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Updating Slope Topography During Erosion Simulations with the Water Erosion Prediction Project

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ABSTRACT

The Water Erosion Prediction Project (WEPP) is a process-based continuous simulation erosion prediction model. However, WEPP currently assumes a fixed soil surface topography that does not change due to predicted detachment and/or deposition through a simulation period. While this approach might be satisfactory for slopes with uniform management, we hypothesized that long-term erosion predictions could be seriously altered by modifications of profiles having non-uniform slope, soil, and management properties. In this study, a computer program was written to modify the input slope file for WEPP based on predicted erosion and deposition amounts and slope shapes observed in flume and field studies. Currently, WEPP creates an output soil loss summary file that contains horizontal distance, elevation, and erosion or deposition at 100 points for each hillslope element. The slope updating program begins with this output file as input, assumes a bulk density and, maintaining a mass balance, redistributes sediment deposition predicted within and upslope of the grass strip in such a way that no slope reversal occurs. A new slope file is then exported for use in subsequent WEPP model erosion simulations. Results showed that updating slope profile had little effect on predicted runoff amounts. However, after 8 years, erosion was increased by 12% on a uniform slope without grass hedge because of increased steepness, while erosion was decreased by 49% on a slope with three grass hedges as a result of bench terrace formation. These results demonstrate the potential importance of considering slope steepness changes for long-term conservation planning on non-uniform slopes.

INTRODUCTION

The Water Erosion Prediction Project (WEPP) is a process-based continuous simulation erosion prediction model (Laflen et al., 1991) whose input files include climate, crop management, slope, and soil descriptions. Continuous simulation means that the computer program can simulate a number of years with varying input climatic data and generate predicted changes in soil moisture, soil roughness, surface residue cover, canopy height, canopy cover, and soil erosion updated on a daily or storm basis.

Two WEPP limitations make modeling the impact of grass hedges on hillslopes challenging: (1) backwater effects are not considered within WEPP and (2) topography is static throughout a WEPP simulation. Both of these effects may have only minor impacts when modeling slope segments that are relatively uniform and for overland flow elements that are wide compared to backwater lengths. However, grass hedges result in conditions where both conditions are not met. Backwater lengths can be many times longer than hedge width (Dabney et al., 1995).

Further, when hedges are aligned close to contours of sloping land, slope steepness of the cropped segments may be altered over a relatively short time due to sediment deposition in and upslope of the hedges and soil detachment downslope of the hedges (Kemper et al., 1992). Tillage translocation of soil also contributes significantly to the development of benches on sloping cropland (Dabney et al., 1999). In this situation, long-term estimation of soil erosion on a cropped field with grass hedges might be poor if a fixed slope profile is used.

Vegetative barriers or grass hedges are narrow permanent grass strips of tall, erect, stiff-stemmed vegetation, densely planted in parallel rows along contours and/or cross concentrated-flow area, perpendicular to the dominant slope of the field (Fig. 1). On plots, grass hedges have trapped up to 75% of sediment by reducing runoff velocity, spreading runoff and increasing sediment settling time (McGregor et al., 1999). Hedges can trap a similar fraction of aggregated sediment even where flow has become becomes concentrated. For example, controlled flume studies using four types of sediment, several grass species, several hedge widths, and flow rates ranging from 0.0055 to 0.0455 m^3s^{-1} showed that grass hedges could slow runoff and created backwaters that extended 5 to 6 m upstream with a flume grade of 0.05 (Fig. 2). Sediment deposition in the backwater was the primary reason for sediment trapping. Nearly all sediment larger than 125 μm was trapped, about 20% of sediment less than 32 μm was trapped, while trapping of intermediate size sediment depended on flow conditions (Dabney et al., 1995; Meyer et al., 1995). Differences between grass species were caused only by differences in the ability of the grasses to create backwaters and switchgrass (*Panicum virgatum*) was found to be among the best species in this regard that is widely adapted for growth in the U.S. Watershed observations have also showed that switchgrass hedges can prevent ephemeral gully growth (Fig. 3). Slope steepness in the deposition area upslope of the grass hedge has been decreased to about 30% of its original slope (Zhu et

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al., unpublished data) but steepness through the grass hedge is increased.

