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Modeling Runoff and Sediment Yield from a Terraced Watershed Using WEPP

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Abstract. *The watershed version of WEPP (Water Erosion Prediction Project) was used to estimate 50-year runoff and sediment yields for a 291 ha watershed in eastern Nebraska that is 90% terraced and which has no historical gage data. The watershed has a complex matrix of elements, including terraced and non-terraced subwatersheds, multiple combinations of soils and land management, a grassed-waterway network, and natural stream channels leading to the outlet. The objectives of this study were to model the study watershed using WEPP and to evaluate model results compared to literature values. WEPP estimated the sediment yield to be 1.9 T/ha/yr, the sediment delivery ratio to be 0.22 and the percent of sediment contribution from the main channel to be 31% of the total sediment yield. These results are consistent with values reported in the literature.*

Keywords. WEPP, runoff, sediment yield, soil erosion, terraced, conservation terraces.

Introduction

A 50-year continuous hydrograph and sediment graph was needed for a small agricultural watershed (291 ha) in eastern Nebraska that has no historical gauge data. The hydrograph and sediment graph were needed for input into the CONCEPTS model (Conservational Channel Evolution and Pollution Transport System) (Langendoen 2000), which we are using to model the evolution of a stream channel immediately downstream of the watershed. While other runoff and erosion prediction models were available (e.g. SWAT, EPIC, GLEAMS), WEPP was chosen for the fact that it is a process-based continuous simulation model with a distinct capability of estimating soil loss from individual components within the watershed model (Flanagan and Nearing 1995). The study watershed has a complex matrix of elements, including terraced and non-terraced subwatersheds, multiple combinations of soils and land management, a grassed-waterway network, and natural stream channels leading to the outlet. In the case of terraced watersheds, WEPP is capable of predicting runoff and sediment yield or deposition for each terrace hillslope and terrace channel defined in the model. In order to evaluate the WEPP model results, literature values were used for comparison of discharge, precipitation, sediment yield, sediment delivery ratio, and the percent of sediment contribution from the main channel (3rd order stream) of the watershed. The objectives of this study were to model the study watershed using WEPP and to evaluate model results compared to literature values.

Study Site

The study area is a 291 ha watershed located northwest of Burr, Nebraska in Otoe County. Located in the southeastern region of the state, this area has an average annual precipitation of 810 mm and average annual runoff of 102 - 114 mm (Engel and Steele 1987). The watershed forms the headwaters of Little Muddy Creek, a tributary of the Little Nemaha River, which drains into the Missouri River. Land use in the watershed is comprised of 75% row crops (corn/soybean rotation), with the remaining 25% used for CRP and pasture (Harper 2003). Based on field observations, the areas of row crops and CRP have broad based terraces draining to grassed waterways, therefore an estimated 90% of the total watershed area is terraced (fig. 1). The uplands are dominated by Wymore silty clay soil (47%). Side-slope and floodplain soils are Mayberry clay loam (12%), Nodaway-Colo complex (11%), Judson silt loam (10%), Pawnee clay loam (6%), Pawnee clay (4%), Morrill clay loam (5%), and Morrill-Malmo complex (5%) (USDA 2007).

Figure 1. Aerial photograph showing the extent of terracing on one section (256 ha) which encompasses most of the Little Muddy Creek upper watershed area.

Methods

Model Selection

Four runoff and soil erosion prediction models, WEPP, SWAT, EPIC and GLEAMS, were considered for their ability to meet the following criteria: (1) long-term continuous model, (2) suitable for watershed scale projects, (3) produces a continuous hydrograph and sediment loading graph, (4) capable of modeling terraced landscapes, and (5) routes sediment in the channel network.

While all four models met the first requirement, long-term continuous model, EPIC and GLEAMS were eliminated from consideration as they were not suitable for watershed scale projects. WEPP and SWAT were then further considered for their ability to produce continuous runoff hydrograph and sediment loading graph, their approach to modeling terraces, and model output that allowed for a detailed analysis of sediment routing through the channel network.

