flanagan et al., 2007). WEPP simulates many of the important physical processes that impact the detachment, transport, and deposition of sediment by rainfall and flowing water. The model can be executed in both a single storm and continuous simulation mode, and can be applied to hillslope profiles and small field-scale catchments. WEPP was initiated in 1985, and publicly released in 1995, and has been continuously maintained and updated by the ARS NSERL since then. The latest release of the model is version 2010.1, in January 2010 (USDA-ARS, 2010). The WEPP system consists of a variety of user interface programs and nationwide databases for climate, soils, and land/management. There are also geospatial interfaces available for use on watershed for which detailed geo-referenced topographic, soils, and land-use information are available, including GeoWEPP (Renschler et al., 2002; Renschler, 2003) which is an ArcView/ArcGIS extension. Input files for WEPP and GeoWEPP are described in Table 1.

Table 1. GeoWEPP and WEPP input files and sources of data.

GeoWEPP input files	**Sources of data for AS field sites**	**Sources of data for BME watershed**
DEM	RTK-GPS elevation measurements	USGS 10-m DEM
land use file	farmer	USDA-NASS data
soil file	collected soil samples	SSURGO data
WEPP input files	**Sources of data for AS field sites**	**Sources of data for BME watershed**
climate file	measured weather data	measured and CLIGEN-generated
slope file	developed by GeoWEPP from DEM	developed by GeoWEPP from DEM
management file	farmer	USDA-NASS and WEPP database
soil file	collected soil samples	SSURGO data

Model Inputs and Data Layers Developed

AS1 and AS2 are small agricultural field watersheds located in DeKalb County in northeastern Indiana, at an elevation of approximately 275 meters above sea level. AS1 has an area of 2 ha and has been managed as a no-till field in corn and soybean production for the past 20 years. AS2 is slightly larger, with an area of 2.5 ha, and has been in a rotational tillage system (since 2004), consisting of spring tillage prior to corn planting, and no-tillage for soybean production (prior to 2004, this field was also in long-term continuous no-till). Monitoring of climate, runoff and sediment losses has been conducted at the outlets of these two sites since 2004 by the NSERL. Continuous WEPP model simulations were conducted using observed climate, soil, slope, and management information for the 3-year period from 2006 to 2008.

The first step in creating the WEPP model setups was creation of digital elevation models (DEM). DEMs were developed based on elevation measurements using RTK-GPS data for each watershed collected in 2003, having a resolution of 1 m^2 per pixel. The DEM was used as inputs to the TOPAZ program (Garbrecht and Martz, 1997) in GeoWEPP, to delineate watershed boundaries, hillslope regions and channel sections, and generate slope input files for every model component (hillslopes and channels). Both AS1 and AS2 model structures consisted of 3 channels and 8 hillslopes (Figure 4), with slope gradients ranging from 0-10%.

One management file and one soil input file were assigned to each model component (each hillslope profile or channel), and a single breakpoint climate file was used for both watersheds simulated. Management files were organized according to field operation descriptions and dates provided by the farmer. A corn and soybean rotation was present in both watersheds. In the no-till AS1 watershed, only a no-till planter was used to plant corn and a no-till drill to plant soybeans. In the AS2 watershed, rotational tillage was performed with a single gang disk-field cultivator-harrow before corn planting, and with a no-till drill for planting soybeans. The tillage database, which is part of WEPP, was used to determine detailed tillage parameters (e.g. ridge interval, mean tillage depth). In the initial conditions input, the initial plant (soybeans for both sites) was specified, number of days since last tillage, the number of days since last harvest and the cumulative rainfall since last tillage. Default values were used for the remaining parameters.

Apart from descriptions of the crops planted and implements used, the management input file interface also provides an option to specify drainage existing in the watersheds. Although there are no exact drawings of drainage systems, a tile is located approximately in the middle of each field in the direction of the outlet. In AS2, the single tile splits into two tiles somewhere in the middle of the field. The drainage is composed of a perforated plastic pipe 0.1 m in diameter buried 1 m deep in AS1 (0.15 m in diameter and 0.8 m deep in AS2). In both watersheds, the spacing of tiles was estimated to be 70 meters.

