Steven D. Warren[1], US Forest Service, Rocky Mountain Research Station, 735 N 500 E, Provo, Utah 84604

Thomas S. Ruzycki, Center for Environmental Management of Military Lands, Colorado State University, 1490 Campus Delivery, Ft. Collins, Colorado 80523

Robert Vaughan, Redcastle Resources, Inc., 644 17th Avenue, Salt Lake City, Utah 84103

and

Peter E. Nissen, US Army, Joint Base Lewis-McChord Yakima Training Center, Directorate of Public Works—Environmental Division, 970 Firing Center Road, Yakima, Washington 98908

Validation of the Unit Stream Power Erosion and Deposition (USPED) model at Yakima Training Center, Washington

Abstract

During the last seventy years, numerous models have been developed to predict soil erosion; some models also predict concomitant sediment deposition. All have been proven inadequate and/or inaccurate in one respect or another. This paper discusses the application of the new-generation Unit Stream Power Erosion and Deposition (USPED) model at the US Army's Yakima Training Center (YTC), Washington. We incorporated a novel approach that compares model results with observed soil erosion and sediment deposition across the landscape in a spatially distributed fashion. The model results matched visually estimated values 90% of the time, providing an encouraging validation of the model. Historically, erosion models have been compared with sediment outflow from watersheds, providing no information regarding sources and sinks of erosion and deposition within watersheds. The USPED model is relatively simple to apply and the validation approach provides information in terms of 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.

Keywords: accuracy assessment, sediment deposition, soil erosion, USPED model, Yakima Training Center

Introduction

Scientific models are often used to approximate, predict, or represent natural processes, behaviors, or consequences based on observations or measurements of related phenomena where frequent or precise measurement is not feasible. One such natural process is soil erosion and concomitant sediment deposition. Soil erosion affects the quality of soil and its capacity to yield a productive vegetative cover (Verity and Anderson 1990) and causes significant environmental degradation and economic costs (Pimentel 2006). In the United States, attempts have been made over the past seven decades to describe and model the soil erosion process (Laflen and Flanagan 2013). Numerous models have been developed, attempting to fully and accurately explain and represent soil erosion and to predict its consequences (Harmon and Doe 2001). The models have been both empirical and process-based and have become increasingly complex, yet none have achieved their goal of 100% accuracy in predicting soil erosion and sediment deposition.

Among the earliest, most popular, and widely-used empirical erosion models are the Universal Soil Loss Equation (USLE; Wischmeier and Smith 1978) and the Revised Universal Soil Loss Equation (RUSLE; Renard et al. 1997). 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. A major drawback, however, of these and

[1] Author to whom correspondence should be addressed.
Email address: swarren02@fs.fed.us

even many 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 within the watershed. Alternatively, landscapes have been computationally divided into a 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 most existing erosion models is that they predict soil erosion only and do not predict sediment deposition. Furthermore, most models predict erosion even where deposition may occur. Thus, at landscape or watershed scales, soil erosion, as predicted by these models, likely misrepresents actual conditions and tends to overestimate erosion (e.g., 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 deposition and exclude them from analysis (Mitasova et al. 1997).

Geographic information systems (GIS) provide the capability to at least consider the effects of topographic complexity on soil erosion. 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 considered by determining the upslope area that contributes to flow across each point in the watershed, not just along straight lines. When the upslope contributing area is substituted for slope length, the resulting LS analog is equivalent to the traditional LS factor on planar surfaces but is applicable to complex slope geometries (Moore and Burch 1986, Moore and Wilson 1992). Equations for the computation of the LS analog, based on upslope contributing area, have been developed by Mitasova et al. (1996) and 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. The improved equation has been named the Unit Stream Power Erosion and Deposition (USPED) model (Warren et al. 2005).

