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Validation of a 3-D enhancement of the Universal Soil Loss Equation for prediction of soil erosion and sediment deposition

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Abstract

A study was conducted on three U.S. military training areas to validate the Unit Stream Power Erosion and Deposition (USPED) model, a 3-dimensional enhancement to the Universal Soil Loss Equation (USLE). The USPED model differs from other USLE-based models in the manner in which it handles the influence of topography on the erosion process. As a result, the USPED model predicts both erosion and deposition, while most other USLE-based models are limited to predictions of erosion only. Erosion and deposition from a small watershed at Fort Hood, Texas, USA was quantified using ^{137}Cs, a radioactive isotope found in soils around the world as a result of fallout from post-World War II nuclear testing. We compared ^{137}Cs-derived erosion/deposition measurements with estimates derived from the USPED model and two applications of the USLE. Soil erosion and sediment deposition estimates generated by the USPED model were more accurate and less biased than results of the USLE applications. Both applications of the USLE consistently and significantly overestimated soil erosion; the USPED model did not. The USPED model was subsequently applied to Camp Guernsey, Wyoming, USA and Fort McCoy, Wisconsin, USA. Model

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estimates of soil erosion and sediment deposition were compared with field estimates of the same parameters. Based on 3 levels of soil erosion and 3 levels of sediment deposition, the model results agreed with field estimates 76 and 89% of the time at the two locations, respectively.

Keywords: Erosion modeling; ^{137}Cs; USLE; Unit stream power theory; Sediment deposition

1. Introduction

The Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) and the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997) are among the most widely accepted and used erosion models in the world. The models estimate long-term average annual sheet and rill erosion (E) as a product of factors representing rainfall and runoff erosivity (R), inherent soil erodibility (K), the length and steepness of slope (LS), plant cover (C), and conservation support practices (P). At least part of their popularity can be accounted for by the ease with which they are applied. However, a major drawback of these and even many of the new-generation process-based models (e.g., Water Erosion Prediction Project [WEPP]; Flanagan and Nearing, 1995) is the 1-dimensional approach used to account for the effects of topography. Landscapes have generally been treated as homogenous, planar features. Average erosion rates have been assigned to entire hillslopes and watersheds, thus providing no information regarding sources and sinks of eroded materials. Alternatively, complex landscapes have been computationally divided into series of semi-homogenous planes, and erosion has been calculated for each plane, thus giving some consideration to slope convexity and concavity (Foster and Wischmeier, 1974). In both approaches, erosion is calculated only along straight flow lines without full consideration of the influence of flow convergence and divergence. Neither approach provides adequate spatially distributed information on erosion necessary to effectively optimize erosion and sediment control efforts.

A second shortcoming of the USLE and the RUSLE is that they predict soil erosion only; they do not predict sediment deposition. Furthermore, both models predict erosion "universally", even where deposition may occur. Thus, at landscape or watershed scales, the spatial distribution of soil erosion as predicted by these models will likely misrepresent actual conditions and will tend to overestimate erosion (e.g., Jensen, 1983; Busacca et al., 1993). The only practical way to apply the models is to identify a priori those portions of the landscape subject to deposition and exclude them from analysis (Mitasova et al., 1997).

Geographic information systems (GIS) provide the capacity to more fully consider the effects of topographic complexity on soil erosion. Application of erosion models within GIS has become increasingly popular as the technology has evolved (e.g., Fistikoglu and Harmancioglu, 2002; Shi et al., 2004). Spatially distributed elevation data stored in a GIS can be analyzed to produce slope length (L) and steepness (S) values for any given point in a watershed. More importantly, the effects of flow convergence and divergence can be more fully considered by determination of the upslope area that contributes flow across each point in the watershed. When upslope contributing area is substituted for slope length, the resulting LS factor is equivalent to the traditional LS factor on planar surfaces, but has the added benefit of being applicable to complex slope geometries (Moore and Burch, 1986; Moore and Wilson, 1992). Equations for the computation of the LS factor based on upslope contributing area have been developed by Desmet and Govers (1996) and Mitasova et al. (1996).

The WAter and Tillage Erosion Model (WATEM), developed by Van Oost et al. (2000), incorporates the LS factor equations of Desmet and Govers (1996). The WATEM model calculates the mean annual soil erosion rate and the mean annual sediment transport capacity for each grid cell in the GIS. Where sediment inflow into a cell exceeds the sediment transport capacity, deposition occurs. Thus, both soil erosion and sediment deposition may be calculated for each grid cell.