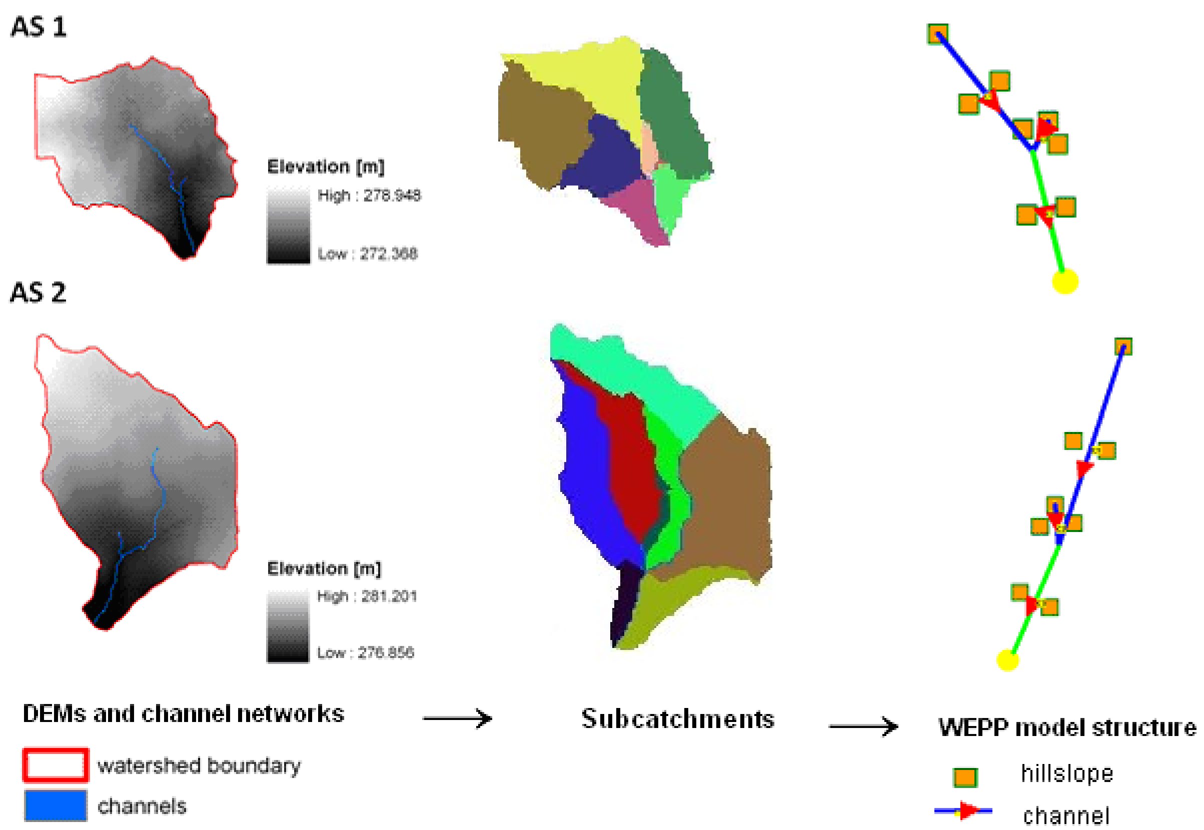

Figure 4. Digital elevation models of AS1 and AS2 watersheds, respective subcatchments and WEPP model structures.

Soil characteristics were obtained from a texture analysis of soil samples. Samples were collected at 5 depths (50, 150, 300, 450 and 600 mm) in a 35 x 35 meter spatial network at both sites (Figure 5). There were 19 sample locations at AS1, and 23 at AS2. Texture data represents averages of all samples collected at each site. Values of albedo, initial saturation level, organic matter content, cation exchange capacity (CEC) and rock percentage were estimated. Values of baseline interrill erodibility (K_i), rill erodibility (K_r), critical hydraulic shear (τ_c) and effective hydraulic conductivity (K_b) were calculated by using the equations suggested in the WEPP User Summary (Flanagan and Livingston, 1995). Soil input parameters are summarized in Tables 2 and 3. Use of SSURGO soil data was also considered, but when comparing the textures of the prevailing soil types (Glynwood loam on AS1 and Blount silt loam on AS2) with the field measured soil sample analysis results, major differences in texture were observed (up to

15% for AS1, and up to 30% for AS2). Thus, the SSURGO soil data were not used for the small field watersheds.

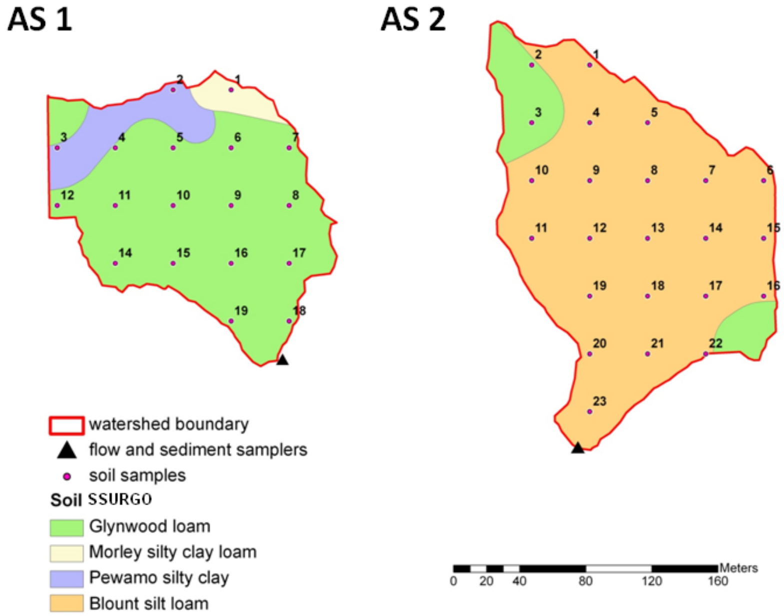

Figure 5. Locations of collected soil samples and soil types according to SSURGO.

Table 2. Soil input data for different soil layers.

Watershed	Depth [cm]	Sand [%]	Clay [%]	Silt [%]	Texture	Organic matter [%]	CEC [meq/100g]	Rock [%]
AS1	0-5	46.4	17.1	36.5	loam	4.0	10	5
	5-15	42.3	20.7	37.0	loam	3.0	10	5
	15-30	37.6	26.0	36.4	loam	2.0	10	5
	30-45	45.7	30.9	23.4	sandy clay loam	1.0	22	5
	45-60	36.4	36.5	27.1	clay loam	0.5	22	5
AS2	0-5	34.2	21.7	44.1	loam	4.0	10	5
	5-15	27.7	26.4	45.9	loam	3.0	10	5
	15-30	25.4	33.4	41.2	clay loam	2.0	22	5
	30-45	26.3	38.0	35.7	clay loam	1.0	22	5
	45-60	25.1	39.4	35.5	clay loam	0.5	22	5

Table 3. Soil input data for small field watersheds.

Watershed	Albedo	Initial sat. level [%]	K_i [kg*s/m^4]	K_r [s/m]	τ_c [Pa]	K_b [mm/h]
AS1	0.12	70	4340680	0.004513	4.41	10.38
AS2	0.12	70	4162987	0.004236	3.65	6.74

One climate input file was used for simulations at both sites, since they are located only ~0.5 km apart. Weather data were obtained from gauges at AS1, where solar radiation, wind speed, wind direction, air temperature, relative humidity, and rainfall are measured. A breakpoint precipitation format WEPP input climate file was created for 2006-2008. Total observed rainfall was 1024 mm in 2006, 1090 mm in 2007, and 940 mm in 2008.