The basic equation for the USPED model is

$$E = R \times K \times LS \times C \times P$$

where average annual sheet and rill erosion (E; Mg ha^{-1} yr^{-1} or tons ac^{-1} yr^{-1}) is estimated as the product of the component factors. Values for these factors are determined from various maps, tables and nomographs (Renard et al. 1997). The USPED model substitutes the LS analog computed as

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

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 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

$$ED = (d (E \cos a) / dx) + (d (E \sin a) dx)$$

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

The objective of the present study was to validate the USPED model at Yakima Training Center (YTC), Washington, an actively used US Army maneuver training area. Evaluation of the accuracy of erosion models has been historically limited by the lack of long-term measured erosion data with which to compare model results (Hseih et al. 2009), tremendous variability in that data (Nearing and Hairsine 2011), and the fact that, even when that data is available, comparisons do not account for spatial variability of erosion and deposition processes within watersheds (Jetten et al. 2003). We used an alternative method of accuracy evaluation that compares spatially distributed erosion and sediment deposition estimates with observations of average long-term soil erosion and sediment deposition rates at the same points. We hypothesized that the model predictions would match observed levels of soil erosion and/or deposition at least 80% of the time, recognizing that actual observations and measurements may vary due to uncontrollable and unquantifiable variables inherent in natural settings.

Methods

Study Area

Field work for the effort was conducted at the Yakima Training Center (YTC), Washington. In 1951 the Army purchased approximately 105,623 hectares (261,000 acres) for the Yakima Firing Center, which would become the modern Yakima Training Center. Today the YTC comprises approximately 132,332 hectares (327,000 acres) used for a maneuver and live-fire training. The training center is located in the south-central portion of the state of Washington. It is bounded on the west by Interstate 82, on the south by the city of Yakima, on the north by the city of Ellensburg and Interstate 90, and on the east by the Columbia River. YTC consists primarily of shrub-steppe, making it one of the largest areas of shrub-steppe habitat remaining in state of Washington. The terrain is undulating, which is common for shrub-steppe. Vegetation consists of sagebrush, bitterbrush, and bunchgrass. Most precipitation falls during the winter as snow. Temperatures range from less than –17 °C (0 °F) in the winter to above 38 °C (100 °F) in the summer. Elevation ranges from 152 to 1,285 m (500 to 4,216 ft). Variation in local relief contributes to considerable variation in wind and temperature over short distances. Weather is modified by the Cascade Mountains to the west and the Rocky Mountains to the east. Winds are generally light with speeds averaging less than 16 kph (10 mph). Prevailing wind is from the west in the winter and from the west-northwest in the summer. Summers are sunny with clear skies 80 percent to 85 percent of the time. Soils are highly variable having been derived from alluvial deposits, glaciofluvial deposits, loess, fine interbedded sediment, and residuum and colluvium derived from basalt and loess (USDA Natural Resources Conservation Service 2006).

Model Parameters and Observation Data

The precipitation or rainfall (R-factor) for YTC was determined to have a value of 10 as derived from an isoerodent map available in Renard et al. (1997). The R-factor is generally constant across an area the size of the YTC, and with only moderate extremes in elevation.

The inherent soil erodibility (K-factors) for each soil map unit on YTC was derived from digital spatial and tabular soils data derived from USDA Natural Resources Conservation Service (2018). Where soil mapping units were listed as complexes of more than one component, K-factors were calculated as weighted averages of map unit components, and this value was assigned to the entire mapping unit.

The length and steepness of slopes (LS-factor analog) utilized by the USPED incorporates the upslope contributing area and slope steepness. A digital elevation model (DEM) produced by the US Geological Survey (2018) was used to derive the LS-factor parameters for each raster pixel or grid cell. The grid cell resolution was 10 m. Based on visits to the training area, it was empirically determined that sheet erosion predominated at YTC. 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 a LS data layer.

