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Application of the Unit Stream Power Erosion and Deposition (USPED) Model at Fort Campbell, Kentucky/Tennessee

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ABSTRACT

During the last century, numerous models have been developed to predict soil erosion and concomitant sediment deposition. Most have been shown to be inadequate and/or inaccurate in one respect or another. Historically, erosion model results have been compared with sediment outflow from watersheds, providing no information regarding sources and sinks of erosion and deposition within them. This paper documents the application of the new-generation Unit Stream Power Erosion and Deposition (USPED) model at the U.S. Army's Fort Campbell, Kentucky / Tennessee. The USPED model is relatively simple to apply and its novel approach compares model results with observed soil erosion and sediment deposition spatially across the landscape. The model results matched visually-estimated erosion/sediment deposition values 85% of the time, providing an encouraging test of the model. The approach we used provided information regarding the intensity and spatial distribution of soil erosion and sediment deposition that can be used to optimize the placement and size of soil erosion and sediment control efforts.

INTRODUCTION

The first author was hired by the Army Corps of Engineers in the mid-1980's to integrate the Universal Soil Loss Equation (USLE) with the Integrated Training Area Management (ITAM) program of the U.S. Army (2021a) with the goal of improving large-scale, areal estimates of erosion and deposition. A major shortcoming of the USLE and similar models is the one-dimensional approach used to account for the effects of topography on the erosion process. Landscapes have generally been treated as homogenous planar features, and average erosion rates have been assigned to entire hillslopes and watersheds, thus providing no information regarding within-watershed sources and sinks of eroded soil. Alternatively, complex landscapes have been computationally divided into a series of semi-homogenous planes, and erosion has been calculated separately for each plane, thus giving more consideration to slope convexity and concavity (Hoffmann Oliveira et al. 2013). In both approaches, erosion is calculated only along straight flow lines without full consideration of the influence of flow convergence and divergence that can affect soil erosion greatly (Rieke-Zapp and Nearing 2005). Neither approach provides adequate, spatially-distributed information about erosion necessary to effectively optimize erosion and sediment control efforts.

An additional significant shortcoming of the Universal Soil Loss Equation and related models is that they predict soil erosion 'universally', i.e., they do not predict sediment deposition. Thus, at landscape or watershed scales, the models tend to overestimate erosion over the entire watershed (Jensen 1983; Busacca et al. 1993). The only practical way to apply such models is to identify *a priori* those portions of the landscape subject to sediment deposition and exclude them from analysis.

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The objective of this study was to evaluate the accuracy of the USPED (Unit Stream Power Erosion and Deposition) model at Fort Campbell, Kentucky/Tennessee (Figure 1), an active U.S. Army training area subject to considerable physical disturbance. The USPED, USLE, and related models have the format of E = R x K x LS x C x P were erosion (E) is computed as the product of multiplying factors related to rainfall erosivity (R), inherent soil properties such as soil texture and chemistry (K), topographic parameters affecting soil erosion such as the length and steepness of slopes (LS), plant cover (C), and erosion prevention actions (P). The USPED model has been shown to be acceptably accurate at Eglin Air Force Base, Florida (Warren et al. 2019a) and Schofield Barracks, Hawaii (Warren and Ruzycki 2022) that receive considerably more precipitation; and at Fort Hood, Texas (Warren et al. 2019b) and Yakima Training Center, Washington (Warren et al. 2019c) that receive considerably less precipitation.

Study Area

Located astride the boundary between the states of Kentucky and Tennessee (Figure 1), U.S. Army Fort Campbell lies between Hopkinsville, Kentucky and Clarksville, Tennessee. The fort is the home of the 101st Airborne Division (Air Assault) and 160th Special Operations Aviation Regiment. Fort Campbell covers 164 square miles or 102,404 acres (~41,441 ha). Approximately 74% of the Fort is forested, whereas about 26% is non-forested. Fort Campbell lies in an area previously maintained as a semi-open land mixture by the Cherokee and other Indian tribes, and by lightning strikes. The presence of large, non-forested areas was instrumental in the selection of the area that became Fort Campbell because such terrain is important for contemporary military training doctrine. Similar areas with sparse overstory vegetation, scant understory vegetation, and often overlaid on shallow karst soils are sometimes known as barrens, glades (Bartgis 1993), or balds (Cain 1930). The terms have been used interchangeably in the southeastern USA to describe similar landscapes (Cartwright and Wolfe 2016). Part of Fort Campbell is the tiny remnant of the area that was previously known as the Big Barrens (Baskin et al. 1994), which covered southern Illinois and Ohio to northern Alabama. Sadly, as much as 99% of the Big Barrens habitat has been lost over the last two centuries by the absence of fire, the replacement of grasslands by forests, agriculture, buildings, etc. The Army maintains the semi-open landscape of the remnant parts of the of the Big Barrens by using regular, prescribed fires (U.S. Army 2022), a common practice to manage barrens habitat elsewhere in the United States (Forman and Boerner 1981; Patterson and Clarke 2007; Clark et al. 2015).