The equations of Mitasova et al. (1996) more fully account for topographic complexity by considering both the profile curvature (in the downhill direction) and the tangential curvature (perpendicular to the downhill direction) (Warren et al., 2000). Net erosion or deposition within a grid cell are calculated as the divergence of sediment flow (change in sediment transport capacity) in the direction of flow. Given the nature and extent of improvements to the traditional USLE/RUSLE that are based on the unit stream power theory (Moore and Burch, 1986; Moore and Wilson, 1992), the improved version has been named the Unit Stream Power Erosion and Deposition (USPED) model.

The basic equation for the USLE, RUSLE and USPED models is

$$E = R \times K \times LS \times C \times P \tag{1}$$

Values for these factors are determined from various maps, tables and nomographs based on field measurements (Renard et al., 1997).

The USPED model substitutes an LS analog computed as

$$LS = A^m (\sin\beta)^n \tag{2}$$

where A is upslope contributing area, β is slope angle, and m and n are constants that depend on the type of flow and soil properties. For situations where rill erosion dominates, these parameters are usually set to $m = 1.6$ and $n = 1.3$; where sheet erosion prevails, they are set to $m = n = 1.0$ (Moore and Wilson, 1992; Foster, 1994). Because the USPED model computes both erosion and deposition (ED) as a change in sediment transport capacity across a GIS grid cell, a further computation is required. A computationally simple formulation of the equation is

$$ED = \frac{\mathrm{d}(E\cos a)}{\mathrm{d}x} + \frac{\mathrm{d}(E\sin a)}{\mathrm{d}y} \tag{3}$$

where a is slope aspect in degrees in the direction of steepest slope.

The objectives of this research effort were two-fold. First, we desired to compare the accuracy of erosion and deposition estimates produced by the USPED model with traditional applications of the USLE. Erosion models have often been compared and validated using sediment discharge from small plots (e.g., Risse et al., 1993; Tiwari et al., 2000) or watersheds (e.g., Madeyski and Banasik, 1989; Santhi et al., 2001). While such comparisons have their place, they provide no information on the spatial accuracy of the predicted patterns of erosion and deposition within a watershed. For the purposes of this study, we chose to measure erosion and deposition using ^{137}Cesium (^{137}Cs), a nuclear radioisotope resulting from post-World War II aboveground nuclear testing. The second objective of this study was to compare soil erosion and sediment deposition estimates from the USPED model with field estimates of the same parameters.

2. Study areas and methods

2.1. Comparison of USLE and USPED estimates using ^{137}Cs

2.1.1. Study area

The comparison of the USLE and USPED models was conducted on a small, 15.5-ha prairie watershed at Fort Hood, an active Army training area in central Texas, USA. Annual precipitation averages 76 cm. The area is used frequently by wheeled and tracked military vehicles, and has been subjected to heavy cattle grazing. A deeply incised gully has formed where runoff converges at the bottom of the slopes. Three soil mapping units are represented in the watershed: the Brackett soil is a deep, well-drained, gravelly loam on the upper ridges; the Topsey soil is a deep, well drained, silty clay loam to clay loam occurring on the side slopes; the Slidell soil occurs in the valley bottom and consists of deep, well-drained silty clay. Slopes within the watershed range from 0–7%.

2.1.2. ^{137}Cs-based estimation of erosion and deposition

Post-World War II thermonuclear weapons testing injected ^{137}Cs into the stratosphere where it circulated globally before slowly returning to earth (Longmore, 1982). Deposition of fallout ^{137}Cs reached a maximum in the early 1960's; fallout since the mid 1980's has been below detection levels (Cambray et al., 1989). Regional patterns and rates of deposition of the isotope to the land surface are related to local rainfall rates and patterns (Davis, 1963).

^{137}Cs is rapidly and strongly adsorbed by clay particles in the surface soil and is essentially nonexchangeable once adsorbed to these clay surfaces (Livens and Rimmer, 1988). Distribution of ^{137}Cs in soil profiles at undisturbed sites shows an exponential decrease with depth (Campbell et al., 1982) while plowed soils show uniform mixing of ^{137}Cs in the plowed layer (Loughran et al., 1987). On the average, less than 1% of the ^{137}Cs moves from a catchment in solution immediately after fallout deposition, and generally less than 0.1% moves in solution per year after the initial flush (Eakins et al., 1984; Helton et al., 1985). Although biological and chemical processes can move limited amounts of ^{137}Cs, the dominant factors affecting the movement of ^{137}Cs within landscapes are the same physical processes that affect the movement of the soil particles to which it is attached, i.e., water and wind erosion. Heterogeneous spatial distribution of ^{137}Cs within a watershed is directly and proportionately related to spatial redistribution of soil through erosion and sediment deposition processes. Because there are no natural sources of ^{137}Cs, its distribution on the landscape provides an estimate of erosion and deposition during the period since the peak of aboveground nuclear testing.