Both WEPP and SWAT are capable of outputting continuous hydrograph and sediment loading graphs. For modeling terraced landscapes in WEPP, it is possible to input a network of individual terraces and terrace channels rather than assigning a terraced area to be a single hydrologic response unit, as is done in SWAT. WEPP model output includes sediment yield and discharge entering and exiting each channel segment in the network, allowing for an analysis of the amounts and locations of deposition or scour within the channel network. Since WEPP allows for modeling of individual terraces and terrace channels, detailed channel analysis is possible for individual terrace channels, grassed waterways and the main channel exiting the waterway.

Watershed Delineation and Stream Network Analysis

ArcGIS was used to delineate the study watershed, find area and average watershed slope and generate the stream network. Based on a procedure developed by Tarboton (1997), a 10-m DEM was located for our study area and run through a series of calculations for flow direction, basins, flow accumulation, stream links and finally a watershed delineation based on the precise stream link at the outlet of our study watershed. The watershed area and average watershed slope were then calculated using ArcGIS. The generated stream network in figure 2 shows streams designated as first, second and third order. First order and second order streams approximately represent the ephemeral grassed waterways in the study watershed, while the third order channel corresponds with the perennial portion and headwaters of Little Muddy Creek. The stream network was analyzed further to determine the total lengths of each stream order which were used in developing the stream network for the WEPP model.

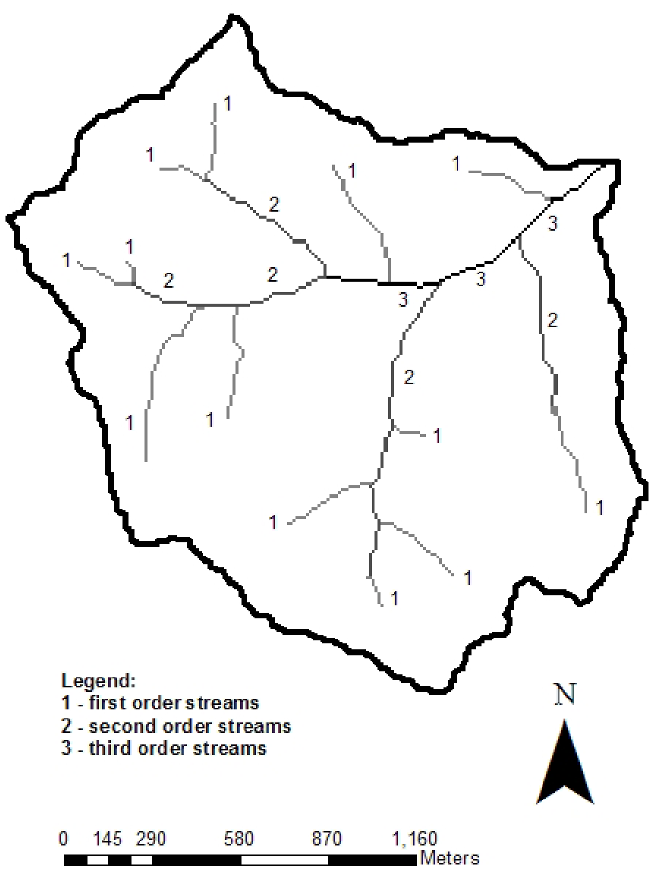

Figure 2. Study watershed shown with stream network generated using ArcGIS.

WEPP Watershed Diagram

The study watershed was modeled in WEPP as 8 subwatersheds (36 ha per subwatershed) representing combinations of four different watershed management files and two different soil files. Within each subwatershed, runoff is routed through a first order stream. Runoff from subwatershed pairs collects in a second order stream, then into a third order stream. Approximately 90% of the watershed landscape (256 ha) has broad based terraces, therefore 7 of the 8 subwatersheds were further divided into 18 terrace hillslopes which drain into 18 terrace channels. Terraced subwatersheds were oriented with two groups of nine terrace hillslopes going upslope, with each hillslope draining into a terrace channel, then draining laterally into a first order stream running up the middle of the subwatershed (fig. 3).