Near the western juncture of Kentucky and Tennessee is a region known simply as "the barrens" (U.S. Army 2021b). Barrens are typically areas of sparse vascular vegetation, considerable bare soil, and abundant microorganisms forming biological soil crusts that exist on the exposed bare soil (Belnap and Lange 2003). Such crusts were historically thought to be restricted to arid lands, but they are now known to occur globally on any soil that remains denuded due to aridity or disturbance (Corbin and Thiet 2020; Taft 2020). They have been shown to occur on barren lands elsewhere (Anderson and Schwegman 1991; Gilbert and Corbin 2019). Biological soil crusts occur when viruses, fungi, archaea, bacteria, terrestrial algae, and bryophytes (Shah et al. 2011; Warren et al. 2019d) bind near-surface soil particles into a consolidated surface crust that resists soil erosion (Belnap and Büdel 2016) and cycles plant nutrients (Nevins et al. 2020).

METHODS

To apply the USPED model at Fort Campbell, it was necessary to first populate all parameters of the model spatially inside a Geographic Information System (GIS) database. Because the R-factor (rainfall erosivity; MJ mm / ha hr yr) typically varies minimally across an area the size of the training area, we consulted an isoerodent map available in Renard et al. (1997) and selected an appropriate R-factor of 225.

K-factors (inherent soil properties; ton ha hr / ha MJ mm) are generally published in Natural Resources Conservation Service (NRCS) soil maps and surveys. For Fort Campbell, we selected the soil survey by the United States Department of Agriculture (2021), and assigned the appropriate K-factors for each soil series present to create a K-factor map