^{137}Cs emits a strong gamma-ray, making its measurement in soil samples relatively easy and accurate without special chemical preparation or separation. Methods for measuring ^{137}Cs in soil samples using gamma-ray spectrometry are well-established (Walling and Quine, 1993). Determination of areas of soil erosion or deposition on the landscape is based on a comparison of measured ^{137}Cs in a soil profile with the ^{137}Cs originally input to the site. Because local measurements of input to a site are usually not available, a local reference site must be chosen where little disturbance or soil erosion has occurred since the 1950's. Local variation of fallout ^{137}Cs on the landscape can be significant and thus several reference profiles should be measured near each study site (Nolin et al., 1993, Wallbrink et al., 1994). A comparison between the sampled soil site and the reference site provides information on gains or losses of ^{137}Cs. Sites with a loss of ^{137}Cs are eroding while sites with a gain of ^{137}Cs are aggrading.

For this study, soil samples were collected systematically on an approximate 50 m by 50 m grid throughout the study watershed. At each grid intersection, four 2.5 cm diameter soil cores were extracted to a depth of 24 cm. To minimize the potential effects of localized heterogeneity, a centrally located core was surrounded by three additional cores spaced at 1 m from the central core and forming an equilateral triangle. The four cores representing each grid intersection were combined into a single composite soil sample. Grid intersections falling in the central gully were ignored because the depth of soil erosion far exceeded the depth to which ^{137}Cs is found in the soil profile.

Two cemeteries located approximately 4 km from the study watershed were selected as reference areas. The cemeteries have been fenced to exclude military training and livestock since about 1954. The soil within the cemeteries is predominantly Topsey clay loam. Two sites per cemetery were sampled. At each site five narrow pits were dug. A central pit was surrounded by four additional pits located 1 m from the central pit in each of the cardinal directions. From the sides of each pit, 3 cm deep slices were collected to a depth of 24 cm. The five samples representing the same depth increments at each site were combined into composite samples. Suitable undisturbed reference areas were not locally available for the Brackett and Slidell soils, so only samples from the Topsey soil were used in our comparisons.

Soil samples from the reference areas and study watershed were transported to a laboratory where they were sieved using a standard ASTM 1.18 mm sieve to remove small stones and other debris. From each homogenized soil sample, a 100 g subsample was placed into a 250 ml glass beaker. A Compton suppression gamma-ray spectrometer was used to detect 662 keV photons decaying from ^{137}Cs. This system greatly reduces the background from naturally occurring radioactive decay products and improves the signal to noise ratio, making detection of small peaks easier (Landsberger, 1994). International Atomic Energy Agency standard reference material was used to calibrate the system. Samples were counted for 14 to 24 h.

The vertical profile of ^{137}Cs at the reference areas was computed by calculating the mean concentration at each depth increment (Fig. 1). Net erosion or deposition at the study watershed was computed using the Profile Distribution Model (Walling and He, 1997). Application of the model requires the computation of a ^{137}Cs reference inventory (A_{REF}) or average ^{137}Cs concentration within the reference profiles. The A_{REF} for the Topsey reference profile was 6.7 Bq kg^{-1}. Using least squares, a coefficient (h_0) was calculated to describe the shape of the reference profile curve. The coefficient for the Topsey profiles was computed as 34.3. Finally, because ^{137}Cs binds primarily to fine soil particles that are

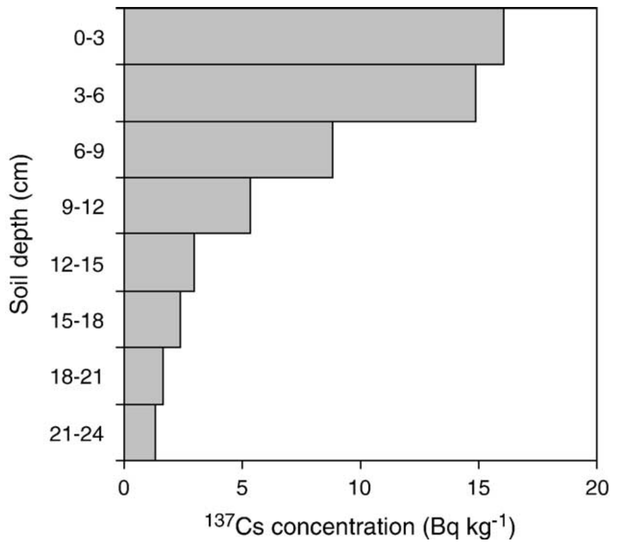

Fig. 1. The reference profile of ^{137}Cs concentration for the Topsey soil series at Fort Hood, Texas, USA.

more likely to erode than coarse particles, a particle size correction factor was used to avoid overestimation of erosion. At locations where the ^{137}Cs concentration differed by >10% from the respective reference inventories, we applied a particle size correction factor of 1.05 or 0.95 for net erosion or deposition, respectively.