Appropriate plant cover (C-factors) were derived using Landsat 8 imagery for YTC. Two images collected on 10 June 2013, LC80450272013161LGN00 (path 45, row 27) and LC80450282013161LGN00 (path 45, row 28), were used. The images were 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 scenes were then mosaicked together and clipped to the edge of the USGS Hydrologic Unit Code 12 watershed boundaries that include YTC. The normalized difference vegetation index (NDVI) was calculated (near infrared – red)/(near infrared + red) on the resulting image. The NDVI GIS dataset was clipped to the YTC boundary and then reclassed into 6 classes of approximately equal area. This NDVI raster dataset was then converted into a GIS polygon dataset to run a random points generator in ArcGIS. Ten points were randomly placed into each of the six classes for a total of 60 points. To ensure that the points fell entirely within the polygons, they were not allowed to fall within 10 meters of polygon boundaries. These points were converted into a kml file and overlayed on aerial imagery in Google Earth. C-factors for each of the 6 NDVI categories were made based on visual inspection of the image and reference to C-factors published in Wischmeier and Smith (1978). The polygons of the NDVI GIS dataset were populated with the estimated C-factors. This dataset was rasterized into a C-factor layer, which was used as an input into the USPED calculations.

Conservation support factors such as contour furrows and terraces are generally not compatible with military training exercises and are seldom used on maneuver training areas. Hence, the P-factor was assigned a value of 1.0 such that it had no effect on the erosion and sediment calculations. The remaining factors were multiplied together on a cell-by-cell basis to create a spatially distributed ED data layer.

The USPED values were divided into six categories representing levels of erosion or deposition (Table 1), and an ED data layer was created. As the purpose of the study was to compare modeled ED levels with actual observed ED, it was necessary to make field observations within the modeled ED levels. To accomplish that goal, 10 random points were assigned within each of the six ED categories represented on the ED data layer (60 points). To ensure that the points fell entirely within polygons representing the ED categories, they were not allowed to fall within 10 meters of the boundary of the polygons. These points were also converted into a kml file and overlaid on aerial imagery in Google Earth. We navigated within the imagery to the points and visually estimated the actual ED values for each point. Table 1 was used to assist in the visual estimation of actual erosion and deposition. The team had previously determined that an 80% agreement between the ED values calculated by the USPED equation and the actual levels of observed ED, while not perfect, would be acceptable agreement between the calculated ED and the observed ED.

Results

Using the six categories of erosion and deposition (ED), we found that the USPED model produced ED estimates that agreed with field observations 54 of 60 times or 90% of the time. As the predetermined threshold for acceptability was 80%, the accuracy of the USPED model was more than acceptable. Moreover, even among USPED estimates that did not agree with field estimates, few were incorrect by more than a single category. Figure 1 illustrates the spatial distribution of the 6 ED categories at Yakima Training Area.

Discussion

Historically, evaluation of the accuracy of erosion models has been limited by the lack of long-term measured erosion data with which to compare model results and the tremendous variability found in that data (Nearing and Hairsine 2011). Furthermore, comparisons have mostly been made with sediment yield data from watershed outlets. Hence, erosion prediction has been only moderately successful, at least partially because such approaches do not account for spatial variability of erosional and depositional processes within watersheds (Jetten et al. 2003). The methodology employed to determine the accuracy of the USPED model in this study is as novel as the model itself, i.e., the USPED model predicts soil erosion and sediment deposition both spatially and quantitatively within watersheds. We compared spatially distributed model estimates of soil erosion and sediment deposition with spatially distributed observations of the same variables, something that has seldom, if ever, been attempted previously. The 90% agreement is particularly encouraging

TABLE 1. Erosion/deposition categories and descriptions used for field validation of the USPED 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}) soil erosion. Significant signs of erosion generally evident, including scouring of the soil surface, litter dams, and pedestaling of plant crowns and surface stones. Often on sloped areas. Surface often significantly rockier or gravellier than uneroded areas due to removal of fine soil particles. Runoff patterns such as rills and gullies generally present. Density and vigor of plants often lower than in 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 will be eroded away.
CATEGORY 2 (Medium Erosion): 11.2–22.4 Mg ha^{-1} yr^{-1} (5.01–10 tons ac^{-1} yr^{-1}) soil erosion. Marginal signs of erosion generally evident, such as scouring, litter dams, and some pedestaling of plant crowns and surface stones. Surface may appear marginally rockier or gravellier than uneroded areas due to the loss 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 tons ac^{-1} yr^{-1}) soil erosion. 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}) 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.
CATEGORY 5 (Medium Deposition): 11.2–22.4 Mg ha^{-1} yr^{-1} (5.01–10 tons 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 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}) 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 significantly less than half of the deposits should be gone.

and supports earlier evidence of the model validity (Warren et al. 2005).