Calibration and Validation Approach Employed on Small Field Watersheds

Continuous simulations were run on both watersheds, beginning on January 1, 2006 and ending on December 31, 2008. The goal was to calibrate the model to surface runoff and sediment yields by comparing simulated values with data obtained from the NSERL runoff and sediment samplers.

The model calibration and validation on runoff was done by comparing daily runoff for days when the rainfall exceeded 25 mm, for all other days, for all observed days, and by comparing annual values. There were a total of 31 days with observed runoff on AS1 and 59 days on AS2 in the 3-yr period. Rainfall exceeded 25 mm on 8 days on AS1 and on 11 days on AS2.

Because there was a large number of missing or bad observed data points for sediment yields, model calibration and validation for soil loss was done by comparing daily values for selected days only. Due to the occasional malfunction of the sediment sampler, the reliability of the observed data was questionable. As the dates and times of the samplers' malfunctions were not recorded, it was impossible to completely distinguish correct and incorrect data. However, as the times and rates of runoff are recorded when sediment samples are pulled, it was possible to fairly well identify correctly sampled soil loss event. In this way, sediment data from 7 event dates were selected for AS1 and 12 event dates were selected for AS2.

The division of the identified storm events into ones used for sediment calibration and validation was done with consideration of the magnitude of the data values, so that small and large values of sediment yields were evenly distributed between calibration and validation. The range of values used for calibration was 0.3 – 1032 kg/day of sediment, the range of values used for validation was 0.3 – 644.4 kg/day.

Statistical evaluation methods used

The models were calibrated first on runoff by optimization of baseline effective hydraulic conductivity. Consequently, a sensitivity analysis was performed to determine whether for these watersheds WEPP would respond most to interrill erodibility, rill erodibility or critical shear stress. The most sensitive parameters were then optimized during the model calibration of sediment yield. The goal of the calibration process was to obtain values of parameters which, when applied to the model, would provide the best matching results with the observed data for a given series of events. To impartially determine the goodness of fit between 2 datasets, an objective function was selected. Because the value of this function reflects the goodness of fit, a search algorithm was employed to find its minimum or maximum (depends on the type of selected function). For this study, the Nash-Sutcliffe model efficiency (known also as the coefficient of efficiency, Nash and Sutcliffe, 1970) was used as the objective function and the Golden Search (search by golden section, Himmelblau, 1972) as the search algorithm.

The Nash-Sutcliffe model efficiency represents how well the predicted data compares to the 1:1 line (line of measured values equals predicted values), and it takes the correlation and bias of these two datasets into account. The value of the efficiency ranges from $-\infty$ to 1, with 1 being a perfect prediction. A model gives reasonable predictions if its efficiency is between 0 and 1. If the value is negative, the predictions are unreliable and an average of output values is a better estimate than the predictions. So the goal of the calibration process was to maximize the value of efficiency, or at least to achieve positive values. Nash–Sutcliffe model efficiency is defined as:

$$E = \frac{\sum_{i=1}^{n}(Q_m - Q_{avg})^2 - \sum_{i=1}^{n}(Q_m - Q_p)^2}{\sum_{i=1}^{n}(Q_m - Q_{avg})^2} \qquad [1]$$

where: E is the Nash–Sutcliffe efficiency, Q_m is the measured value, Q_{avg} is the arithmetic mean of the measured values, Q_p is the predicted value, and n is the number of observations.

The Golden search is an algorithm for a one-dimensional search for the minimum or maximum of a function in a defined interval. This interval is called "initial interval". The algorithm consists of a number of steps, starting with splitting the initial interval into two partially overlapping intervals in the ratio of golden section. The size of interval is reduced until the user specified size is reached. The ratio is defined in the following equations:

$$F_1 = \frac{3 - \sqrt{5}}{2} \approx 0.38 \quad [2]$$

$$F_2 = \frac{\sqrt{5} - 1}{2} \approx 0.62 \quad [3]$$

The Golden search was used for finding the maximum Nash–Sutcliffe model efficiency value. The initial intervals for optimized parameters were defined based on the natural range of optimized baseline values (0.05 – 200 mm/h for effective hydraulic conductivity, 2,000,000 – 11,000,000 kg*s/m^4 for interrill erodibility, 0.001 – 0.03 s/m for rill erodibility and 1 – 6 Pa for critical hydraulic shear).

Application of WEPP to Medium-sized BME watershed description

WEPP was applied to a larger watershed, to assess the potential impacts of various management practices on predicted runoff and soil loss. The BME watershed is also located in DeKalb County in Indiana (Figure 3). It has a total area of 254.6 ha, with 73% in agriculture, 25% in grass or woodland areas, and the rest consisting of impervious residential areas. Monitoring of climate and flow rates in the ditch has been conducted at the outlet of the watershed since 2002 by the NSERL. Water samples for analysis of pesticide and nutrient losses are collected during base flow and events; however, sediment losses have not been measured. Continuous WEPP model simulations were conducted using observed climate, soil, slope, and management information for the 2-year period from 2008 to 2009 to calibrate the model for runoff predictions. These 2 years were selected due to the availability of detailed land management data. Subsequently, 20-year simulations with synthetic climate were conducted to evaluate and compare various land management and conservation practices.

A DEM from the USGS 10-m (1/3 arc second) National Elevation Dataset (USGS, 2010) was projected to Universal Transverse Mercator (UTM) NAD83, Zone 16 for the state of Indiana, re-sampled to an exact 10 meter grid, and burned in one meter with the stream networks from the National Hydrography Dataset (NHD). GeoWEPP was used to develop the WEPP model structure, which for the BME watershed consisted of 98 hillslopes and 40 channels, with slope gradients ranging from 0-10%.