2.1.3. USLE and USPED model estimation of erosion and deposition

While the treatment of topography (LS factor) differs dramatically between the USLE and USPED models, the remaining parameters are shared. At Fort Hood, the *R* factor is 4510 MJ mm ha^{-1} h^{-1} yr^{-1}. The K factor for the Topsey soil is 0.042 t ha h ha^{-1} MJ^{-1} mm^{-1}. The C factor was estimated as 0.04 (dimensionless). No erosion control practices are used in the watershed, so the P factor was assigned a value of 1.0 (dimensionless) such that it had no effect on the erosion calculations.

This project was designed to compare the relative accuracy of erosion/deposition estimates provided by GIS applications of the USLE and USPED models. The first application represents early attempts by the US Army to apply GIS technology to the computation of soil erosion with the USLE where digital representation of topography was unavailable (Warren et al., 1989). Under such circumstances, several field measurements of slope length and steepness were collected within each soil mapping unit in an area of concern. The values were averaged by soil map units and the mean values were assigned to the areas represented by the respective soils. No field measurements were made for this study. However, in order to simulate the practice, we calculated the USLE LS factor (dimensionless) for each cell in the study watershed using the Geographic Resources Analysis Support System (GRASS) GIS and a 2-m digital elevation model (DEM) of the study watershed. LS values were averaged by soil map unit, and the average values were assigned to the area represented by the respective soils. This methodology will hereafter be referred to as $USLE_{OLD}$.

For the second application, we used the same calculations as the first. However, instead of using an average LS value, we retained the calculated LS factor for each cell. By retaining the spatially distributed information, we anticipated significant improvement in the spatial accuracy of USLE erosion estimates. Subsequent discussion of this method will be referred to as USLE_{NEW}. The third application utilized the USPED model as described in Section 1. For all three applications, the GIS data layers representing the various model components were multiplied together (Eq. (1)) to produce respective soil erosion/sediment deposition data layers.

2.1.4. Statistical analyses

We first performed an exploratory visual analysis of the data by plotting the erosion/deposition estimates derived from the ^{137}Cs method against estimates produced by the USLE_{OLD}, USLE_{NEW} and USPED models at the same positions in the watershed. Next, we assessed the overall performance of the methods with the root–mean–square error (RMSE), which is calculated as

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(x_\text{i} - t_\text{i})^2}{n - 1}} \tag{4}$$

where x_i and t_i are the model-based and ^{137}Cs-based estimates at a given location (i), respectively, and n is the sample size. A lower RMSE indicates greater predictive ability (i.e., the model-based estimates deviate less from the ^{137}Cs-based estimates). We estimated the variance of the RMSE values with the jackknife procedure (Manly, 1991). Confidence intervals for the values were then calculated as $\pm\ t_{\text{n}-1}$SE, where SE is the standard error of the jackknifed distribution and $t_{\text{n}-1}$ is the critical value of a two-sided 95% confidence interval from a t-distribution with n-1 degrees of freedom. The G-test of goodness of fit with correction for continuity (Sokal and Rohlf, 1995) was applied to determine whether the frequency of over-estimation differed significantly from the frequency of under-estimation. For unbiased models, the number of under- and over-predicted erosion/deposition estimates should be approximately equal.

2.2. Comparison of the USPED model results with field estimates

2.2.1. Study areas

Comparisons of erosion and deposition estimates produced by the USPED model were made with field estimates of the same parameters at Camp Guernsey, Wyoming, USA and Fort McCoy, Wisconsin, USA, two active military training areas located in divergent topographic, edaphic and climatic settings. Camp Guernsey is located in southeastern Wyoming and comprises approximately 12,110 ha. The climate is considered semiarid with a total annual precipitation of 33 cm. Peak precipitation occurs during May and June. Average daily temperatures range from -1 °C in the winter to 21 °C in the summer. Elevation ranges from 1310 to 1610 m above sea level. Rolling hills with scattered rock outcrops are typical. The dominant vegetative communities are mixed-grass prairie, montane shrublands and conifer woodlands. Soils range from sands to silt loams.