The fact that some discrepancies existed between some model results and corresponding observations suggests that efforts be made to identify the causes of the apparent errors. While it is tempting to blame errors on the USPED model itself, other factors, particularly observer error, may have been at fault. It is possible that some error arose from inaccurate observer placement of erosion and deposition into the appropriate categories. In some cases, our reliance on visual approximations of ED compared to Table 1 may have been incorrect. In addition, a likely source of erroneous assignment to an ED class may have resulted where and when our opinion of ED was swayed by assigning over-emphasis on visual clues at a single point within a polygon rather than giving equal weight to the entire polygon under consideration.

In the quest to achieve greater accuracy, erosion models have become increasingly complex. However, there is minimal evidence that complex models outperform simpler models (Jakeman and Hornberger 1993, Merritt et al. 2003, Govers 2011). The USPED model is a relatively simple

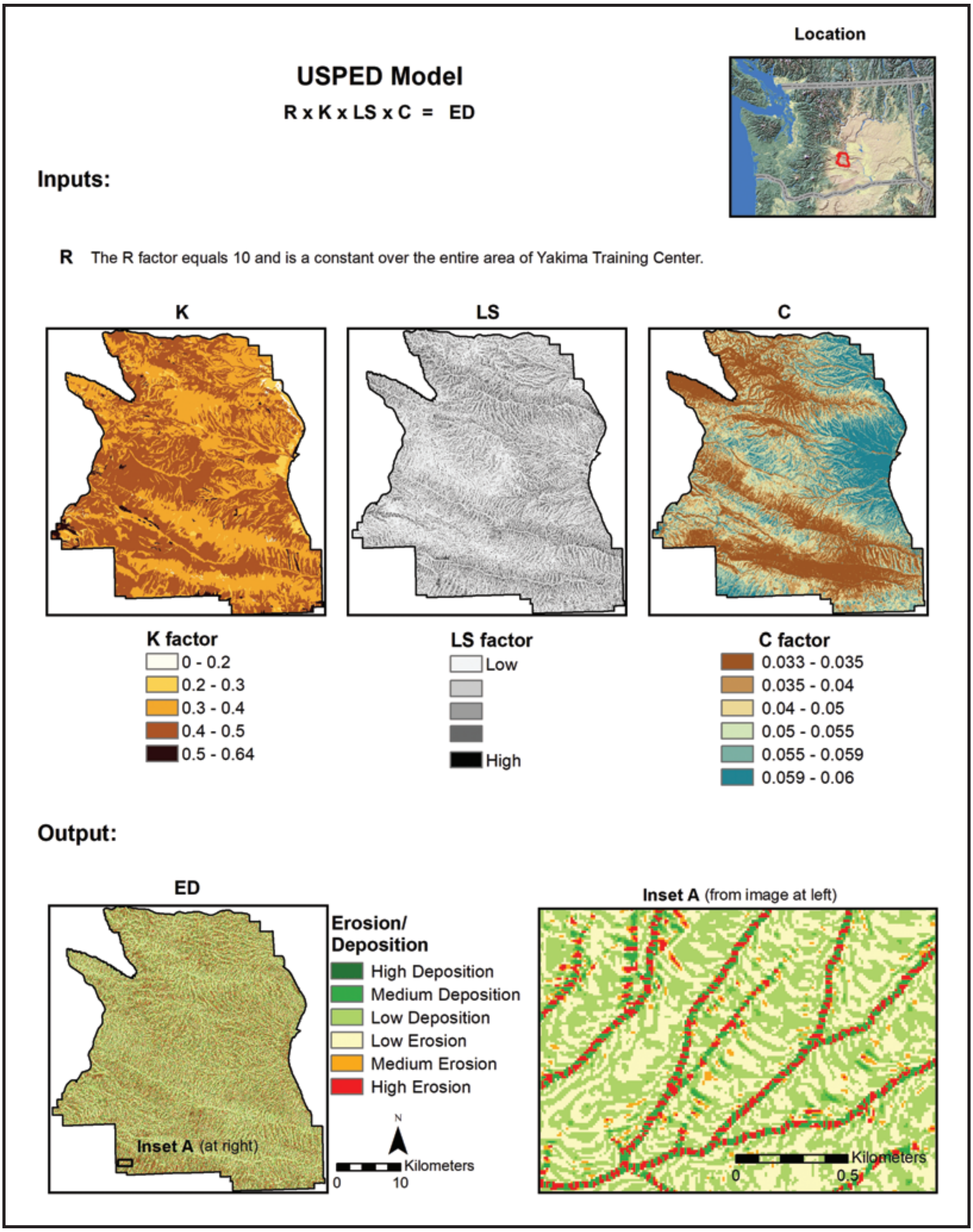

Figure 1. The Unit Stream Power Erosion and Deposition (USPED) model was applied at Yakima Training Center (YTC), Washington using satellite imagery from 7/23/2011. The USPED model formula is shown in the upper center. The location of the training center is depicted in the upper right. Values for the equation parameters (R, K, LS, C) are shown in the center row, where Erosion and Deposition (ED) is a product of factors: R (rainfall and runoff erosivity), K (inherent soil erodibility), LS (length and steepness of slope), and C (plant cover); (see text for a description of how they were derived). The model output, which was compared to visual estimates is shown at the bottom with a higher resolution inset (A) showing greater detail of erosion and deposition patterns at the lower right. The model produced values that matched visual estimates 90% of the time.