The agricultural fields in BME have been managed as no-till, reduced till and conventional till in corn - soybean, corn – small grain (barley was chosen to represent small grain), and soybean – small grain rotations (Table 4). The exact dates of field operations and types of implements used were not known. However, reasonable estimates were used to fill in the missing data. It was assumed that conventional tillage consisted of fall chisel plowing, spring cultivation one week prior to planting and a standard row planter for corn cultivation and a conventional drill for planting soybeans and small grains. Reduced tillage was also simulated with a standard planter for corn and conventional drill for soybeans and small grain, but omitting the fall chisel plow and field cultivation. A no-till row planter and no-till drill were used for no-till management corn and soybean planting, respectively. The dates of field operations were set according to the “Crop Progress & Condition Reports” for Indiana developed by the National Agricultural Statistics Service (USDA-NASS, 2009). Dates of planting/harvesting for a chosen crop were rated at the weeks when the highest percentage of the crop was planted/harvested in Indiana based on the reports. The row width was set to 80 cm for corn, 20 cm for small grain, 30 cm for regular soybeans, and 20 cm for soybeans planted in narrow rows. The management input files “Grass.rot”, “Forest Perennial.rot” and “Pavement.rot”, which are part of the WEPP model distribution, were used to simulate grassed, forested and impervious areas. For the “grass with grazing” areas, a new input file was developed, based on “Grass.rot” file, and adding a grazing schedule beginning 1 April and ending 30 October. Grazing rate was set to 1 cow per 2 hectares. No drainage was specified on BME. All land use types are displayed in Figure 7.

The SSURGO database was used for description of the soil characteristics. The two prevalent soil types were Blount silt loam and Pewamo silty clay (Figure 8).

A 2-year breakpoint climate file was created from the observed climate data and used during runoff calibration. The WEPP climate generator, CLIGEN version 4.3, was used to create a 20-year set of synthetic climate using parameters from the Waterloo, Indiana station.

Table 4. Description of land use types in BME watershed.

Land use name	Crop		Tillage
	2008	2009	
corn 1	small grain	corn	conventional
corn 2	soybean	corn	no-till
corn 3	small grain	corn	reduced
corn 4	soybean	corn	reduced
small grain	soybean	small grain	no-till
soybean 1	corn	soybean	no-till
soybean 2	small grain	soybean	no-till
soybean 3	soybean	soybean	conventional
soybean 4	soybean	soybean	reduced
soybean 5	soybean	soybean narrow row	no-till
soybean 6	corn	soybean narrow row	no-till

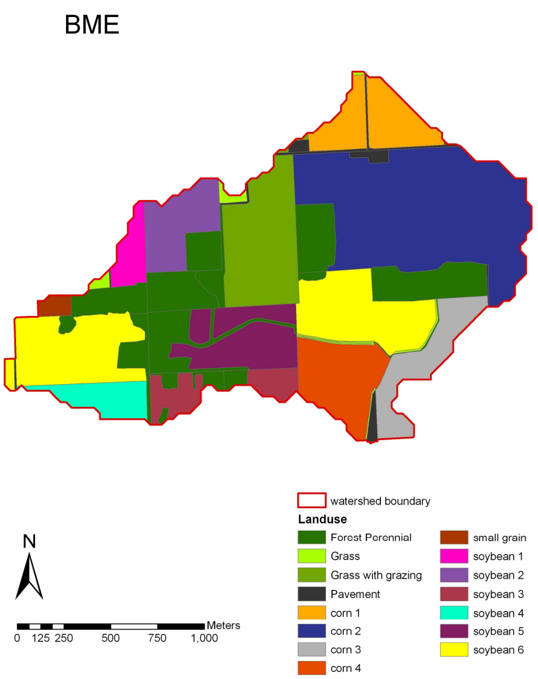

Figure 7. Map of land use in BME watershed.

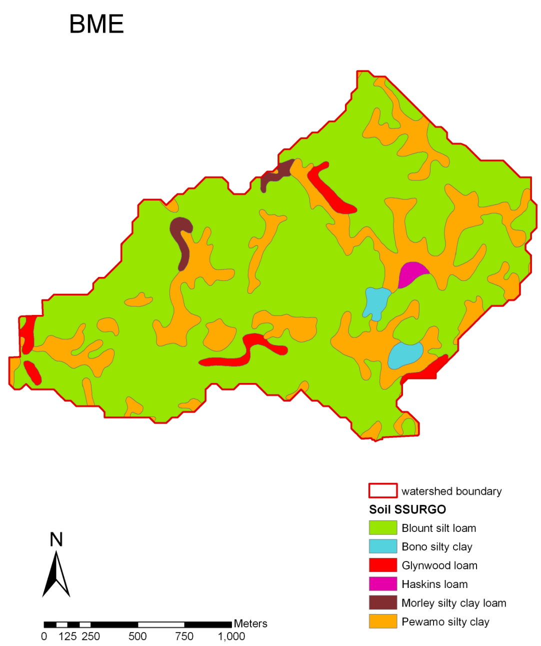

Figure 8. Map of soil types in BME watershed.

Results and Discussion

Results on AS-1 and AS-2 sites

The model was first calibrated for runoff at the two sites. By using the procedure described above, different scenarios were simulated with the aim to maximize Nash-Sutcliffe model efficiencies for daily runoff values for days when the rainfall exceeded 25 mm ("large rainfall events"), daily runoff values for all other days ("all days with rainfall positive but less than 25 mm"), daily runoff values for all observed runoff days, and annual values. Daily values were compared for days when some runoff was measured (31 days for AS1, 59 days for AS2). Annual values were calculated as sums of daily runoff for the measuring seasons each year (typically from April/May till August/October). Apart from optimizing baseline hydraulic conductivity (K_b), the effect of the initial saturation value, presence of tile drainage and restricting layer were examined. The greatest achieved model efficiencies for each scenario and calibrated values of K_b are shown in Tables 5 and 6. These values of K_b were then used for sediment loss simulations. On AS1, the scenario "AS1-B" conformed to the highest model efficiency when comparing results for both all days and all days except large rainfall events.