When the same total hillslope elevation and length is achieved with a series of steeper and less steep segments vs. segments of uniform (average) steepness, and management is uniform, the result will be an increase in average soil erosion if erosion increases with slope steepness raised to a power greater than one, which is usually the case erosion (Zingg, 1940; Musgrave, 1947; Wischmeier and Smith, 1978). In RUSLE, erosion increases faster than slope steepness for grades between about 0.09 and 0.40 (Equation 4-5 in Renard et al., 1997).

Since slope steepness is an important non-linear factor in erosion prediction, updating of a profile's slope data during a WEPP simulation should improve the long-term erosion prediction for slopes with non-uniform management

Figure 1. Grass hedges at Treynor, 1A.

Figure 2. Backwater (40-cm deep) caused by 20-cm wide grass hedge extended upslope 6 meters from hedge (Dabney et al., 1995).

Figure 3. Deposition of sediment in backwater upslope of hedge fills swales fastest.

elements such as grass hedges. The purpose of this study was to develop a computer program to convert distributed WEPP predictions of erosion and deposition into (1) distributed elevation changes and (2) a modified input slope file and to be used in future WEPP simulations. We applied this technique, using the same climate input data for two iterations in order to study how the slope change affected predicted erosion rates and patterns on a hillslope with grass hedges.

MATERIALS AND METHODS

The WEPP model (version 98.4) allows the user to simulate many types of non-uniformities on a hillslope through the use of strips or Overland Flow Elements (OFEs). Each OFE on a hillslope is a region of homogeneous soils, cropping, and management. All of the input files (slope, soil, management, irrigation) must provide information for each OFE on which the user would like to simulate the hydrologic and erosion processes.

To illustrate the potential impact of slope modification, we simulated the approximately 80-m long slope described by (Dabney et al., 1999). The field, located at the UDDA-NRCS Jamie Whitten Plant Materials Center near Coffeeville, MS, had a Loring silt loam soil (fine-silty, mixed thermic Typic Fragiudalf) with about 0.068 slope grade. In 1992, three parallel 1.5-m wide grass hedges were established close to the contour and spaced 19.2 m apart. Areas between grass hedges were tilled fallow. We used WEPP to simulate two scenarios. In scenario 1, we simulated the field with hedges as seven OFEs with grass on upper part (first OFE), followed by six OFEs alternating between the tilled fallow and dense grass hedges (Fig. 4a). For comparison, we designed scenario 2 using the same initial slope profile but with only two OFEs, the upper grassed hilltop followed by a continuous area of tilled fallow (Fig. 4b). In both scenarios, we set the time-varying effective soil conductivity parameter, K_e, for tilled areas at 1.6 mm h^{-1}, the default value for Grenada silt loam the WEPP database, while the K_e for grassed areas was increased 9-fold as suggested for meadow by Flanagan and Nearing (1995).

We ran the simulation of each scenario using 4-years of measured rainfall data at the site (Dabney et al., 1999). We then applied the slope updating procedure described below, and ran the simulation on the updated slope profiles using the same 4-years of climatic data for a second and third time in order to estimate the erosion that could be expected after 8 years of slope modification.

After the initial simulation period, WEPP output file (.plo file) contained horizontal distance (m), initial elevation (m), and erosion or deposition (kg m^{-2}) at 100 points within each OFE. We wrote a FORTRAN program to translate the information in this file into an updated input slope file (.slp file), as described below. This program determines the amount of sediment trapped in each grass hedge and redistributes it upslope and within in the grass hedges so that no slope reversals (negative slopes) occur, a requirement of WEPP input slope files.

Figure 4. Two scenarios were simulated for non-uniform slope with grass, tilled fallow, and grass hedges (a, top) and uniform slope without frass hedges (b, bottom).

