Application of the Unit Stream Power Erosion and Deposition Model at Eglin Air Force Base, Florida

Steven D. Warren[1], Thomas S. Ruzycki[2], and William N. Pizzolato[3]

[1]U.S. Forest Service, Rocky Mountain Research Station, Shrub Sciences Laboratory, 735 North 500 East, Provo, UT 84604
[2]Center for Environmental Management of Military Lands, Colorado State University, 1490 Campus Delivery, Fort Collins, CO 80523-1490
[3]US Air Force, Eglin Air Force Base Natural Resources, Niceville, FL 32542

Abstract Soil erosion is a serious phenomenon which can be accelerated beyond sustainable levels by anthropogenic activities such as military training. Soil erosion modeling can be utilized in an effort to identify accelerated erosion and concomitant sedimentation before they reach unsustainable levels. Regrettably, most models are deficient in the way they account for topographic heterogeneity. While occasionally producing reasonable estimates of total soil erosion and sediment production from within a watershed, they provide no information regarding sources and sinks of eroded sediments within the watershed. Thus, placement and sizing of erosion and sedimentation control efforts can be deficient. This paper discusses the application of the new generation Unit Stream Power Erosion and Deposition (USPED) model at Eglin Air Force Base, Florida. We incorporated a novel approach that compared model results with observed soil erosion and sediment deposition at 60 spatially distributed points within the watershed. The model results agreed with spatial observational estimates 83% of the time, exceeding a pre-determined threshold of 80% agreement to define acceptability. The USPED model is relatively simple to apply. Broad application of the model by the cognizant international scientific community suggests that, despite the large number of models available, the USPED model offers valuable capabilities that are either unavailable or operationally unfeasible in other models due to data demands.

Key words Soil erosion, sediment deposition, predictive model, military training

Introduction

Soil erosion is a natural phenomenon resulting from the forces of wind and water causing the movement and removal of soil particles onto and from a landscape. The process is said to have become *accelerated* when anthropogenic factors result in more rapid and/or extensive soil erosion than would have occurred in the absence of such forces (Butzer 1974). War and military training for war can accelerate soil erosion. Tracked and wheeled vehicles compact the soil and damage or destroy both herbaceous and woody vegetation (Wilson 1988, Shaw and Diersing 1990, Thurow et al. 1993). Unpaved roadways, borrow areas utilized for roadway earthfill, and periodic vegetative clearing for test and training areas can be significant causes of soil erosion and deposition of sediments. Construction of

Corresponding author: Steven Warren, swarren02@fs.fed.us

training infrastructure such as emplacements, firing points, and targets can cause soil displacement, resulting in extensive localized damage. Soil erosion may accelerate as the soil surface becomes increasingly disturbed and protective vegetation is lost or damaged. If allowed to continue unchecked, extensive damage from gullying may occur. Such damage is costly to repair, diminishes the realism and quality of the military training experience, and jeopardizes the safety of soldiers and equipment.

Soil erosion may also create off-site impacts. Nationally, sediment is the single largest contributor to non-point source runoff pollution. As much as 92% of suspended sediments in waterways is attributable to non-point sources (Clark et al. 1985). Excessive sedimentation contributes to eutrophication of surface waters, impaired wetlands, and diminished recreational values. The financial cost of non-point source pollution in the United States has been estimated as high as $9 billion annually (Ribaudo 1992). Section 208 of the federal Water Pollution Control Act and section 319 of the 1987 amendment to the federal Clean Water Act require resource managers and planners to assess the extent of non-point source water pollution problems and to develop and implement area-wide best management practices (BMPs) to prevent water pollution from non-point sources. The 1960 Sikes Act and the 1997 Sikes Improvement Act direct the Secretary of Defense to implement conservation and rehabilitation of natural resources on military installations. Such programs allow for the sustainable, multipurpose use of natural resources and must provide public access to installations subject to military security and safety requirements.