Fort McCoy comprises approximately 24,300 ha in southwestern Wisconsin. The climate at Fort McCoy is characteristically continental with four distinct seasons. Average annual precipitation is 76 cm. Peak precipitation occurs during the summer months. Peak snowfall occurs during January with an average of about 25 cm. Average daily temperatures range from -10 °C in January to 23 °C during July. Forests dominate the installation, with lesser amounts of wetlands, prairie and savannah also present. The elevation at Fort McCoy ranges from approximately 246 to 441 m above sea level. Topography ranges from nearly flat to steeply sloping. Soils are primarily sands derived from sandstone bedrock although loams and peat are also present.

2.2.2. USPED model application

In order to apply the USPED model at Camp Guernsey and Fort McCoy, it was necessary to determine values for the various components of the USPED model at each location. Based on maps provided by Renard et al. (1997), the R factors for Camp Guernsey and Fort McCoy were determined to be 545 and 2553 MJ mm ha^{-1} h^{-1} yr^{-1}, respectively. Because the R factor generally varies little within areas the size of the study sites, there was no need to develop spatially distributed GIS data layers for this parameter.

GIS data layers showing spatially distributed K factors for the two study areas were created by reclassification of the respective soil data layers using online databases provided by the Natural Resources Conservation Service. Where soil mapping units were listed as complexes of more than one soil series, a weighted average was computed and assigned to the mapping unit.

Digital elevation models of the two study areas were used to compute the upslope contributing area and slope steepness for each GIS grid cell at the respective study locations. Map algebra was then used to compute the equation for the improved LS factor (Eq. (2)) to produce an LS data layer for each study area.

To create C factor data layers for the study areas, LANDSAT 5 Thematic Mapper (TM) images #LT5034030031099174 (23 June 1999) and #LT5025029009915910 (08 June 1999) were obtained for Camp Guernsey and Fort McCoy, respectively. Statistical regressions were computed by comparing C factors from vegetation transects collected at each location during the summer of 1999 with parameters from the satellite image, including each of the raw spectral bands and various vegetation indices. The vegetation indices were the Normalized Difference Vegetation Index (NDVI), the Ratio Vegetation Index (RVI; Lillesand and Kiefer, 1987), the Transformed Vegetation Index (TVI; Tucker, 1979), the Soil Adjusted Vegetation Index (SAVI; Heute, 1988) and the Modified SAVI (MSAVI; Qi et al., 1994). Because the vegetation transects were 100 m long and the image pixel size was approximately 30 m, each transect traversed from 3 to 5 pixels, depending on orientation. We determined the mean spectral values for the pixels traversed by the transects and correlated those values with C factor for each transect. At Camp Guernsey, the best correlation was obtained with the LANDSAT TM raw band 2 which represents reflectance in the green portion of the visible spectrum (Table 1). The best-fit regression equation for the relationship was

$$\text{C Factor} = (0.002 \times \text{raw band2}) - 0.043 \tag{5}$$

Table 1
Correlation coefficients when C factors from vegetation transects were correlated to the various LANDSAT TM raw bands and vegetation indices at Camp Guernsey, Wyoming, USA

	LANDSAT TM raw bands							Vegetation indices			
	1	2	3	4	5	6	7	RVI	TVI	SAVI	MSAVI
Correlation Coefficient	0.67	0.73	0.72	0.61	0.56	0.24	0.59	–0.34	–0.37	–0.36	–0.37

A correlation coefficient of 1.0 represents a perfect correlation. The shaded box represents the choice used to derive a regression equation.

Initial attempts to correlate C factors from the vegetation transects with the various raw bands and vegetation indices at Fort McCoy yielded unacceptably low correlation coefficients. Correlation was improved by comparing each vegetation type with the satellite imagery separately (Table 2). Based on the improved correlations, regression equations were computed individually for each vegetation type (Table 3). The best-fit regression equations were used to reclassify the satellite imagery to produce a spatially distributed C factor data layer for each study area.

No erosion control practices are used at either study area, so the P factor was assigned a value of 1.0 such that it had no effect on the erosion calculations. By multiplying the component data layers together on a cell by cell basis with the GIS, maps were developed for Camp Guernsey and Fort McCoy showing the spatial distribution of predicted soil erosion and sediment deposition.