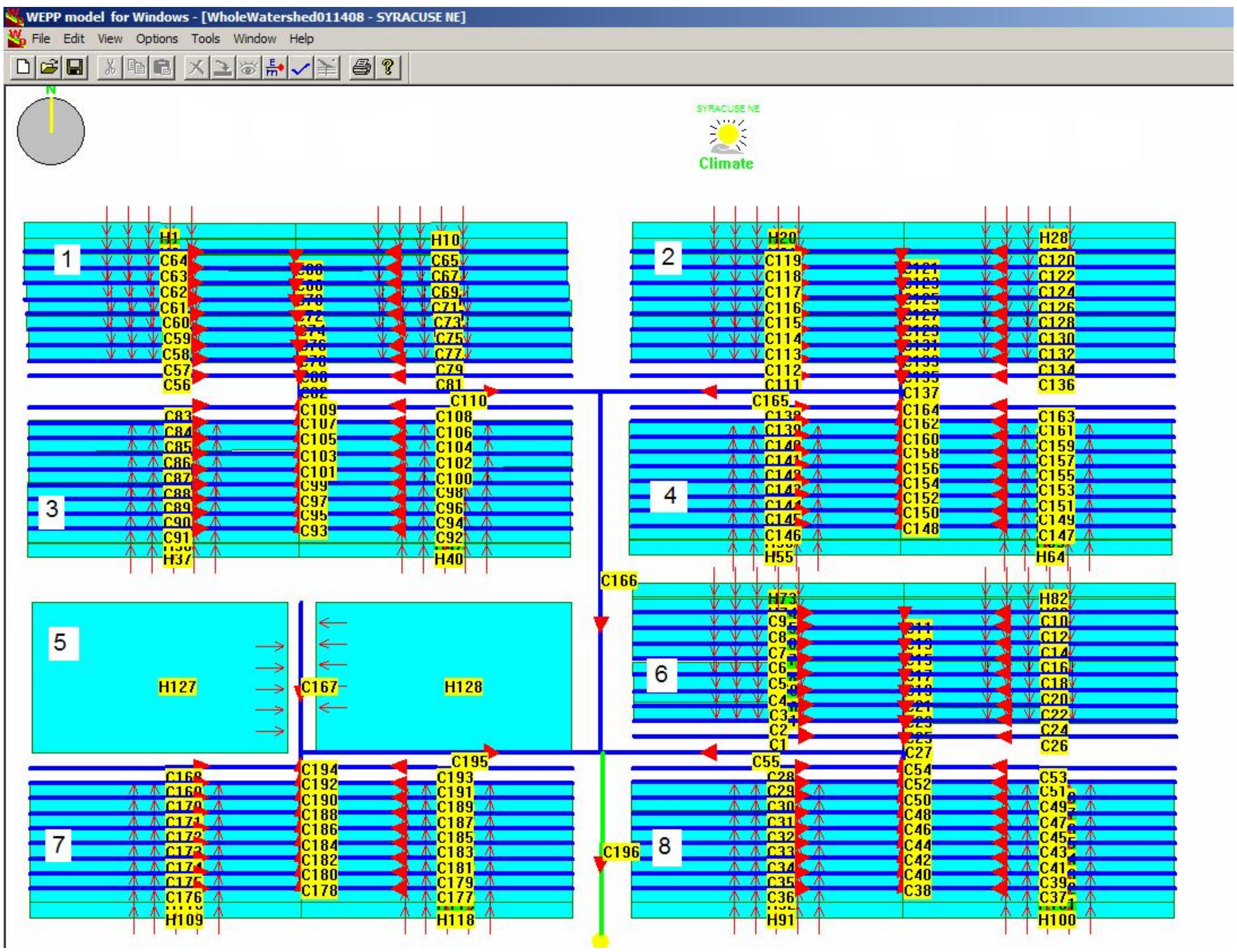

Figure 3. WEPP watershed schematic with hillslopes depicted as rectangles and channels represented as lines, each having flow direction arrows. Terrace channels drain laterally to the first order streams. Each of the four second order streams (C110, C165, C195, C55) drains two subwatersheds. Second order streams connect to the third order channel, which consists of two segments (C166, C196). Numbers in white squares label the eight subwatersheds.