model that takes advantage of modern technologies, especially remote sensing and digital elevation modeling, to produce estimates of spatially distributed erosion and deposition that accurately approximate field observations most of the time.

The ability to accurately predict the extent and spatial distribution of soil erosion and sediment deposition provides significant advantages over many other models. The ability to identify where and how much erosion or deposition is taking place in a watershed can provide focus on where to attack the problems and avoid misdirected and costly erosion and deposition control measures that are misplaced, inappropriately sized, or otherwise ineffective.

Literature Cited

Busacca, A. J., C. A. Cook, and D. J. Mulla. 1993. Comparing landscape-scale estimation of soil erosion in the Palouse using Cs-137 and RUSLE. Journal of Soil and Water Conservation 48:361-367.

Chandler, G., B. L. Markham, and D. L. Helder. 2009. Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. Remote Sensing of Environment 24:459-479.

Flanagan, D. C., and M. A. Nearing, editors. 1995. USDA Water Erosion Prediction Project: hillslope profile and watershed model documentation. National Soil Erosion Research Laboratory Report No. 10. US Department of Agriculture, Agriculture Research Service, West Lafayette, IN.

Foster, G. R., and W. H. Wischmeier. 1974. Evaluating irregular slopes for soil loss prediction. Transactions of the American Society of Agricultural Engineering 17:305-309.

Govers, G. 2011. Misapplications and misconceptions of erosion models. *In* R. P. C. Morgan and M. A. Nearing (editors), Handbook of Erosion Modelling. Wiley-Blackwell Publishing, Chichester, UK. Pp. 117-134.

Harmon, R. S., and W. W. Doe, editors. 2001. Landscape erosion and evolution modeling. Kluwer Academic, New York.

Hsieh, Y. P., K. T. Grant, and G. C. Bugna. 2009. A field method for soil erosion measurements in agricultural and natural lands. Journal of Soil and Water Conservation 64:374-382.