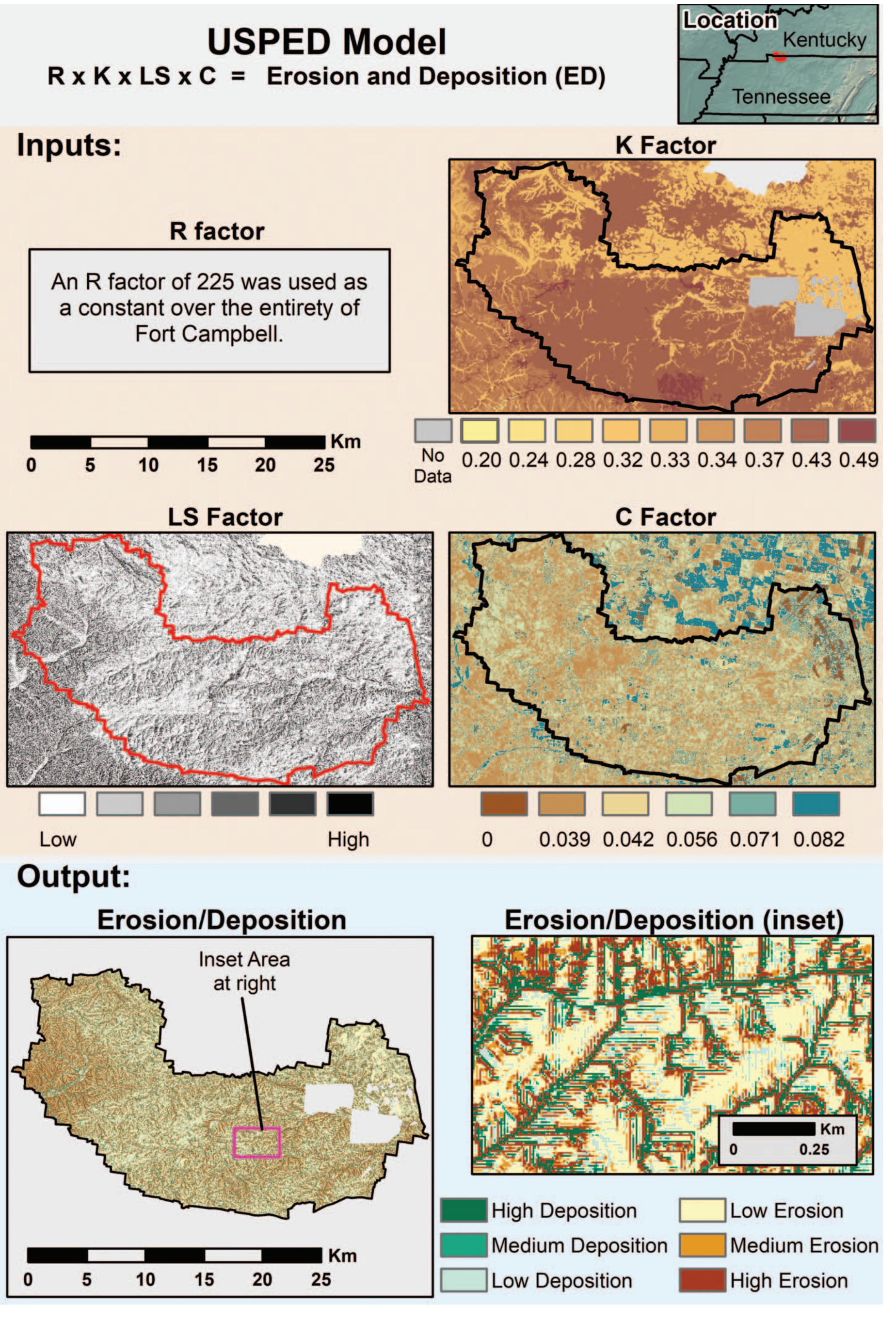

Figure 1. The spatial distribution of the USPED model components and product at Fort Campbell, KY. The map at upper-right shows the location of Fort Campbell within Kentucky and Tennessee. The computational model equation is shown with its components – R factor (rainfall erosivity, a constant), K factor (inherent soil properties), LS factor (length and steepness of slopes), and C factor (plant cover) – whose spatial distribution is shown in the maps under "Inputs". The model output for the entirety of Fort Campbell is an erosion/deposition map shown at bottom-left, color-coded to areas of low to high deposition and low to high erosion. The bottom-right map is an enlargement showing these areas with more detail.

(Figure 1). Where soil mapping units were listed as complexes of more than one component, K-factors were calculated as the weighted averages of K-factor values of the map unit components by percent of map unit composition, and this value was assigned to the entire mapping unit. Some areas at Fort Campbell had no K-factors. Those areas corresponded to artillery impact areas where the soil surveyors felt uncomfortable or unsafe to dig in the soil.

LS-factors (slope length and steepness) were calculated from the upslope contributing area and the slope steepness for each grid cell in a GIS map of Fort Campbell (Figure 1) using a digital elevation model (DEM), produced by the United States Geological Survey (2021a). The primary improvement of the USPED model versus the USLE model is how it computes the LS-factors. The USPED model substitutes an LS analog computed as $LS = A^m(\sin ß)^n$ 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 constants are usually set to $m = 1.6$ and $n = 1.3$; where sheet erosion prevails, they are both set to $m = n = 1.0$ (Moore and Wilson 1992). Because the USPED model computes both erosion and deposition (ED) as a change in sediment transport capacity across a GIS grid cell, a further calculation is required. A computationally simple formula is:

$$ED = \left(\frac{d(E\cos a)}{dx}\right) + \left(\frac{d(E\sin a)}{dx}\right)$$

where ED is the average annual soil erosion or sediment deposition and *a* is the slope aspect (in degrees) in the direction of steepest slope (Warren et al. 2000).

C-factors (plant cover; dimensionless) were determined in a two-step process. First, the Normalized Difference Vegetation Index (NDVI) was calculated spatially from an unsupervised classification of a recently-acquired, growing season, Landsat TM satellite image for Fort Campbell. A 30-m resolution, remotely-sensed image was gathered from the USGS (2021b). The range of NDVI values was separated into 6 equally-sized categories across the represented range of values. Appropriate C-factors were derived using Landsat 8 imagery for Fort Campbell, collected on 15 June 2021 (LC08_L2SP_022034_20210615_20210622_02_T1, path 22, row 34). The images were corrected for atmospheric effects by converting each scene for at-sensor radiance, and then for top of atmosphere (TOA) reflectance, using methods from Chandler et al. (2009). The normalized difference vegetation index (NDVI) was calculated (near infrared – red) / (near infrared + red) for each pixel or cell in the images. This NDVI raster dataset was then converted into a GIS polygon dataset to run a random point generator in ArcGIS.