Sediment yield is most influenced by interrill erodibility, rill erodibility and critical shear, so ideally all these values should be optimized. However, the procedure specified above allows optimization of just one parameter at a time. Therefore a sensitivity analysis was done to determine which of these three parameters has greatest impact on the simulated results. We found that rill erodibility influenced the results most in the AS1 watershed and critical shear the most in the AS2 watershed. Calibration of sediment yield was done for all scenarios identified during the calibration of runoff (3 scenarios for AS1 and 4 scenarios for AS2), and the results for the identified individual storm events examined (Tables 7 and 8).

When calibrating on runoff by optimizing K_b, the model predicted very low or no runoff on some days, when the observed runoff was high. Thus, runoff was clearly simulated incorrectly, especially on one of the days (25 April 2007). On this day the observed runoff was 272.4 m^3 on AS1 and 193.88 m^3 on AS2 (which are some of the highest recorded runoff volumes observed in the watersheds), but WEPP didn't predict any runoff, despite the fact that the precipitation depth was 44 mm. Several tests were conducted to determine the reason for this discrepancy. Changes in management, slope, Manning's roughness for channels, residue parameters and precipitation data were made, but none of them resulted in any runoff on 4/25/2007, nor caused significant changes in calculated runoff on the other days. Some runoff on 4/25/2007 was calculated only when the soil texture was changed dramatically (clay content was increased by 20% in all soil layers), but this was considered as inappropriate, since the soil texture was determined by detailed soil analysis. Finally the problem was solved by setting a restrictive layer in the soil input file, while leaving all other parameters without any changes. Best model efficiencies (Table 5) were achieved by defining the restricting layer as "shale" at a depth of 1000 mm (depth of deepest soil layer was increased from 600 mm to 1000 mm). This corresponds with SSURGO soil data, which for Glynwood loam (which is the predominant soil type on AS1) allege the depth of a restrictive glacial till layer to be between 640 – 1270 mm, and for Blount silt loam (predominant on AS2) the restrictive layer depth is estimated as between 760-1520 mm. Although adding a restricting layer increased the model efficiencies when comparing the daily runoff values on AS1 and daily runoff values for days with large rainfall events on AS2, it caused overprediction of the annual runoff values, especially in 2008.

Simulations were done both with and without presence of drainage tiles on both watersheds, but all scenarios achieved better result when simulated without the drainage. The reason for better simulation results without drainage could be the malfunction of the real tiles in the field due to their age and destruction. Current investigation of the WEPP drainage tile code logic has also indicated problems with its performance in the current model version.

Initial saturation value differs on the two watersheds. While the simulations for AS2 watershed gave better results when the initial saturation was set to 70%, AS1 generally worked better with a value of 90%. The scenarios "AS1-A" and "AS1-B" deviate from each other only in the value of initial saturation. Results for both of them were not significantly different, but the initial saturation of 70% gave slightly better results for daily runoff values on days without large rainfall events and an initial saturation of 90% gave better results for the days with large rainfall events.

Table 5. Results of calibration on runoff by optimizing baseline hydraulic conductivity for different scenarios on AS1.

	Scenario	AS1-A	AS1-B		AS1-C
Scenario description	Best scenario for	large rainfall events	days with small rainfall events	all runoff days	annual runoff
	K_b [mm/h]	15	15		10
	Tile drainage	no	no		no
	Initial saturation [%]	90	70		90
	Restricting layer	shale, depth 1000mm	shale, depth 1000mm		none
Nash-Sutcliffe	Large rainfall events	-0.477	-0.527		-0.953
	All days except large rainfall events	0.659	0.762		-0.205
	All days	0.202	0.203		-0.239
	Annual runoff	-7.859	-7.430		-0.265
Year	**Observed annual runoff**	**Predicted annual runoff**			
2006	1246.53	946.75	797.25		392.88
2007	875.13	1228.13	1213.49		339.75
2008	165.40	1722.54	1721.3		297.16

Table 6. Results of calibration on runoff by optimizing baseline hydraulic conductivity for different scenarios on AS2.

	Scenario	AS2-A	AS2-B	AS2-C	AS2-D
Scenario description	Best scenario for	large rainfall events	days with small rainfall events	all days	annual runoff
	K_b [mm/h]	11	20	13	6.7
	Tile drainage	no	no	no	no
	Initial saturation [%]	70	70	70	70
	Restricting layer	shale 1000mm	none	none	none
Nash-Sutcliffe	Large rainfall events	-0.236	-0.676	-0.442	-0.945
	All days except large rainfall events	-0.954	-0.141	-0.223	-0.551
	All days	0.011	-0.102	0.014	-0.316
	Annual runoff	-5.539	-1.664	-1.076	-0.870
Year	**Observed annual runoff**	**Calculated annual runoff**			
2006	1246.53	907.33	135.46	381.07	850.58
2007	875.13	1775.14	371.46	440.06	763.01
2008	165.40	1903.6	511.43	726.32	1144.79

Table 7. Results of calibration on sediment yield on AS1. Values of interrill and rill erodibility and critical shear were optimized: K_i = 2000000 kg*s/m^4, K_r = 0.001 s/m, TAUc = 6 Pa.