The terraces were assumed to have a 30 m spacing based on design guidelines for broad based terraces from USDA-NRCS (USDA 1975). The terraced landscape was represented in the model with each terrace represented by two separate components, a hillslope and channel.

Terrace hillslopes were 30 m long and 550 m wide. Terrace channels ran along the bottom edge of each terrace hillslope, with all terrace channels being 550 m in length. Given the extent of terracing in this watershed and the fact that each terrace was modeled as a separate hillslope and terrace channel, the total number of hillslopes in this model was 128 and the total number of channel segments was 196. The total length of second and third order streams in the WEPP model was based on estimates from the ArcGIS generated stream network (table 1). Total lengths of first order streams in the WEPP model were not based on ArcGIS estimates but were influenced by assumptions of terrace spacing and terrace length.

Table 1. Total stream lengths by stream order, comparing lengths generated by the ArcGIS stream network to those used in the WEPP model.

Stream order	ArcGIS-total length (m)	WEPP model - total length (m)
1	3724	2195
2	2482	2438
3	1076	1097

WEPP Input - Soils

Each hillslope in a WEPP model is assigned a soil file which includes information including percent organic matter, sand, clay and rock for different soil layers, soil texture, interrill erodibility, rill erodibility, critical shear and effective hydraulic conductivity. While WEPP has several soil files already available with the model, it is also possible to create your own file.

USDA-NRCS WebSoil Survey (USDA 2007) was used to identify soils in the study watershed along with their associated areas. WebSoil Survey data were cross-referenced to the Otoe County Soil Survey (USDA 1982) for reasonableness of the output. The Little Muddy Creek study watershed uplands were 47% Wymore silty clay loam. Side-slope and floodplain soils were comprised of Mayberry clay loam (12%), Nodaway-Colo complex (11%), Judson silt loam (10%), Pawnee clay loam (6%), Pawnee clay (4%), Morrill clay loam (5%), and Morrill-Malmo complex (5%).

The WEPP model was simplified by assigning half of the watershed area the Wymore soil file and the other half assigned a user-defined soil file based on average values of the remaining seven soils. This conglomerate soil was labeled as the "side slope soil" (SSS). The decision to simplify the seven soil types into one conglomerate soil was also weighed by the fact that there were four different land management practices within the watershed (corn-soybean with no-till, corn-soybean with fall chisel, CRP and pasture). Assigning combinations of soil type and land management to each hillslope became a more reasonable task by simplifying the soil files into two types: Wymore and SSS.

Both of the WEPP soil files, Wymore and SSS, were developed based on available information from the Soil Survey of Otoe County, Nebraska (USDA 1982), including soil texture, percent rock and organic matter. In the case of the Wymore soil file, soil texture and soil layer data were obtained directly from the soil survey (fig. 4). Default values were accepted for albedo and initial saturation level.