2.2.3. Field estimates of soil erosion and deposition

We conducted a field survey to validate the soil erosion and deposition estimates provided by the USPED model. Based on previous field experience we defined six erosion/deposition categories (Table 4). We used the GIS to randomly select survey points in each of the categories on the soil erosion/deposition map. The number of survey points assigned per category was relative to the percent of the land area occupied by the category. We used a minimum polygon size of 0.1 ha to maximize the likelihood of identifying the polygons in the field. In addition, survey points were placed no closer than 10 m from the edges of the polygon to compensate for potential error in global positioning system (GPS) technology and in the georeferencing of the map layers.

Using a global positioning system, we navigated to each random point. On arriving at the survey points, we observed the general soil conditions within a 10 m radius and assigned the points to an erosion/deposition category (Table 4).

3. Results and discussion

3.1. Comparison of USLE and USPED estimates using ^{137}Cs

A scatter diagram plotting erosion model estimates against ^{137}Cs-based estimates is shown in Fig. 2. Notably, the ^{137}Cs data exhibit a wide range of values (x-axis), whereas

Table 2
Correlation coefficients for individual vegetation types when C factors from vegetation transects were correlated to the various LANDSAT TM raw bands and vegetation indices at Fort McCoy, Wisconsin, USA

Vegetation type	LANDSAT TM raw spectral bands							Vegetation indices				
	1	2	3	4	5	6	7	RVI	NDVI	TVI	SAVI	MSAVI
All combined	.57	.59	.58	−.09	.58	.37	.64	−.41	−..47	−.48	−.47	−.49
Oak	.47	.46	.47	−.28	.49	.37	.56	−.46	−.48	−.48	−.48	−.48
Oak/Jack Pine	.45	.38	.44	−.14	.45	.41	.51	−.37	−.44	−.45	−.44	−.46
Jack Pine	.79	.78	.82	.13	.72	.44	.79	−.54	−.67	−.69	−.67	−.71
Plantation	.94	.96	.99	−.45	.96	.84	.97	−.93	−.96	−.96	−.96	−.96
Shrubby	.54	.76	.63	.30	.71	−.07	.75	−.34	−.32	−.32	−.32	−.32
Mixed	.70	.70	.70	−.34	.61	.47	.70	−.60	−.70	−.71	−.70	−.72
Grassland	.86	.87	.88	.07	.81	.07	.90	−.89	−.91	−.91	−.91	−.92

A correlation coefficient of 1.0 represents a perfect correlation. Shaded boxes represent the choice of raw band or vegetation index used to derive a regression equation within each vegetation type.

Table 3
Regression equations relating satellite imagery to vegetation transects within various vegetation types at Fort McCoy, Wisconsin, USA

Vegetation type	Regression equation
Oak	C factor = 0.0003(Band 7) + 0.004
Oak /Jack Pine	C factor = 0.0003(Band 7) + 0.001
Jack Pine	C factor = 0.001(Band 3) − 0.004
Plantation	C factor = 0.0003(Band 3) + 0.002
Shrubby	C factor = 0.001(Band 7) − 0.017
Mixed	C factor = − 0.055(MSAVI) + 0.052
Grassland	C factor = − 0.151(MSAVI) + 0.1

the erosion estimates produced by the $USLE_{OLD}$ method (y-axis) are limited to a single value. This is due to the process of assigning average erosion values to the entire soil mapping unit. The $USLE_{NEW}$ and USPED methods produce spatially distributed erosion estimates that are much more representative of real-world situations. A second important observation is that all erosion/deposition values produced by the $USLE_{OLD}$ and $USLE_{NEW}$ are negative, i.e., all values indicate net erosion. This is consistent with the fact that most

Table 4
Erosion/deposition categories used for field validation of the USPED erosion/deposition estimates at Camp Guernsey, Wyoming and Fort McCoy, Wisconsin, USA

>20 t ha^{-1} yr^{-1} erosion. Significant signs of erosion evident. Scouring, litter dams, and pedestaling of plant crowns and surface stones evident. Surface may appear rockier or heavier textured than uneroded areas due to loss of fine soil particles. Runoff patterns evident. Significant rills and gullies often present. Density and vigor of plants often lower than uneroded areas due to loss of soil fertility. Species composition likely to include more weeds than uneroded areas due to loss of soil fertility, exposure of subsoils and importation of seeds via overland flow of water. When erosion occurs through colluvial deposits in channels, significantly more than half of the deposits eroded away.

10 – 20 t ha^{-1} yr^{-1} erosion. Signs of erosion evident. Scouring, litter dams, and some pedestaling of plant crowns and surface stones generally evident. Surface may appear marginally rockier or heavier textured than uneroded areas due to erosion of fine soil particles. Runoff patterns and small rills may be evident. Density and vigor of plants may be lower than uneroded areas due to loss of soil fertility.