Scenario			AS1-A	AS1-B	AS1-C
Nash-Sutcliffe	Calibration		0.520	-6.864	-1.068
	Validation		-5.632	-13.486	-5.657
	All days		-0.733	-8.130	-1.983
	Date	Observed sediment yield [kg]	Calculated sediment yield [kg]		
Calibration	6/21/2006	65.1	105.5	209.3	148.6
	8/28/2006	0.2	0.2	57.5	0.2
	4/25/2007	56.5	52.6	0	43
	8/23/2007	4.3	0	0	0
Validation	7/14/2006	24.2	82.8	131.3	83.5
	8/20/2007	48.4	98.7	88.4	98.1
	8/24/2007	6.0	0	0	0

Table 8. Results of calibration on sediment yield on AS2. Values of interrill and rill erodibility, and critical shear were optimized: K_i = 2000000 kg*s/m^4, Kr = 0.001 s/m, TAUc = 6 Pa.

Scenario			AS2-A	AS2-B	AS2-C	AS2-D
Nash-Sutcliffe	Calibration		0.444	-0.011	0.704	0.063
	Validation		0.677	0.233	0.577	0.741
	All days		0.512	0.056	0.661	0.268
	Date	Observed sediment yield [kg]	Calculated sediment yield [kg]			
Calibration	5/31/2006	583.7	1021.2	271.5	708.3	1469.4
	6/19/2006	238.6	5.1	0	0	15.7
	6/21/2006	1032.7	716.1	167.8	609.9	1057.3
	7/4/2006	0.3	1.1	0	0	0
	7/27/2006	1.5	0	0	0	0
	4/26/2007	136.7	537.2	0	0	0
	8/24/2007	7.6	0	0	0	0
Validation	5/13/2006	0.8	0.1	0	0	0
	7/14/2006	644.4	279	80.1	225.8	395.6
	8/28/2006	0.3	26.2	0.3	16.6	213.9
	8/9/2007	0.3	0	0	0	0
	8/23/2007	1.6	0	0	0	0

Watershed AS1 was calibrated on daily sediment yield by optimizing rill erodibility (K_r). After the value of K_r was optimized, the model efficiencies for all 3 scenarios were still very low and negative (from -2.4 to -25.9) and sediment yield was overpredicted, although the optimized K_r equaled the lower boundary of the initial interval (0.001 s/m). Therefore the other erodibility parameters were also changed to decrease the simulated amount of sediment. Interrill erodibility (K_i) was minimized (K_i = 2,000,000 kg*s/m^4) and critical shear (TAUc) maximized (TAUc = 6 Pa). In spite of improving the model efficiency with these changes, sediment yield was still overpredicted for the larger events and efficiencies remained mostly negative (Table 7).

Watershed AS2 was calibrated on daily sediment yield by optimizing critical shear (TAUc), and the same result as on AS1 occurred. The optimized value of TAUc equaled the upper boundary of the initial interval (6 Pa), but the model efficiencies for all 4 scenarios were still negative (from -0.01 to -7.9) and the sediment yield was overpredicted. As on AS1, better results were achieved by setting K_i to 2,000,000 kg*s/m^4 and K_r to 0.001 s/m, and the Nash-Sutcliffe model efficiencies were positive for the majority of scenarios.

A number of things may contribute to the poor simulation of sediment losses at the AS1 site. The poor prediction of runoff probably was a major factor. Also, WEPP (and any erosion model for that matter) is known to do a better job at predicting larger sediment losses. Because of the tillage management system and slope gradients at AS2, soil losses measured there were at least an order of magnitude greater than at AS1. The no-till management at AS1 and lower channel slope gradient (and grassed waterway) resulted in extremely low sediment concentrations and losses (maximum sediment yield of 65 kg on 6/21/2006 corresponds to a soil loss rate of only 0.028 t/ha). Sampler malfunction, as well errors in processing some of the sediment samples in the laboratory (related to correction for alum added) may also have impacted the results. The very low number of reliable runoff sediment events (7 on AS1 and 12 on AS2), also provided fairly limited information for good comparisons of observed and predicted soil loss.

Recommendations for future monitoring and modeling at AS sites

For future work with these small field watersheds, we recommend improvement of the quality of the measurement techniques, conducting further investigations of soil profile properties, and checking of the functionality of the tile drainage system.

Quality of the measured data, particularly sediment yield, should be improved by recording the dates and times of the sampler's inactivity. That would provide the information necessary for distinguishing between the data which are appropriate to use for calibration and validation and those which are not. Choosing the "correct" data just by comparing time and flow values, as was done in this study, is insufficient. Overall, improved QA/QC is needed for sediment samples and calculated losses from these sites.

The soil profile should be investigated to depth of 1200 mm (instead of just 600 mm), which is the maximum depth included in WEPP calculations. If a restricting layer is found, the depth and type of bedrock or glacial till material need to be determined.

Better description of the tile drainage system in place in these fields, along with its functionality is needed. Water leaving the fields through the tile drains need to be measured as well, to allow for a complete accounting of water. In the WEPP model code, the tile drainage component needs to be carefully examined and checked for errors, and appropriate fixes and enhancements made to improve its functionality.

BME model application results and discussion

The WEPP model application in the BME watershed was calibrated only for the observed ditch flow, because sediment loss wasn't measured. The observed runoff data represents the ditch flow, which includes surface runoff, subsurface tile flow, and groundwater base flow. Therefore the observed data had to be reduced by subtracting base flow, because WEPP doesn't simulate deep groundwater flow to channels. The separation was done by uploading the observed daily ditch flow data to the Web based Hydrograph Analysis Tool (WHAT) (Lim et al., 2005) and using the Eckhart recursive digital filter method (Eckhart, 2005). In order to achieve the base flow percentage (BFI) of approximately 48% (reported for Cedar Creek by Beaty, 1996) , the filter parameter was set to 0.980 and the Baseflow Index Maximum (BFI_{max}) was set to 0.9. The achieved BFI was 48.8%.