The main steps of the slope updating program are as follows:

1. Read soil loss summary output WEPP (.plo) file that contains 100 segments for each Overland Flow Element (OFE). Read the initial slope (.slp) profile description and determine the steepness of the last several segments of each OFE.
2. Sum up total soil erosion and deposition for each OFE and calculate the "WEPP elevation" for each point by dividing predicted erosion or deposition at a point by an assumed bulk density (kg m-3) and adding the quotient to the input elevation of that point.
3. Check for reverse slopes created just below each hedge and, if necessary, eliminate them using regression analysis to extend the WEPP elevation slope located between 0.1 and 0.15 (fraction of tilled OFE) to a "modified slope" between 0.0 and 0.1 of the tilled OFE.
4. If the first point of an OFE shows sediment deposition, assume that OFE is a grass hedge and process as follows. Assume that sediment is deposited in two approximately triangular areas (one in the hedge and one covering part of the OFE immediately upslope of the hedge). Choose an initial estimate of sediment deposit depth at the start of the hedge OFE, based on 1/3 of the total sediment being trapped in the hedge, and iteratively adjust that depth until the sum of the triangular areas above the initial surface agree, within 1%, to the area of sediment WEPP predicted was deposited within the hedge OFE (#2 above) plus any deposited within the next upslope OFE due to slope concavity. The slope of the line projected upslope of the hedge is set at the greater of: 30% of the initial slope (#1 above) or 0.01. The depth of sediment deposition at the downslope edge of the grass hedge is assumed zero. The modified elevation between 0.1 and 1.0 of the OFE upslope of the hedge is taken as the greater of the WEPP elevation or the projected line. Within the hedge OFE, the modified elevation is determined as the linear interpolation between the sediment elevation at the upslope edge of the hedge and the original elevation at the downslope edge of the hedge.
5. Calculate new slope gradients for 20 segments per OFE from new elevations. Export new slope file in a format that can be directly used by the WEPP model as input in subsequent erosion simulation runs. Important restrictions of the WEPP slope input files include: (1) the maximum number of segments for an OFE is 20, (2) the location (fractional distance) of the first point in an OFE slope description must be 0.0 and that of the last point must be 1.0, and (3) the slope of the last segment of an OFE must match that of the first element of the adjacent OFE (Flanagan and Nearing, 1995).

RESULTS

Slope changes due to erosion and deposition

Soil surface elevations after the first 4-yr simulation are shown in Figs. 5a for the hillslope with grass hedges and 5b for the slope with grass only in the upper part of the field followed by uniform tilled fallow. Slopes in the grassed area on the upper part of the slope for both scenarios remained almost the same because little erosion occurred in that area.

For the uniform slope scenario, average grade of the tilled fallow area increased slightly from 0.068 to 0.069 (Fig. 5b) because erosion rates increased downslope as runoff accumulated. It was assumed that runoff and sediment could freely drain from the simulated profile in this scenario.

In contrast, the hillslope containing grass hedges became complex with areas of both detachment and deposition (Fig. 5a). After sediment redistribution above and within the grass hedges, the profiles resembled the actual deposition patterns obtained by flume and field survey observations (Dabney et al., 1995; Dabney et al., 1999).

In the first tilled OFE, erosion increased with increasing distance downslope as accumulated runoff increased transport capacity. For the other tilled OFE, however, maximum erosion occurred immediately downslope of a hedge, reflecting a large difference between transport capacity and sediment load after deposition of much sediment within the hedge. Because WEPP does not consider backwater effects, all predicted deposition in the first 4-year simulation occurred within the grass hedges (Fig

5a). This deposition caused WEPP elevations to have slope reversals at the upslope edge of each hedge OFE because the amount of sediment deposited exceeded the natural fall of the land in each segment. Such slope reversal was the main reason that we developed the sediment redistribution model. After redistribution, sediment within each hedge tapered to zero thickness over the original surface at the downslope margin of the hedge where the elevation remained fixed.

Slope steepness within tilled OFEs was variable after modification. Because WEPP predicted significant erosion at the start of each tilled OFE and the elevation at the downslope edge of each hedge was assumed fixed, the steepness of the first segment of each tilled OFE was steeper than the average for that OFE. In contrast, the slope of the sediment wedge at the lower end of the tilled OFE was gentler than average.

When the modified hillslope was passed back through WEPP for a second erosion simulation using the same weather file, several new erosion and deposition patterns developed (Fig. 6a). First, a “scour hole” developed immediately downslope of each grass hedge. We believe this results from the steep slope of the first segment of each tilled OFE and the lack of backwater controls on the depth of possible erosion. Second, deposition was no longer restricted to the grass hedge area but rather began when slope steepness decreased within the tilled OFE. Thus, the modified slope profile partially overcame the limitation of WEPP not considering deposition in backwater areas because sediment deposition now occured upslope of the grass strips. It is noteworthy that the width of the projected gentle-slope benches increases steadily as one proceeds down slope.