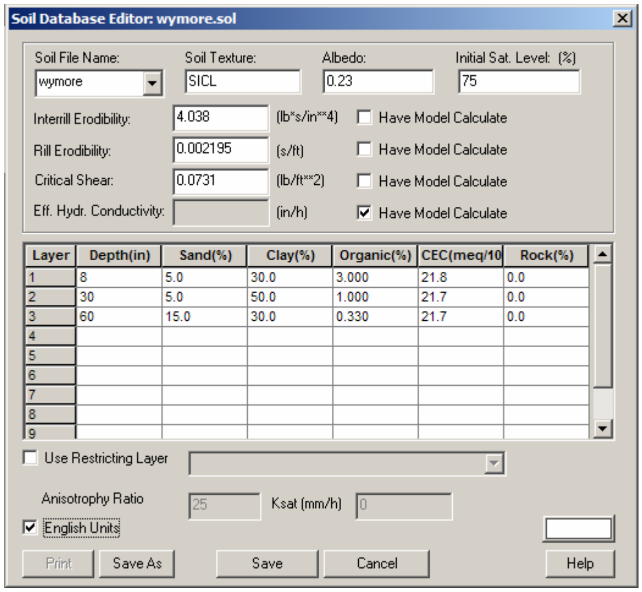

Figure 4. WEPP soil file window for user-defined Wymore soil.

In the case of the conglomerate "side slope soil" (SSS), soil composition properties for each of the seven soils were again obtained from the soil survey (USDA 1982) and included percent sand, clay, organic matter and rock. Since the soils had different layer depths as well as a varying number of defined layers (1-4) in the soil survey tables, soil composition data were first averaged for one soil (i.e. one homogenous layer per soil). Soil composition values for all the soils were then averaged to represent the conglomerate soil (SSS). Based on the resulting percent sand-silt-clay of the conglomerate soil, the USDA soil textural triangle was used to assign the soil texture as clay (CL). Default values were accepted, as for the Wymore soil file, for albedo and initial saturation level. Values for interrill erodibility, rill erodibility, critical shear and effective hydraulic conductivity for the SSS were calculated by the WEPP model (table 2).

Table 2. Soil properties used in WEPP soil files for Wymore and SSS soil files.

Soil Property	Wymore Soil	Side Slope Soil (SSS)
Soil texture	silty clay loam	clay
% Sand	5	24
% Silt	65	33
% Clay	30	43
% Organic Matter	3	3
% Rock	0	2
Interrill Erodibility (kg-s/m^4)	4400100	3683410
Rill Erodibility (s/m)	0.0072	0.0069
Critical Shear (Pa)	3.5	3.5

WEPP Input - Watershed Management

A total of 75% of the watershed area (218 ha) was estimated to be in corn/soybean rotation with the remaining area equally divided between CRP and pasture subwatersheds (table 3). The row-crop area was further subdivided by cultivation practices with 144 ha (4 subwatersheds) of no-till and 72 ha (2 subwatersheds) of fall chisel. Further distinction between row-crop areas was made by assigning one no-till and one fall chisel watershed as having side slope soil (SSS).

Table 3. Study watershed divided into 8 subwatersheds, varying by management, landscape features and soils. Each subwatershed has an area of 36 ha.

Subwatershed Number	Subwatershed Management	Landscape Features	WEPP Soil File	Hillslopes in subwatershed
1	Corn/Soy No Till	Terraced	Wymore	18
2	Corn/Soy No Till	Terraced	Wymore	18
3	CRP	Terraced	SSS	18
4	Corn/Soy Fall Chisel	Terraced	Wymore	18
5	Pasture	Non-terraced	SSS	2
6	Corn/Soy No Till	Terraced	Wymore	18
7	Corn/Soy Fall Chisel	Terraced	SSS	18
8	Corn/Soy No Till	Terraced	SSS	18
		Total number of hillslopes:		**128**

WEPP Input - Slopes

For the WEPP model, slopes were needed for hillslopes and channels. Using ArcGIS the average slope of the watershed was calculated to be 5.6%. This value was used for all hillslopes in the WEPP model, including pasture and terrace hillslopes. Slopes for channels varied for the four different types of channels in the network: terrace channels, primary grassed waterways (1st order), secondary grassed waterways (2nd order) and main channel (3rd order). Slope of all terrace channels was set at 1%. While estimates of sediment delivery ratio based on Renard et al (1997) would be 1.0 for a terrace channel with 1% grade, it was deemed to be an acceptable grade based on a calculation of maximum velocity for terrace channels. Using ASABE design standard, ASAE S268.4 FEB03 (ASABE 2006), this channel grade allows for good drainage with a calculated maximum velocity of 0.51 m/s, falling below the maximum velocity recommended for most soils (0.6 m/s).