Measuring soil erosion and resultant sediment deposition to determine when a military installation is out of compliance with regulatory mandates is difficult and subject to considerable subjectivity and error. Hence, the estimation of erosion and deposition by computerized models is frequently used. Two of the most commonly used erosion prediction models are the Universal Soil Loss Equation (USLE; Wischmeier and Smith 1978) and the Revised Universal Soil Loss Equation (RUSLE; Renard et al. 1997). At least part of the popularity of the models can be attributed to the ease with which they are applied. However, a major drawback of these and even many more complex process-based models (e.g., Water Erosion Prediction Project [WEPP], Flanagan and Nearing 1995) is the one-dimensional approach used to account for the effects of topography. 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 sources and sinks of eroded materials. Alternatively, complex landscapes have been computationally divided into 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 which can affect soil erosion. Neither approach provides adequate spatially distributed information on erosion necessary to effectively optimize erosion and sediment control efforts.

An additional significant 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,' i.e., even where deposition occurs. Thus, at landscape or watershed scales, the spatial distribution of soil erosion as predicted by these models misrepresents actual conditions, and tends 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. 1996).

The basic equation for the USLE and RUSLE models is E = R x K x LS x C x P, where E is the average annual soil erosion (ton ha^{-1} yr^{-1}), R (MJ mm (ha hr $yr)^{-1}$) represents the erosivity of local rainfall and runoff, K represents the inherent erodibility of the soil, LS is a dimensionless topographic factor based on slope length and steepness, C is a dimensionless factor representing vegetative cover, and P is a dimensionless conservation support practice factor. Values for these factors are determined from various maps, tables and nomographs based on field measurements (Haan et al. 1994, Renard et al. 1997). An important modification of the USLE/RUSLE backbone used by the USPED was derived by Moore and Burch (1986) and applied by Desmet et al. (1995) and Mitasova et al. (1996). The modification involves replacement of the slope-length (LS) factor with the upslope contributing area, which allows the model to predict increased erosion due to concentrated flow without the need to define these areas as inputs for the model *a priori*. An LS analog is computed for each grid cell as LS=Am(sinß)n, where A is the upslope contributing area per unit width, ß is the slope angle and m and n are constants that depend on the type of flow and the soil properties. 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). Moore and Burch (1986) further proposed that a modified USLE can be used as a proxy for sediment flow and sediment transport capacity. Using this concept, the USPED model computes both erosion and deposition (ED) as a change in sediment transport capacity across a GIS grid cell. In complex topography, sediment flow is represented as a bivariate vector field with the magnitude given by E and the direction given by the water flow direction. Change in sediment flow is then derived as a divergence, leading to a computationally simple formulation for estimating the net erosion or deposition rates as ED = ((E cos a)/x) + ((E sin a)/y), where a is the slope aspect (in degrees, equivalent to flow direction (Warren et al. 2000, Mitasova and Mitas 2001).

Geographic information systems (GIS) provide the capacity to more fully consider the effects of topographic complexity on soil erosion. Application of erosion models within a 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 and steepness (LS) 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). These equations 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 is calculated as the change in sediment transport capacity in the direction of flow. Collectively, the improvements to the traditional USLE/RUSLE that are based on the unit stream power theory (Moore and Burch 1986, Moore and Wilson 1992) have been named the Unit Stream Power Erosion and Deposition (USPED) model.

Study area. Eglin Air Force Base is one of the largest forested Air Force Bases in the United States, with more than 187,515 hectares (463,360 acres) of land ranges and facilities in the pan-handle of Florida and more than 224,034 km^2 (86,500 mi^2) of water ranges in the Gulf of Mexico. In 1931, the US Army Air Corps saw the potential of the sparsely populated forested areas and the vast expanse of the adjacent Gulf of Mexico. With the outbreak of war in Europe, a proving ground for aircraft armament was established at Valparaiso Bombing and Gunnery Base by 1935 and later renamed Eglin Field in 1937. The U.S. Forest Service ceded Choctawhatchee National Forest to the War Department the in 1940. During a 1992 reorganization, the Air Force Material Command was established and remains Eglin Air Force Base's parent command to this day.