Surface elevations after the second 4-yr simulation for the hillslope without grass hedges (Fig. 6b) generally resembled the original slope, but average grade over the tilled fallow area increased 3% from the original 0.068 to 0.07 after the second 4-yr simulation.

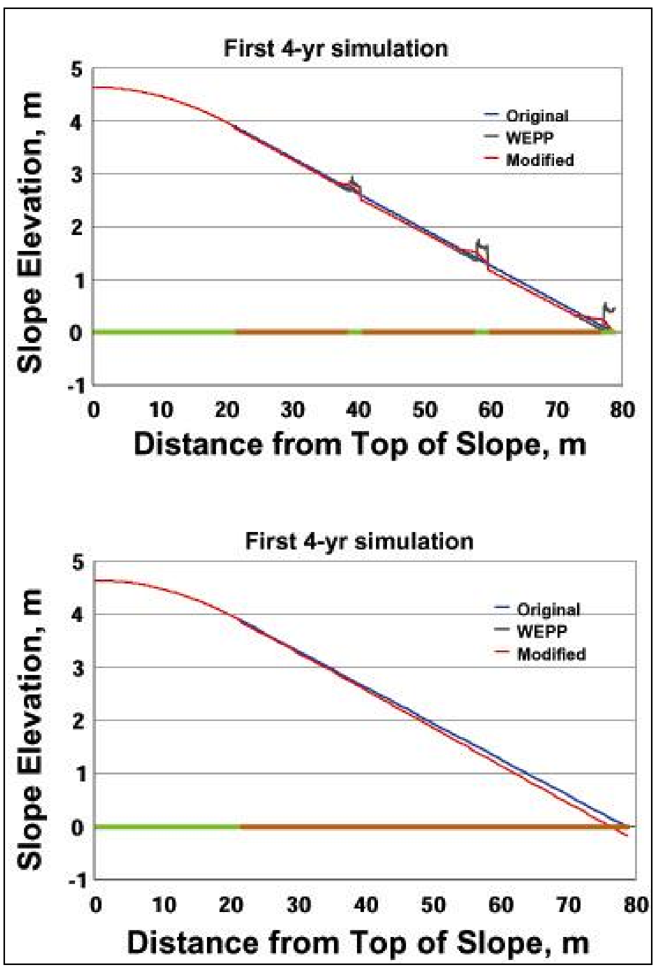

Figure 5. Soil surface elevation after the first 4-yr simulation for non-uniform slope with grass, tilled fallow, and grass hedges (a, top) and uniform slope without grass hedges (b, bottom).

Runoff and erosion prediction due to slope change

The effects of grass hedges and of updating the slope profile on runoff and erosion simulations are shown in Table 1. Using the original slope profile, predicted mean annual runoff was 84 mm y^{-1} with grass hedges vs 217 mm y^{-1} without grass, reflecting the assumed increased permeability of grassed areas vs tilled fallow. Changing the slope profile had very little effect on predicted annual runoff for either scenario.

Slope modification had a major impact on predicted soil erosion. With the original slope, grass hedges reduced soil