Calibration was done by using the method described above (maximizing Nash-Sutcliffe model efficiency using the Golden search algorithm) and by comparing the summarized monthly calculated values of runoff and reduced values of ditch flow. Monthly runoff values for 7 months (April – October) from 2008 were used for calibration, and for 5 months (April – August) from 2009 were used for validation. The ditch flow wasn't measured during the remaining (winter) months. Baseline effective hydraulic conductivity of the predominant soil type (Blount silt loam) was optimized.

The optimized value of K_b of Blount silt loam was 1 mm/h (the original value from SSURGO was 3.56 mm/h). Because the calculated monthly runoff values were underestimated comparing to the observed data, a restrictive layer was added. The WEPP model gave the best results when the restrictive layer was defined as shale at a depth of 800 mm. This corresponds with the SSURGO data, which indicates that a restrictive (glacial till) layer between 760-1520 mm deep. The model efficiency was further enhanced by adjusting the K_b value of the second most prevalent soil type (Pewamo silty clay) to 1 mm/h (1.79 mm/h originally in SSURGO) and initial saturation to 90%. Although the highest achieved Nash-Sutcliffe model efficiency was negative for calibration (Table 9), it was positive for validation, and also when comparing all observed months (then the efficiency was 0.187). Due to the other uncertainties in the model input parameterization (estimation of land management data, etc.), this was considered sufficient.

After the calibration of the model, the effect of different alternative management practices on the average annual runoff and sediment losses was tested. In order to obtain representative annual averages, a CLIGEN climate input file for 20 years was generated. CLIGEN version 4.3 and the database for the closest weather station (Waterloo, Indiana) were used. 9 scenarios for alternative management practices were developed and the results were compared to the results of the scenario "0". The scenario "0" was the model with calibrated values of the soil, without any management change, and the annual average results obtained from a 20-year simulation using the generated CLIGEN file. Other scenarios differed from scenario "0" only in the management input files, which were modified according to the alternative management practices. Average annual runoff and sediment loss were calculated as the sums of average annual runoff and sediment yield from all hillslopes (runoff and sediment yield from the channels were not used in these alternative hillslope management comparisons).

Four main types of alternative management practices were examined – buffer strips, land use changes on selected hillslopes, no-till management, and extreme scenarios. A summary of the various scenario descriptions is in Table 10.

Buffer strips (scenarios SC111 and SC112) were 10 m wide strips of grass or forest on both side of every channel. The buffer strips were applied only to the hillslopes that had existing agricultural management, not to areas in grass, grass with grazing, forest, or impervious areas. "Grass.rot" and "Forest Perennial.rot" input files were used to simulate the cropping/management of the buffer strips.

Land use changes were targeted at hillslopes that had maximum runoff per hectare (scenarios SC211 and SC212) and for hillslopes with the greatest sediment yield per hectare (scenarios SC221 and SC222). In scenarios SC211 and SC212, the management on hillslopes with average annual runoff greater than 2000 m^3/ha/year was changed to "Grass.rot" and "Forest Perennial.rot", respectively. In scenarios SC221 and SC222, the management on hillslopes with an average annual predicted sediment yield greater than 2000 kg/ha/year was changed to "Grass.rot" and "Forest Perennial.rot", respectively.

Table 9. Results of runoff calibration/validation for BME watershed.

Nash-Sutcliffe		Calibration	-0.738
		Validation	0.194
	Month	**Observed runoff (without base flow) [m^3]**	**WEPP Calculated runoff [m^3]**
Calibration - year 2008	April	61721	12372
	May	4965	3518
	June	41777	16739
	July	79360	35658
	August	0	28
	September	52137	130215
	October	0	49
Validation – year 2009	April	211182	63344
	May	121554	77418
	June	77423	46551
	July	2171	3358
	August	3936	786

Table 10. Alternative management practices – descriptions of different scenarios

Scenario	Scenario description
0	Calibrated values based on current land management
SC111	Buffer strips, 10m wide, grass
SC112	Buffer strips, 10m wide, forest
SC211	Land use change - hillslopes with maximal runoff (>2000 m^3/ha/year), grass
SC212	Land use change - hillslopes with maximal runoff (>2000 m^3/ha/year), forest
SC221	Land use change - hillslopes with maximal sediment yield (>2000 kg/ha/year), grass
SC222	Land use change - hillslopes with maximal sediment yield (>2000 kg/ha/year), forest
SC310	No-till management on all agricultural fields
SC410	“Best case“ - all areas forested (except residential)
SC420	“Worst case“ - conventional tillage on all agricultural fields

Scenario SC310 represented the situation where no-till management was applied to all agricultural fields.

Extreme scenarios (SC410 and SC420) describe the “best” and “worst” case from the surface runoff and sediment yield point of view. In the best case (SC410), all areas, except the impervious residential areas, are forested ("Forest Perennial.rot"). The worst case scenario (SC420) assumes conventional tillage on all agricultural fields.

Results of the various scenario simulations are in shown in Table 11. Runoff and sediment yield differences are reported relative to the existing scenario "0". If negative, the runoff or sediment yield is lower than in scenario "0".

As was expected, the greatest reduction of average annual runoff and sediment yield was calculated for the "best case" scenario SC410. However, while this case resulted in extreme reductions in predicted runoff (61% decrease) and sediment yield (96% decrease), it is very unrealistic, given the private ownership of the land in BME and the high amount of agricultural production.

Also as expected, the greatest increase in runoff and sediment yield was predicted for the "worst case" scenario SC420. This indicates that sediment losses could potentially increase by almost 300% if tillage practices were to change from the current large composition of no-tillage and reduced tillage, to more intense conventional tillage (with soil inversion and residue burial).

Table 11. Results of 20-year WEPP simulations of different management scenarios in BME watershed.