In Step 2, ten random points were assigned into each soil erosion or sediment deposition category (10 points × 6 categories = 60 points total). These points were converted into a kml file to overlay on aerial imagery in *Google Earth*. A C-factor was then assigned to each of the NDVI categories based on visual inspection of the image and reference to a C-factor table published in Wischmeier and Smith (1978). The respective polygons of the NDVI GIS dataset were then populated with the estimated C-values. This dataset was rasterized into a C-factor layer, which was then used as an input into the USPED calculations (Figure 1).

The P-factor (erosion prevention actions; dimensionless) is not used in the USPED model because conservation support practices typically affect plant cover (e.g., grassed waterways) and topography (e.g., terraces), and because such management effects are now accounted for in a spatially distributed manner by the C and LS values of the USPED model using satellite imagery and digital elevation models (DEM), respectively. As a result, the P-factor has become largely irrelevant and is not used. Hence, it was assigned a value of 1.0 such that it had no effect on the erosion and sediment calculations.

After populating maps for each USPED parameter, the model was solved for each pixel or grid cell. The USPED erosion and deposition values were divided into six categories representing the levels of erosion or deposition typically encountered (Table 1), and an erosion/deposition (ED) data layer was created. As the purpose of the study was to assess the modeled ED (ton / ha / yr) amounts compared to observed ED amounts, it was necessary to compare modeled ED values with observations of the same. To accomplish that goal, 10 random points were assigned within each of the

Table 1. Erosion/deposition categories and descriptions used for field validation of the USPED model erosion/deposition estimates (modified from Warren et al. 2005).

CATEGORY 1 (High Erosion): >22.4 Mg $ha^{-1}yr^{-1}$(>10 tons $ac^{-1}yr^{-1}$). Signs of erosion clearly evident, including scouring, litter dams, and pedestaling of plants and surface stones. Often on sloped areas. Surface often rockier or more gravelly than non-eroded areas due to removal of fine soil particles. Runoff patterns such as rills and gullies generally present. Plant density and vigor often less than in non-eroded areas due to loss of soil fertility. Weedy species often resent, subsoils exposed, and importation of seeds via overland flow of water. When erosion occurs through deposits in channels, often more than half of the deposits eroded away.

CATEGORY 2 (Medium Erosion): 11.2–22.4 Mg $ha^{-1}yr^{-1}$(5.01–10 tons $ac^{-1}yr^{-1}$). Marginal signs of erosion generally evident, including soil scouring, litter dams, and pedestaling of plant crowns and surface stones. Surface may appear marginally rockier or gravellier than in non-eroded areas due to the loss of fine soil particles. Runoff patterns and small rills may be evident. Plant density and vigor may be lower than in non-eroded areas due to loss of soil fertility.

CATEGORY 3 (Low Erosion): 0–11.2 Mg $ha^{-1}yr^{-1}$(0–5.0 tons $ac^{-1}yr^{-1}$). Few signs of water movement and erosion. Minimal evidence of scouring, litter dams, pedestaling of plant bases and surface stones apparent. Slopes generally minor.

CATEGORY 4 (Low Deposition): 0–11.2 Mg $ha^{-1}yr^{-1}$(0–5.0 tons $ac^{-1}yr^{-1}$). 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.

CATEGORY 5 (Medium Deposition): 11.2–22.4 Mg $ha^{-1}yr^{-1}$(5.01–10 tons $ac^{-1}yr^{-1}$). Signs of deposition evident. Generally located in flatter areas at the bottoms of slopes, in swales or draws. Soil will generally be marginally deeper than surrounding areas as a result of deposition. Few rocks in the soil profile. Surface texture will tend to be silty, but sand and clay may be present depending on upslope soils. Vegetation may be marginally more robust than surrounding areas.

CATEGORY 6 (High Deposition): >22.4 Mg $ha^{-1}yr^{-1}$(>10 tons $ac^{-1}yr^{-1}$). Significant signs of deposition evident. Generally located in flatter areas at the bottoms of slopes, in swales or draws. Soil generally deeper than surrounding areas. Few rocks in the soil profile. Surface texture finer than surrounding soils. Vegetation more robust than surrounding areas due to greater water holding capacity and nutrient status of deposited fine soil particles. Gullies present in channels, but significantly less than half of the deposits should be gone.

six ED categories represented on the ED data layer (60 points total). The points were converted into a kml file to overlay on aerial imagery in *Google Earth*. We observed the satellite imagery at each point and visually assigned the actual ED values to them. Table 1 was used to assist in the visual assignment of actual erosion and deposition.