Jakeman, A. J., and G. M. Hornberger. 1993. How much complexity is warranted in a rainfall-runoff model? Water Resources Research 29:2637-2649.

Jensen, M. E. 1983. Applicability of the Universal Soil Loss Equation for southeastern Idaho wildlands. Great Basin Naturalist 43:579-584.

Jetten, V., G. Govers, and R. Hessel. 2003. Erosion modelling: quality of spatial predictions. Hydrological Processes 17:887-900.

Laflen, J. M., and D. C. Flanagan. 2013. The development of US soil erosion prediction and modeling. International Soil and Water Conservation Research 1:1-11.

Merritt, W. S., R. A. Letcher, and A. J. Jakeman. 2003. A review of erosion and sediment transport models. Environmental Modeling and Software 18:761-799.

Mitasova, H., J. Hofierka, M. Zlocha, and L. R. Iverson. 1996. Modelling topographic potential for erosion and deposition using GIS. International Journal of Geographical Information Systems 10:629-641.

Mitasova, H., J. Hofierka, M. Zlocha, and L. R. Iverson. 1997. Reply to comment by Desmet and Govers. International Journal of Geographic Information Systems 11:611-618.

Moore, I. D., and G. Burch. 1986. Physical basis of the length-slope factor in the Universal Soil Loss Equation. Soil Society of America Journal 50:1294-1298.

Moore, I. D., and J. P. Wilson. 1992. Length-slope factors for the revised universal soil loss equation: simplified method of estimation. Journal of Soil and Water Conservation 47:423-428.

Nearing, M. A., and P. B. Hairsine. 2011. The future of soil erosion modelling. *In* R. P. C. Morgan and M. A. Nearing (editors), Handbook of Erosion Modelling. Wiley-Blackwell Publishing, Chichester, UK. Pp. 389-397.

Pimentel, D. 2006. Soil erosion: a food and environmental threat. Environment, Development and Sustainability 8:119-137.

Renard, K. G., G. R. Foster, G. A. Weesies, D. K. McCool, and D. C. Yoder. 1997. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook 703. United States Department of Agriculture, Washington, DC.

USDA Natural Resources Conservation Service. 2006. Soil Survey of Yakima Training Center, parts of Kittitas and Yakima counties, Washington. US Department of Agriculture, Washington, DC.

USDA Natural Resources Conservation Service. 2018. SSURGO by State. US Department of Agriculture, Washington, DC. Available online at https://nrcs.app.box.com/v/soils/folder/64615474196 (accessed 15 June 2018).

US Geological Survey. 2108. The National Map. USGS National Geospatial Program, Reston, VA. Available online at https://www.usgs.gov/core-science-systems/national-geospatial-program/national-map (accessed 15 June 2018).
Verity, G. E., and D. W. Anderson. 1990. Soil erosion effects on soil quality and yield. Canadian Journal of Soil Science 70:471-484.
Warren, S. D., H. Mitasova, M. R. Johnson, W. M. Brown, B. E. Johnson, D. M. Johnston, P. Y. Julien, L. Mitas, D. K. Molnar, and C. C. Watson. 2000. Digital terrain modeling and distributed soil erosion simulation/measurement for minimizing environmental impacts of military training. Center for Ecological Management of Military Lands Technical Publication Series TPS 00-14. Colorado State University, Ft. Collins.
Warren, S. D., H. Mitasova, M. G. Hohmann, S. Landsberger, F. Y. Iskander, T. S. Ruzucki, and G. M. Senseman. 2005. Validation of a 3-D enhancement of the Universal Soil Loss Equation for prediction of soil erosion and sediment deposition. Catena 64:281-296.
Wischmeier, W. H., and D. D. Smith. 1978. Predicting rainfall erosion losses—a guide to conservation planning. Agricultural Handbook 537. United States Department of Agriculture, Washington, DC.

Received 02 February 2018
Accepted 13 December 2018