Florida's panhandle climate is warm, humid-temperate and characterized by short mild winters. Average annual temperature is 19°C (67°F). Approximately half of the annual rainfall occurs during June through September as brief, intense thunderstorms (51-103 mm; 2-4 in. over 1-2 hrs). Torrential rain defined of at least 3 inches (76 mm) in a single day occurs most frequently at Niceville, FL near Eglin AFB than any other location in Florida. (Winsberg undated). Tropical disturbances can deliver a greater concentration of precipitation, but account for less than 381 mm; 15 in. every five years a tropical cyclone makes landfall across the western Florida panhandle.

Soils are primarily sands in the uplands or organic muck in bottomland floodplains. Located on the outer coastal plain, variation in elevation is modest, however, unique geomorphic features known as "steep heads" are common. Erosion by spring sapping tends to produce steep-sided U-shaped valleys with a fairly uniform width with box-like, theater-shaped, headwalls. Slopes descend 15-18 m (50 to 60 ft) toward a flat, saturated valley floor. The forests and shores of Eglin Air Force Base are at the center of one of the most biodiverse locations in North America (Stein et al. 2000). Over 50 threatened and endangered species are found on the base, including sea turtles that nest on its white-sand beaches and red-cockaded woodpeckers that thrive in its longleaf pine forests. Longleaf pine forest, a forest type reduced to 5% of its former range in the last few centuries, covers 80,937 hectares (200,000 acres) of the base. Approximately 3.5% of this area is old growth, making Eglin home to one of the most extensive old-growth longleaf pine forests in the world.

Methods

To apply the USPED model at Eglin Air Force Base, it was necessary to first populate all of the parameters inside a GIS database. Because the R-factor typically varies very little across an area the size of Eglin Air Force Base, we consulted an iso-erodent map available in Renard et al. (1997) and selected the appropriate R-factor of 580. The R-factor was considered to be generally constant across an area the size of the Eglin AFB, and with only minimal extremes in elevation.

K-factors are generally published in NRCS soil maps and surveys. For Eglin Air Force Base, we selected the soil survey at https://gdg.sc.egov.usda.gov/GDGOrder.aspx, and assigned the appropriate K-factors for each soil series present to create a K-factor map. Where soil mapping units were listed as complexes of more than one component, K-factor data were calculated as the weighted average 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.

LS-factors were calculated from the upslope contributing area and slope steepness for each GIS grid cell in a map of Eglin AFB using a digital elevation model (DEM). A digital elevation model (DEM) produced by the US Geological Survey and found at the National Elevation Database (http://ned.usgs.gov/) was used to derive these parameters for each raster pixel or grid cell. The grid cell resolution was 10 m. Based on visits to Eglin AFB, it was determined that sheet erosion predominated. Therefore, both the m and n constants were set to 1.0 and the LS equation was solved for each grid cell in the DEM to produce an LS data layer.

C-factors 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 Eglin AFB. A 30-m resolution remotely-sensed image was available at https://earthexplorer.usgs.gov. 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 Eglin AFB. The image was collected on 6 Jun 2011. The image was corrected for atmospheric effects by converting each scene, first 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 image. This NDVI raster dataset was then converted into a GIS polygon dataset to run a random points generator in ArcGIS. Ten points were randomly assigned into each category (10 points x 6 categories = 60 total points total). These points were converted into a kml file and given to a soil erosion expert to overlay on aerial imagery in Google Earth. The erosion expert then approximated the C-factor of 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.

The P-factor 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, respectively, of the USPED model using satellite imagery and digital elevation models (DEM), respectively. The P-factor has become largely irrelevant and is not used in the USPED model**.** Hence, it was assigned a value of 1.0 such that it had no effect on the erosion and sediment calculations.