From the terrace channels, drainage flows to the primary grassed waterways which were given a slope of 5.6%, matching the slope of the hillslopes. Primary grassed waterways drain into secondary grassed waterways which in turn lead to the main channel which is a natural earthen channel. A previous cross-sectional survey of Little Muddy Creek showed the slope of the main channel to be 0.5% (Harper 2003). The secondary grassed waterways were assigned a slope of 3%, being an average between the 5.6% slopes of the primary grassed waterways and 0.5% slope of the outlet channel.

WEPP Input - Climate File

WEPP provides pre-installed climate files for a number of sites throughout the United States. The WEPP climate file closest to the Little Muddy Creek upper watershed was located at Syracuse, Nebraska, 11.5 km from the study site. For climate type, the CLIGEN (Ver 4.3) option was used for a 50 year simulation.

Modeling Process

Simulations were initially run for each of the eight subwatersheds individually in order to assess the reasonableness of the results based on their combination of land management and soil type. Since the "WholeWatershed" model connects the eight subwatersheds with a series of grassed waterways (2nd order streams) and earthen main channel sections (3rd order stream), the "WholeWatershed" model was then evaluated for reasonableness for sediment yield, sediment delivery ratio and sediment contribution from the main channel as it routes water through the channel network after leaving the eight subwatersheds. Through this process, results were evaluated as to how much sediment contribution or deposition occurred in terrace channels and grassed waterways compared to the main channel. The WEPP model was run for the study watershed for a 50 year period.

Over 23 iterations were run for the "WholeWatershed" model to determine a combination of realistic values for model parameters that resulted in reasonable model output based on literature values. Model parameters that were changed between iterations were kept within realistic ranges for the watershed. These parameters included: (1) width of the 2nd and 3rd order channels (varying from 6.1 to 15.2 m), (2) terrace grade (5% - 1%), (3) slope of 2nd order streams (2 - 5.6%), (4) slope of 3rd order streams (0.4 - 0.6%), (5) channel shape (triangular vs. naturally eroded), and (6) channel control section at outlet (critical flow vs. normal flow).

Results and Discussion

Initial simulations were done for individual subwatersheds before linking them up to 2nd and 3rd order stream network. Results for hillslopes of individual subwatersheds (table 4) indicate sediment yield for hillslopes prior to entering a channel. As expected, fall chiseled hillslopes yielded significantly more sediment than no-till hillslopes. Pasture and CRP had the lowest sediment yields with 0.6 and 0.9 T/ha/yr, respectively.

Table 4. WEPP model results for subwatershed hillslopes prior to entering channels.

Subwatershed Management	WEPP Soil File	Sediment Yield (T/ha/yr)
Corn/Soy No Till	Wymore	3.5
Corn/Soy No Till	SSS	3.0
Corn/Soy Fall Chisel	Wymore	26.1
Corn/Soy Fall Chisel	SSS	31.4
CRP	SSS	0.9
Pasture	SSS	0.6

After modeling individual subwatersheds, they were connected with the stream network. The parameter changes which most significantly affected model output were the channel control section at outlet (critical flow vs. normal flow) and channel shape (triangular vs. naturally eroded). The normal flow option was chosen for the control section at outlet for all channel segments, as using the critical flow option resulted in sediment yields that were significantly higher than expected based on literature values. A triangular channel shape was used for terrace channels as well as 1st and 2nd order streams (grassed waterways), while the 3rd order streams (earthen channel) were assigned a naturally eroded shape. All channels were assigned a width of 6.1 m. Slopes for various channels were assigned as: terrace channels (1%), 1st order streams (5.6%), 2nd order streams (3%), 3rd order streams (0.5%). Based on these model parameters, WEPP model results for the "WholeWatershed" model are shown in table 5.

Table 5. Summary of literature values for model parameters compared to WEPP output for the watershed outlet.