0 – 10 t ha^{-1} yr^{-1} erosion. Few signs of erosion. Some signs of scouring and litter dams may be present. Minimal pedestaling of plant crowns and surface stones. Slopes generally minor. Generally not present in channels.

0 – 10 t ha^{-1} yr^{-1} deposition. Few signs of deposition. Generally located in flatter areas or below eroded areas. Surface soil texture may be marginally finer than surrounding areas. Minor sediment deposits may be present on the upslope sides of plants and rocks. Generally not present in channels.

10 – 20 t ha^{-1} yr^{-1} deposition. Signs of deposition evident. Often located in flatter areas at the bottoms of slopes and in swales. Soil generally marginally deeper than surrounding areas as a result of deposition. Few rocks in the soil profile. Surface texture may tend to be silty, but sand and clay may be present depending on upslope soils. Significant sediment deposits may be present on the upslope sides of plants and rocks. Vegetation may be marginally more robust than surrounding areas.

>20 t ha^{-1} yr^{-1} deposition. Significant signs of deposition evident. Generally located in flatter areas at the bottoms of slopes and in swales. Soil generally deeper than surrounding areas as a result of long-term deposition. Few rocks in the near-surface soil profile. Surface texture tends to be finer than surrounding soils. Vegetation tends to be more robust than surrounding areas due to greater water holding capacity and nutrient status of deposited fine soil particles. When deposition occurs in channels, erosion gullies may be present through the deposited sediments, but significantly less than half of the deposits are eroded.

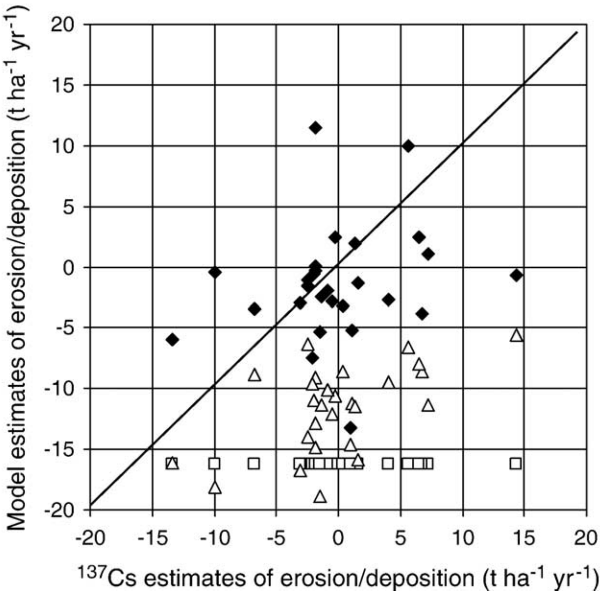

Fig. 2. A comparison of erosion/deposition estimates produced by erosion models and erosion/deposition estimates using the ^{137}Cs method for a small watershed at Fort Hood, Texas, USA. White squares represent the $USLE_{OLD}$ method, white triangles represent the $USLE_{NEW}$ method, and black diamonds represent the USPED model. Positive values represent net deposition, while negative values represent net erosion.

USLE-based models, in their traditional form, cannot predict sediment deposition. The USPED model, however, produces both positive and negative values corresponding to net deposition and net erosion, respectively.

In the scatter diagram (Fig. 2), the diagonal line represents a perfect 1 : 1 relationship. Assuming the erosion/deposition estimates provided by the ^{137}Cs method are correct, the closer the model estimates are to the 1 : 1 line, the more accurate the model. Notably, the USPED estimates are clustered about the 1 : 1 line, whereas the USLE estimates are not. This implies that the USPED model produced generally better results than either application of the USLE. This observational conclusion is supported by calculation of the RMSE. The USPED model produced the smallest RMSE (7.96 ± 0.62), followed in order by $USLE_{NEW}$ (12.98 ± 0.41) and $USLE_{OLD}$ (17.55 ± 0.65). Furthermore, calculation of the RMSE illustrates that applications of the USLE that compute the LS factor for individual GIS grid cells ($USLE_{NEW}$) provide significantly better results than applying a single LS value for an entire hillslope ($USLE_{OLD}$).

A model that provides unbiased estimates of erosion and deposition should over-and under-estimate the actual values with the same degree of frequency. Fig. 2 clearly illustrates that the $USLE_{OLD}$ and $USLE_{NEW}$ are significantly biased, i.e., all data points fall below the 1:1 diagonal line. Meanwhile, the USPED estimates are more equally distributed on either side of the line. Results of the G-test indicate that USPED generated unbiased estimates at our study site. The observed frequency of over- vs. under-estimates did not differ from expected ($G = 0.035$, $p = 0.850$).