After populating map layers for each USPED parameter (the R layer was a constant, the K and LS layers were 10 m resolution, the C layer was derived from 30 m Landsat imagery but was resampled to 10 m resolution), the model was solved for each pixel or cell. The USPED erosion and deposition values were divided into six categories representing levels of erosion or deposition (Table 1), and an erosion/deposition (ED) data layer was created (at 10 m resolution). As the purpose of the study was to assess the modeled ED levels compared to the actual ED, 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 six ED categories represented on the ED data layer (60 points total). The points were converted into a kml file and given to the field soil erosion expert to overlay on aerial imagery in Google Earth. The erosion expert then observed the satellite imagery at each point and visually estimated the actual ED values for

Table 1. Erosion/deposition categories used for field validation of the USPED erosion/deposition estimates at Eglin Air Force Base, FL (modified from Warren et al. 2005).

CATEGORY 1 (High Erosion): >22.4 Mg ha^{-1} yr^{-1} (> 10 ton ac^{-1} yr^{-1}) soil erosion. Significant signs of erosion evident including scouring, rilling and gullying, litter dams, and pedestaling of plant crowns and surface stones. Often on sloping areas. Surface often rockier or more gravelly than uneroded areas due to removal of fine soil particles. Runoff patterns evident. Density and vigor of plants often lower than uneroded areas due to loss of soil fertility. More weedy species present 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 should be eroded away.

CATEGORY 2 (Moderate Erosion): 11.4-22.4 Mg ha^{-1} yr^{-1} (5.01 – 10 ton ac^{-1} yr^{-1}) soil erosion. Signs of erosion evident. Scouring, litter dams, and some pedestaling of plant crowns and surface stones may be evident. Surface may appear marginally more rocky or gravelly 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.

CATEGORY 3 (Low Erosion) 0-11.2 Mg ha^{-1} yr^{-1} (0 – 5.0 ton ac^{-1} yr^{-1}) soil erosion. Few signs of water movement and erosion. Some signs of scouring and litter dams may be present. Minimal pedestaling of plant bases and surface stones. Slopes generally minor. Generally, not present in channels.

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

CATEGORY 5 (Moderate Deposition) 11.2-22.4 Mg ha^{-1} yr^{-1} (5.01 – 10 ton ac^{-1} yr^{-1}) sediment deposition. 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 due to sediment 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 tend to be marginally more robust than surrounding areas.

CATEGORY 6 (High Deposition) > 22.4 Mg ha^{-1} yr^{-1} (>10 ton ac^{-1} yr-1) sediment deposition. 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 may be present in channels, but less than half of the deposits should be gone.

each point. Table 1 was used to assist in the visual estimation of actual erosion and deposition. The ED values determined by the USPED model agreed with observed estimated of ED 83% of the time.

Results

Being familiar with errors inherent in global positioning technology and with human observational bias and error, the research team previously determined that agreement between the ED values produced by the USPED model and the observer would be acceptable at 80%. While not perfect, the actual agreement of 83% exceeded the pre-determined threshold. In almost all cases, the observed values of soil erosion and sediment deposition were less than modeled values. The discrepancies were due, at least in part, to the very high sand content of the soil. Finer soil particles are lighter weight and more readily eroded than sand. Hence, loamy soils, with which the erosion expert was more accustomed, tend to be quicker to exhibit evidence of soil erosion than sandy soils. The lower levels of soil