Parameter	Literature Source	Literature Value	WEPP Output
Average annual precipitation (mm)	Engel and Steele (1987)	810	796*
Average annual runoff (mm)	Engel and Steele (1987)	102 - 114	112
Sediment delivery ratio	Foster and Highfill (1983)	0.11 - 0.64	0.22
Sediment yield (T/ha/yr)	Mueller (2007)	1.9	1.9
	Baker et al (2006)	2.1	
Sediment load from main channel (%)	Mueller (2007)	26	31

**Precipitation calculated internally within WEPP using CLIGEN.*

Precipitation and Runoff

Precipitation volume was estimated by WEPP to be 2316228 m^3/yr, or 796 mm for the 291 ha watershed. This watershed receives an average of 810 mm of annual precipitation and average annual runoff of 102 - 114 mm (Engel and Steele 1987). Runoff volume was estimated by WEPP to be 314341 m^3/yr, or 112 mm for the 291 ha watershed, within the expected range found in Engel and Steele (1987).

Sediment Delivery Ratio

WEPP predicted a sediment delivery ratio for the study watershed to be 0.22, within the range of sediment delivery ratios found by Foster and Highfill (1983) but much below the sediment delivery ratio of 1.0 estimated from Renard et al (1997) based on a 1% terrace grade. Foster and Highfill (1983) reported a range of sediment delivery ratios from 0.11 to 0.64 for terraced watersheds studied at different locations and represent deposition in terrace channel, outlet channel or both, depending on the individual study methods. On the higher end of this range (0.64), soil loss was measured at the outlet of the terrace. The WEPP estimated sediment delivery ratio is for the watershed outlet, therefore representing the combined effects of deposition or scour in the terrace channels, grassed waterways (1st and 2nd order streams) and the main channel (3rd order stream).

Sediment Yield

WEPP predicted sediment yield at the watershed outlet to be 1.9 T/ha/yr. Baker et al (2006) reported data from a long-term study at Treynor, Iowa which compared terraced (level terraces) and unterraced watersheds. These data showed that during a period from 1964-1971, average sediment yield from the terraced watersheds was 2.1 T/ha/yr. In a study by Mueller (2007) in southeast Nebraska, the total sediment load entering Wagon Train Lake, (streambank and watershed erosion combined) was estimated as 1.9 T/ha/yr.

Sediment Contribution from the Main Channel

The WEPP model predicted the sediment contribution from the main channel to be 31%. Sediment load in natural streams consists of a combination of sediment from erosion from the contributing watershed as well as from in-stream contribution from the main channel through streambed and streambank materials. The percentage of sediment contribution from within the channel can vary widely based on factors such as streambank stability, bed materials, and sediment load from the surrounding watershed. In a study in Iowa by Schilling and Wolter (2000), it was estimated that a 12-km reach of Walnut Creek contributed 50% of the annual suspended sediment load. In a study of incised channels in the loess area of the Midwest, Simon et al (1996) estimated that as much as 80% of sediment load is contributed from bank failures.

A study by Mueller (2007) investigated the contribution of sediment from streambanks as compared to the total sediment load entering Wagon Train Lake in Eastern Nebraska. Mueller (2007) studied the 4042 ha watershed of Wagon Train Lake and estimated that streambank erosion contributed 26% of the sediment entering Wagon Train Lake (1,848 Mg/yr out of 7,234 Mg/yr, total sediment entering the lake).

Conclusions

WEPP was able to model our complex terraced watershed comprised of 128 hillslopes and 196 channel segments, with hillslopes being assigned one of six different combinations of four land management files (corn/soybean no-till, corn/soybean fall chiseled, CRP and pasture) and two soil types. Results for precipitation, discharge, sediment delivery ratio, sediment yield and percent of sediment contribution from the outlet channel were reasonable for our watershed location, climate and site conditions compared to literature values. Modeling parameters which most greatly influenced sediment delivery output were control section at outlet (critical flow vs. normal flow) and channel shape (triangular vs. naturally eroded).

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