RESULTS

Based on the six possible categories of soil erosion and sediment deposition (ED), we found that the USPED model produced calculated estimates of ED that agreed with visual estimates 85% of the time (51 of 60 sample points). Based on multiple years working with remotely sensed imagery and GIS, we had previously established a threshold of acceptability for agreement of visual ED estimates and model estimates of 80%. Hence, the observed accuracy exceeded our expectations. Figure 1 illustrates the spatial distribution of the calculated ED values.

DISCUSSION

Evaluation of the accuracy of erosion models has been historically limited by the lack of long-term measured soil erosion with which to compare (Nearing and Hairsine 2011). Furthermore, comparisons have been primarily made only with sediment yield data from watershed outlets, bringing into question the reliability of such comparisons as such data does not account for the spatial variability of erosion and deposition processes within the watersheds (Jetten et al. 2003). Attempting to account for variability in watershed characteristics that affect the efficiency of sediment delivery to the watershed outlet, some researchers have employed a sediment delivery ratio (SDR) defined as the sediment yield from an area divided by the gross erosion of that same area (Lee and Kang 2013). The use of a sediment delivery ratio is a surrogate attempt to account for processes occurring within a watershed that affect sediment transport but suffers from both spatial and temporal variability (Walling 1983;

Woznicki and Nejadhashemi 2013). The use of a SDR is merely a performance factor that can vary seasonally and may produce erroneous results (Kinnell 2004).

The procedure we employed to determine the accuracy of the USPED model in this study is as novel as the model itself. The USPED model predicts both soil erosion and sediment deposition spatially and quantitatively within watersheds. We compared the spatially distributed model results with spatially distributed observations of the same variables, something rarely if ever attempted in the past. The 85% agreement is particularly encouraging.

The fact that some discrepancies existed between model results and corresponding observations suggests that further effort may be required. While it is tempting to blame discrepancies on the model itself, other factors, particularly observer error may have contributed to the discrepancies. Also, we fully acknowledge that Table 1 may not fully account for all variability in erosion/deposition conditions. Visual clues in the table correspond primarily to recent changes and may not be adequate to describe long-term variability as predicted by the USPED model. Furthermore, it is likely that the observer's opinion may have been swayed by focusing on visual clues at specific points rather than considering the entire polygon that it represented.

The level of accuracy of the USPED model was similar to comparisons of soil erosion produced by measuring levels of ^{137}Cesium, a by-product of post-WWII nuclear testing found in the soil (Warren et al. 2005). This suggests that erosion and deposition estimation, by whatever means, may not produce estimates with significantly greater accuracy. One must recall that the USPED model, as are all models, is just a 'model'. As a model of naturally occurring processes in a natural environment where all variability cannot be controlled, it is unrealistic to expect accuracies beyond about 80%. While the USPED and USLE components are designed to be long-term average representations of the respective parameters, each parameter (R, K, LS, and C) may fluctuate greatly on both a spatial and temporal basis. Hence, estimates of average annual erosion and deposition will likewise fluctuate spatially and temporally based on the parameters that feed their calculation.

In the quest to produce more accurate estimates of erosion and sedimentation, predictive models have become increasingly complex. However, there is minimal evidence that highly complex models significantly outperform simpler ones (Jakeman and Hornberger 1993; Merritt et al. 2003; Govers 2010). The USPED model is a relatively simple soil erosion and sediment deposition model that takes advantage of modern technologies such as remote sensing and digital elevation modeling to produce spatially-distributed estimates that accurately approximate visual observations of the same parameters. Such distributed estimates replace the need to make meticulous, spatially-distributed measurements to adequately reflect those processes.

CONCLUSIONS

We applied the USPED model to Fort Campbell, Kentucky/Tennessee using a novel approach in which model results were compared to visual estimates of erosion and/or sediment deposition at 60 randomly selected locations. The model results matched visual determinations of erosion and/or sediment deposition at 51 of the randomly selected points (85%), exceeding the preselected threshold of 80% which we had established for acceptability of model results.

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