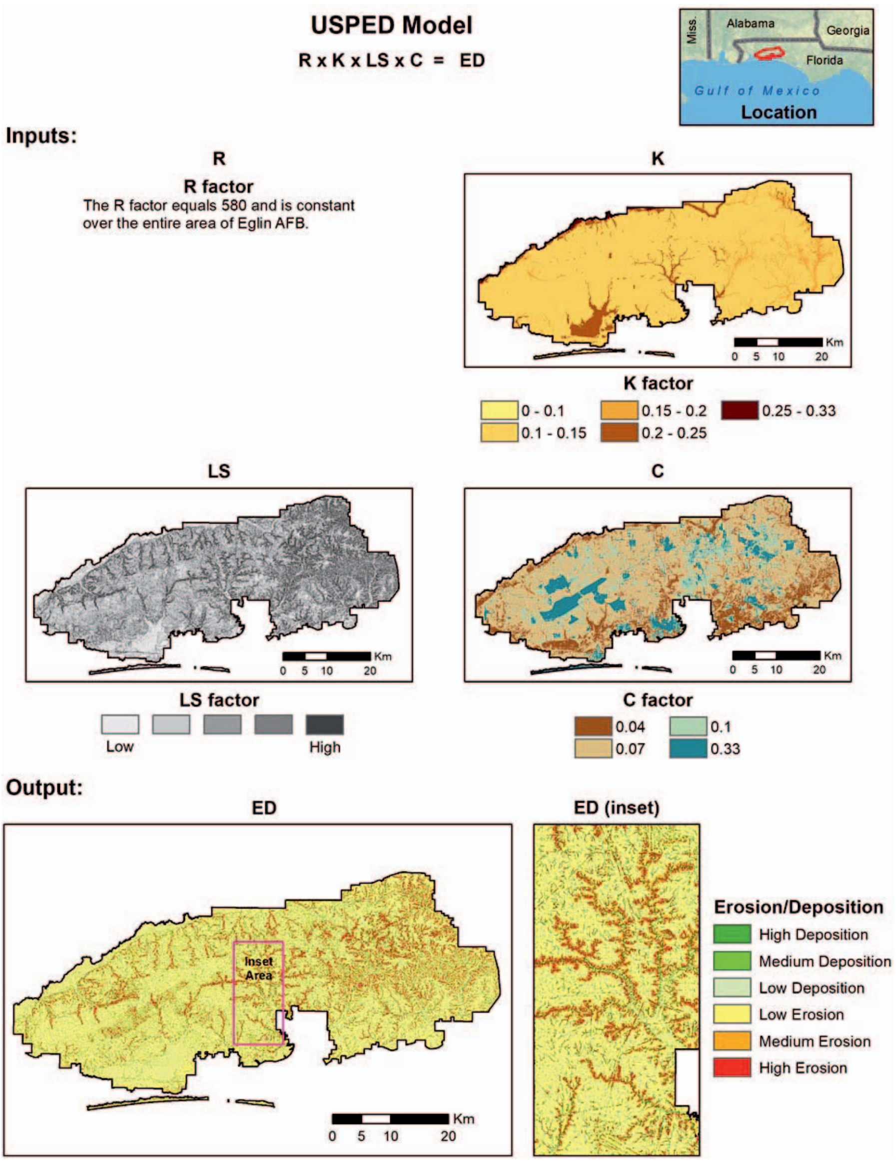

Figure 1. USPED model results and essential components for Eglin Air Force Base, Florida.

erosion and sediment deposition found at Eglin Air Force Dase far exceeded higher levels of the same parameters (Figure 1).

Discussion

The evaluation of the accuracy of erosion models has been historically been limited by the lack of long-term measured soil erosion (Nearing and Hairsine 2011).

Furthermore, comparisons have been made only with sediment yield data from watershed outlets, bringing into question the reliability of such comparisons because such data seldom considers spatial variability of erosional and depositional processes within the watersheds (Jetten et al. 2003). The procedure we employed to determine the accuracy of the USPED model in this study is as revolutionary 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 attempted in the past. The 83% sgreement 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 errors. We fully acknowledge that Table 1 may not fully account for all variability. Visual clues in the table may correspond to recent changes and may be inadequate to describe long-term changes 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 the specific point rather than considering the entire polygon that it represented.

In the quest to produce more and more accurate erosion models, the models have become more complex. However, there is minimal evidence that highly complex models significantly outperform simpler ones (Jakeman and Hornberger 1993, Merritt et al. 2003, Govers 2011). The USPED model is a relatively simple soil erosion and sediment model that takes advantage of modern technology such as remote sensing and digital elevation modelling to produce spatially distributed estimates of soil erosion and sediment deposition that accurately approximate visual observations of the same parameters most of the time.

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