Scenario	Brief Description	Average watershed runoff [m^3/yr]	Avg. sed. yield [t/yr]	Average runoff [m^3/ha/yr]	Average sediment yield [t/ha/yr]	Runoff difference [%]	Sediment yield difference [%]	Agricultural area in the watershed [ha]
0	Existing Baseline	437448	253.0	1718.2	0.99	-	-	184.4
SC111	10-m Grass Buffers	433460	99.6	1702.5	0.39	-0.9	-60.6	166.8
SC112	10-m Forest Buffers	400982	57.1	1574.9	0.22	-8.3	-77.4	166.8
SC211	Target high runoff areas – convert to grass	455804	162.7	1790.3	0.64	4.2	-35.7	153.6
SC212	Target high runoff areas – convert to forest	386632	149.6	1518.6	0.59	-11.6	-40.9	153.6
SC221	Target high eroding areas – convert to grass	454378	169.4	1784.7	0.67	3.9	-33.0	155.5
SC222	Target eroding areas – convert to forest	402953	160.2	1582.7	0.63	-7.9	-36.7	155.5
SC310	No-till mgmt on all cropland	430402	132.1	1690.5	0.52	-1.6	-47.8	184.4
SC410	Forested on all non-urban	169422	9.4	665.4	0.04	-61.3	-96.3	0.0
SC420	Conventional tillage on all cropland	474452	975.5	1863.5	3.83	8.5	285.6	184.4

The SC112 scenario (forested buffer strips) was identified as a best management practice for this watershed. Although the “best case” scenario (SC410) provided the greatest reduction in runoff and sediment yield, at the same time it didn’t allow for any agricultural use and therefore couldn’t be recommended to farmers as a best management practice (except in the case where farmers are willing to switch from agriculture to forestry). Scenario SC112 provided the second greatest reduction in sediment yield (-77.4%) and a relatively high reduction in runoff (-8.3%), by decreasing the agricultural area in the watershed by less than 10%. Forested buffer strips would also serve as a suitable habitat for wild plant and animal species and protect the water in channels from solar heating. Another option would be to change cropping practices to more no-till, as scenario SC310 (no-till management) showed that going entirely to no-till could reduce sediment yields nearly in half.

One observation in these trials indicates that further examination of the WEPP input parameter sets for grass management is needed. Scenarios SC211 and SC221 that converted targeted areas to grass resulted in lower watershed sediment yield, but higher predicted runoff values. In reality it is likely that conversion to permanent grass vegetation would eventually result in both lower runoff and sediment losses. (Greater runoff values per hectare were also observed on hillslopes in scenario “0” that had grass or grass with grazing management.)

Summary and Conclusions

This study applied the WEPP model in watersheds in northeastern Indiana at 2 locations and scales – the AS field sites (~ 2 ha) and BME small catchment site (~ 250 ha). The GeoWEPP software was used in establishing the watershed structures, and then subsequent simulations were run in the watershed mode of the WEPP Windows interface (version 2010.1). Climate input files were developed from data measured by gauges stationed in the watersheds. Management data were obtained from farmers and agricultural statistic surveys, and soil characteristic were based on texture analysis of collected soil samples or soil survey data. Model calibration was performed using the Golden search algorithm to maximize the Nash-Sutcliffe model efficiency.

For the AS sites (AS1 and AS2), 3 years of continuous WEPP model simulations beginning on January 1 2006 were run. For calibration on runoff, different scenarios were tested and daily runoff values for days with large rainfall events (greater than 25 mm/day), daily runoff values for all other days, daily runoff values for all days and annual runoff values were compared. For calibration of sediment, only daily sediment yields on selected days were compared, due to the confidence in only a limited number of observed sediment yield events. Scenarios differed in K_b values, initial saturation values and presence of tile drainage and restricting layers.

Generally, better results of runoff prediction were achieved for AS1, whereas better results of sediment yield were achieved for AS2. Higher model efficiencies were obtained when simulating without tile drainage for all scenarios. Initial saturation of 90% gave better results for AS1, while on AS2 the value of 70% was more appropriate. No universal scenario was determined for the two AS sites, which would give good results for both daily and annual runoff values. Daily runoff values were predicted better with scenarios which included higher K_b values and a restrictive layer, while for the prediction of the annual runoff values scenarios with lower K_b values and without a restrictive layer performed better. For both watersheds, the highest model efficiencies for runoff predictions were achieved when comparing daily runoff values for all days, with and without large rainfall events. For sediment yields, relatively high positive model efficiencies were reached for most of the scenarios on AS2. On the contrary, model efficiencies for sediment yield on AS1 were mostly negative. Overall, WEPP simulation modeling of the AS1 and AS2 sites wasn’t very successful. This was probably due to the rather flat terrain at both sites, and no-till management on AS1, which produced low sediment yields. Lack of observed tile drainage flow data, as well as the inability of the current WEPP version to well represent tile drainage processes also contributed to the poor performance.

For the BME site calibration/validation, 2 years of continuous simulation beginning on January 1, 2008 was performed, and monthly runoff values were compared. Sediment data was not available for this site. After calibration, 9 scenarios describing alternative management practices were developed, and 20-year

WEPP model simulations using CLIGEN-generated climate input files were run, so that average annual runoff and sediment yield could be compared. Three of the scenarios had a large impact on reducing runoff and sediment losses in BME. The first was the scenario where the whole watershed is forested, except the residential impervious areas, and the greatest reduction in runoff volume (61%) and sediment yield (96%) was achieved. However, this is an unrealistic option due to the conversion of all agricultural land to forest. Second was the scenario with no-till management on all agricultural fields, where only the tillage system is changed and no agricultural land is lost, with a reduction in runoff volume of less than 2% but a 48% decrease in sediment yield. A third scenario with 10 m wide forested buffer strips along all channels reduced runoff by 8% and sediment yield by 77%, and decreased agricultural land by less than 10%.

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