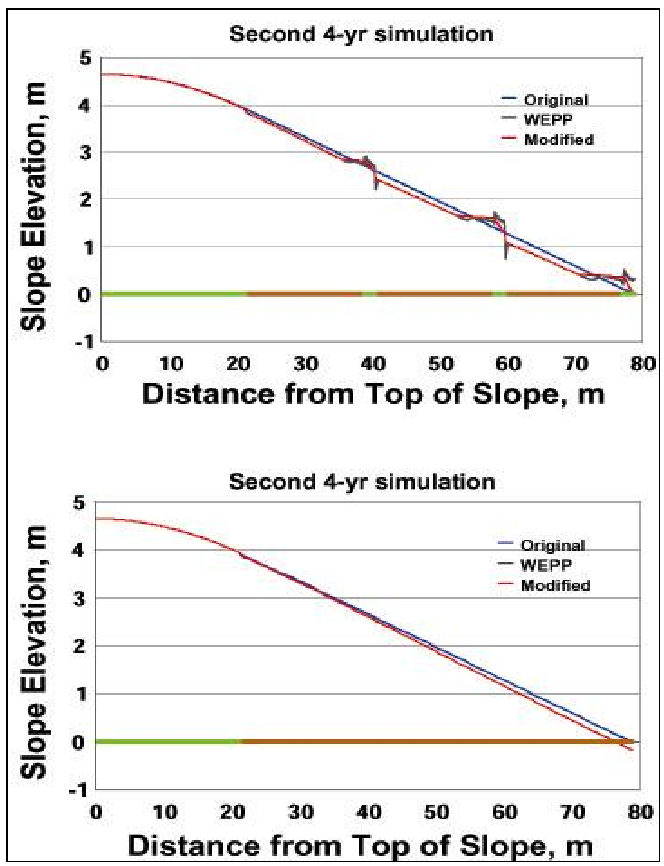

Figure 6. Soil surface elevation after the second 4-yr simulation for non-uniform slope with grass, tilled fallow, and grass hedges (a, top) and uniform slope without grass hedges (b, bottom).

Table 1. WEPP runoff and soil loss predictions using original and updated slope profiles with common climate, management, and soils files.

	Slope Without Hedges		Slope With Hedges	
	Runoff mm y^{-1}	Erosion Mg ha^{-1} y^{-1}	Runoff mm y^{-1}	Erosion Mg ha^{-1} y^{-1}
Original Slope	217	215	84	143
Slope Modified After 4 years	217	228	84	119
Slope Modified After 8 years	218	241	82	74

erosion from 215 to 143 Mg ha^{-1} y^{-1}. Increased slope steepness caused a 12% increase in predicted erosion for the profile without hedges. In contrast, slope modification resulted in a 49% decrease in predicted erosion from the hillslope with hedges after 8 years.

It should also be noted that the benches developed in this study resulted only from water erosion and deposition as predicted by WEPP. Soil translocation caused directly by tillage operations can also move soil downslope (Govers et al., 1994). We believe that such tillage translocation contributed significantly to the benching observed at the Coffeeville site (Dabney et al., 1999), which is similar to that depicted in Fig. 6b (Dabney et al., 2001). If tillage translocation contributed significantly to benching, then water erosion would have been reduced more rapidly than simulated in the present study even though bench size after 8 years might remain the same.

SUMMARY

Current erosion prediction models including WEPP assume a fixed soil surface topography through a simulation period. This approach might be satisfactory for uniform slopes with single management, but it could be a major limitation for profiles having non-uniform slope, soil, and management. In particular, slopes on which grass buffer strips induce significant deposition (in and above the strips) and have large amounts of detachment (below the strips) are difficult to adequately represent with the current WEPP hillslope model. Since slope steepness is a sensitive and important factor for erosion prediction, updating of a profile's slope data during a simulation should improve the erosion prediction for these situations. In this study, a computer program was written to update the input slope file for WEPP based on previously predicted soil erosion and deposition. The program uses soil loss summary output files from WEPP that contain horizontal distance, elevation, and erosion or deposition along a profile. Sediment is redistributed above and in the grass hedges so as to mimic actual deposition patterns observed in flume and field studies. A new slope profile is then calculated based on the new elevations and exported to a file with a format that can be used directly by the WEPP model in subsequent erosion simulations. The slope modification program should be generally applicable where deposition occurs as a result of increased hydraulic roughness in strip-cropped fields. The source code and executable slope modification program are available from the corresponding author.

Updating the slope profile of a hillslope with three grass hedges resulted in significant benching because of soil detachment on the upper part of the tilled fallow strips and sediment deposition and redistribution in and upslope of each grass hedge. This benching resulted in a 49% reduction in predicted erosion after 8 years, demonstrating the importance of considering changes in slope steepness for long-term conservation planning of hillslopes with non-uniform slope, soil, and management. After 8 years, sediment deposition was dominated by changes in slope steepness within the tilled OFEs rather than directly by increased roughness in the grass strips. Thus, the slope modification routine partially overcomes the limitation of not considering backwater effects within WEPP, but increases the importance of understanding and modeling patterns of sediment deposition on concave slopes.

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