Although the USPED model produced the smallest RMSE and proved to be statistically unbiased, the size of the RMSE (seen visually as the amount of scatter in Fig. 2) was disappointing. Several factors may have contributed to the apparent weakness of the relationship between the erosion/deposition estimates provided by the USPED and those determined with ^{137}Cs. For example, in this application of the USLE and USPED models, the C factor was held constant across the entire watershed, a common practice when applying the USLE to large areas (e.g., Busacca et al., 1993; Bartsch et al., 2002). As a result, these applications do not account for variation in soil erosion and sediment deposition as affected by the spatial distribution of vegetation. The ^{137}Cs method is based on spatially distributed samples and is not similarly constrained.

Application of soil erosion/deposition models and the ^{137}Cs technique requires the assumption of uniformity of soil properties within soil map units. However, soil mapping is not an exact science. Considerable variability exists within any given map unit. In addition, the boundaries between soil map units are often difficult to define precisely. Abrupt changes in a soil type are relatively rare; usually there is a gradual transition from one soil type to another.

Another potential source of variability contributing to the weakness of the relationship is that on military training lands factors other than erosion and deposition can affect the redistribution of soil. Soil is transported by the wheels and tracks of military vehicles. During training maneuvers, vehicles are often required to turn rapidly. Depending on the size, weight and speed of the vehicle, large quantities of soil may be displaced by such turns (Braunack, 1986). In addition, some tactical scenarios require digging of defensive positions, anti-tank ditches, etc. Soil erosion and deposition models cannot account for soil displacement by these processes.

Several assumptions are made when using ^{137}Cs as a marker in erosion studies, including uniformity of fallout distribution within geographic regions and rapidity of adsorption to soil particles. Recently, VandenBygaart et al. (1999a) reported that heterogeneity in the distribution of ^{137}Cs can result from overland flow prior to adsorption to soil particles, variation in the amount of precipitation, and variability in soil microtopography and infiltration characteristics. Other factors can also influence the distribution of ^{137}Cs in soils, including soil particle size (He and Walling, 1996), soil pH (Livens and Rimmer, 1988), soil organic carbon content (Absalom et al., 1999), soil cation exchange capacity (Aharoni et al., 1992), soil moisture (VandenBygaart et al., 1999b) and vegetation (Papastefanou et al., 1999). One or more of these sources of variability in the distribution of ^{137}Cs may have been present within the study watershed.

3.2. Comparison of the USPED model results with field estimates

Based on the field validation, the USPED model produced erosion/deposition estimates that were consistent with the field observations 76% of the time at Camp Guernsey and 89% of the time at Fort McCoy. The degree of agreement between model predictions and field observations is encouraging, particularly given the many potential sources of error. For example, some error can be expected due to the nature of the erosion/deposition categories used for the field validation. The categories were based on field experience in many locations; precise correlation of these qualitative categories with quantitative erosion/deposition estimates at a specific location should not be expected.

Field observer errors are also to be expected. For example, in a heavily wooded swale at Fort McCoy, the field observer estimated 0–10 t ha^{-1} yr^{-1} erosion based on the topographic position and minimal visual evidence of soil movement. The USPED model predicted 10 – 20 t ha^{-1} yr^{-1} deposition at the location. On returning to the site in an attempt to discover the cause of the discrepancy, a heavy cover of leaf litter was brushed aside and it was discovered that soil was accumulating on the uphill side of plants, a characteristic consistent with deposition predicted by the USPED model (Table 4).

Even if a precise correlation between qualitative field observations and quantitative erosion/deposition estimates were possible, it is virtually impossible for a field observer to detect small differences between categories (i.e., 9 t ha^{-1} yr^{-1} versus 11 t ha^{-1} yr^{-1} erosion or deposition). Hence, misclassification error should be expected between adjacent categories. Indeed, in the vast majority of cases where the USPED and field estimates differed, the estimates were within one category of each other.

4. Conclusions

Overall, the USPED model, with the enhanced capability to handle complex topography, outperformed both applications of the USLE. When comparing model estimates with ^{137}Cs-based erosion and deposition estimates, the USPED model produced a significantly smaller RMSE than either application of the USLE, indicating significantly greater accuracy. In addition, while both applications of the USLE consistently and significantly overestimated soil erosion (and underestimated sediment deposition), the results of the USPED model were statistically unbiased. USPED estimates of soil erosion and sediment deposition were acceptably consistent with field estimates of the same parameters at Camp Guernsey, Wyoming and Fort McCoy, Wisconsin.

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