



Research Article



Validation of the Unit Stream Power Erosion and Deposition (USPED) Model at Fort Hood, Texas

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Abstract

Soil erosion has been recognized as a significant environmental malady in the United States for over 200 years. Numerous attempts have been made to model and quantify the issue, yet significant issues remain that hinder the accuracy and effectiveness of such models. This manuscript describes an attempt to model soil erosion and concomitant sedimentation with the Unit Stream Power Erosion and Deposition (USPED) model at an active military training installation. The model accurately determined both soil erosion and sediment deposition on a spatial basis at 83% of 60 randomly assigned points where model estimates were compared to visual estimates. While not perfect, the USPED model estimates exceeded a predetermined threshold of 80% established, recognizing that model estimates represent long-term estimates while visual estimates are based on recent conditions only.

Introduction

Soil erosion has been recognized as a significant issue in the United States for over two centuries [1]. During the 1940's and 1950's, research scientists began to develop a quantitative procedure for estimating soil loss, and several factors including slope steepness and management practices that affected soil erosion were identified. Consequently, the Universal Soil Loss Equation (USLE) was developed [2] and later reissued [3]. With widespread acceptance, the USLE has become a major conservation planning tool which is widely used in the United States and other countries in the world. With additional research, experiments, data, and resources, the Revised Universal Soil Loss Equation (RUSLE) was issued [4]. The RUSLE has the same formula as USLE, but has several improvements in determining factors, including revised isoerodent maps; a time-varying approach for soil erodibility factor; a subfactor approach for evaluating the cover-management factor; a new equation to reflect slope length and steepness; and new conservation-practice values. Despite the contribution of the RUSLE model, numerous deficiencies still exist and process-based alternatives have been developed, e.g., the Water Erosion Prediction Project [5].

A major shortcoming of these and even many more complex process-based models 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 within-watershed 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 [6]. 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 on the entire watershed [7,8]. 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 [9].

The basic equation for the USLE and RUSLE models is $E = R \times K \times LS \times C \times P$, where E is the average annual soil erosion (metric ton $ha^{-1} yr^{-1}$), R ($MJ mm ha^{-1} hr^{-1} yr^{-1}$) represents the erosivity of local rainfall and runoff, K (metric ton $ha hr ha^{-1} MJ^{-1} mm^{-1}$) 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 [3,10]. Values for these factors are determined from various maps, tables and nomographs based on field measurements [4,11]. An important modification of the USLE/RUSLE backbone used by the USPED was derived by Moore and Burch [12] and applied by Desmet et al., [13] and Mitasova et al., [14]. 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 $LS = A^m (\sin \beta)^n$, where A is the upslope contributing area per unit width, β 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 $m=n=1.0$ [15,16]. Moore and Burch [12] 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 [17,18]).

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 [19,20]. 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 [12,15]. Equations for the computation of the LS -factor based on upslope contributing area have been developed by Desmet and Govers [21] and Mitasova et al., [14]. 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) [17]. 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 [12]; Moore and Wilson [15]) have been named the Unit Stream Power Erosion and Deposition (USPED) model.

The present manuscript describes the application and testing of the USPED model at Fort Hood, Texas, an active military training installation. As with most training installations, portions may be badly damaged, while other portions are scarcely impacted [22], primarily because some areas are conducive to military training doctrine while others are not [23].

Study Area

Fort Hood, Texas was the site selected for this study. The Fort was established in 1942 in an effort to counter German mobile armored units in World War II. It comprises 88,555 hectares (218,823 acres) in central Texas and has played a significant training role in every major military operation since World War II. Fort Hood is home to two armored divisions that conduct heavy maneuver training across the installation's landscape. It is located in portions of Bell and

Coryell Counties in the northern Edward's Plateau. The climate is characterized by long, hot summers and short, mild winters. Average monthly temperatures range from a low of about 1°C (34°F) in January to a high of 36°C (96°F) in July. Precipitation has two major seasonal peaks: the largest during April and May and the smaller one in September. The landscape is characterized by stair step topography of a dissected remnant plateau. Numerous steep sloped hills and ridgelines rise above the flat to gently rolling plains. The benching is the result of erosion resistant limestone cap rocks of the plateau and mesa-hill structures. The formations are generally composed of massive, structurally sound limestone or a mix of limestone shale known as marl, which crumbles and weathers. Soil is generally shallow to moderately deep, clayey, underlain by limestone bedrock. Elevation ranges from 180 to 375 m (590 to 1230 ft) above sea level with 50 percent of the area below 260 m (853 ft). Vegetation is composed of oak woodlands with grass undergrowth. The oak woodlands are dominated by live oak (*Quercus virginiana*), Texas oak (*Quercus buckleyi*) and Ashe juniper (*Juniperus ashei*). The grasses are dominated by little bluestem (*Schizachyrium scoparium*), Indiangrass (*Sorghastrum nutans*) and the invasive King Ranch bluestem (*Bothriochloa ischaemum* var. *songarica*) in many areas.

Methods

To apply the USPED model at Fort Hood, 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 Fort Hood, we consulted an isoerodent map available in Renard et al., [4] and selected the appropriate R-factor of 270. The R-factor was considered to be generally constant across an area the size of Fort Hood, and with only minimal extremes in elevation.

K-factors are generally published in Natural Resources Conservation Service (NRCS) soil maps and surveys. For Fort Hood, 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 Fort Hood using a Digital Elevation Model (DEM). A digital elevation model 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 10m. Based on visits to Fort Hood, 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 a 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 Fort Hood. 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 Fort Hood. Two images were necessary to cover the study area. The images were collected on 31 Aug 2013: (LC80270382013243LGN00, path 27, row 38) and (LC80270392013243LGN00: path 27, row 39). 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., [24]. 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. Ten points were randomly assigned into each category (10 points x 6 categories = 60 total points). 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 [3]. 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.

Results

After populating maps for each USPED parameter, 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. 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,

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. In an attempt to account for variability in watershed characteristics that affect the efficiency of sediment delivery to the watershed outlet, some researchers have attempted to employ a Sediment Delivery Ratio (SDR) defined as the sediment yield from an area divided by the gross erosion of that same area. The use of a sediment delivery ratio is a surrogate attempt to account for processes occurring within

Category 1 (High Erosion): > 22.4 Mg ha⁻¹ yr⁻¹ (> 10 ton 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 present, 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 ton 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 gravelly 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 ton 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 ton 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 ton 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 ton 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.

Table 1: Erosion/deposition categories and descriptions used for field validation of the USPED erosion/deposition estimates [25].

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 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, indicating good, although not perfect agreement (Figure 1).

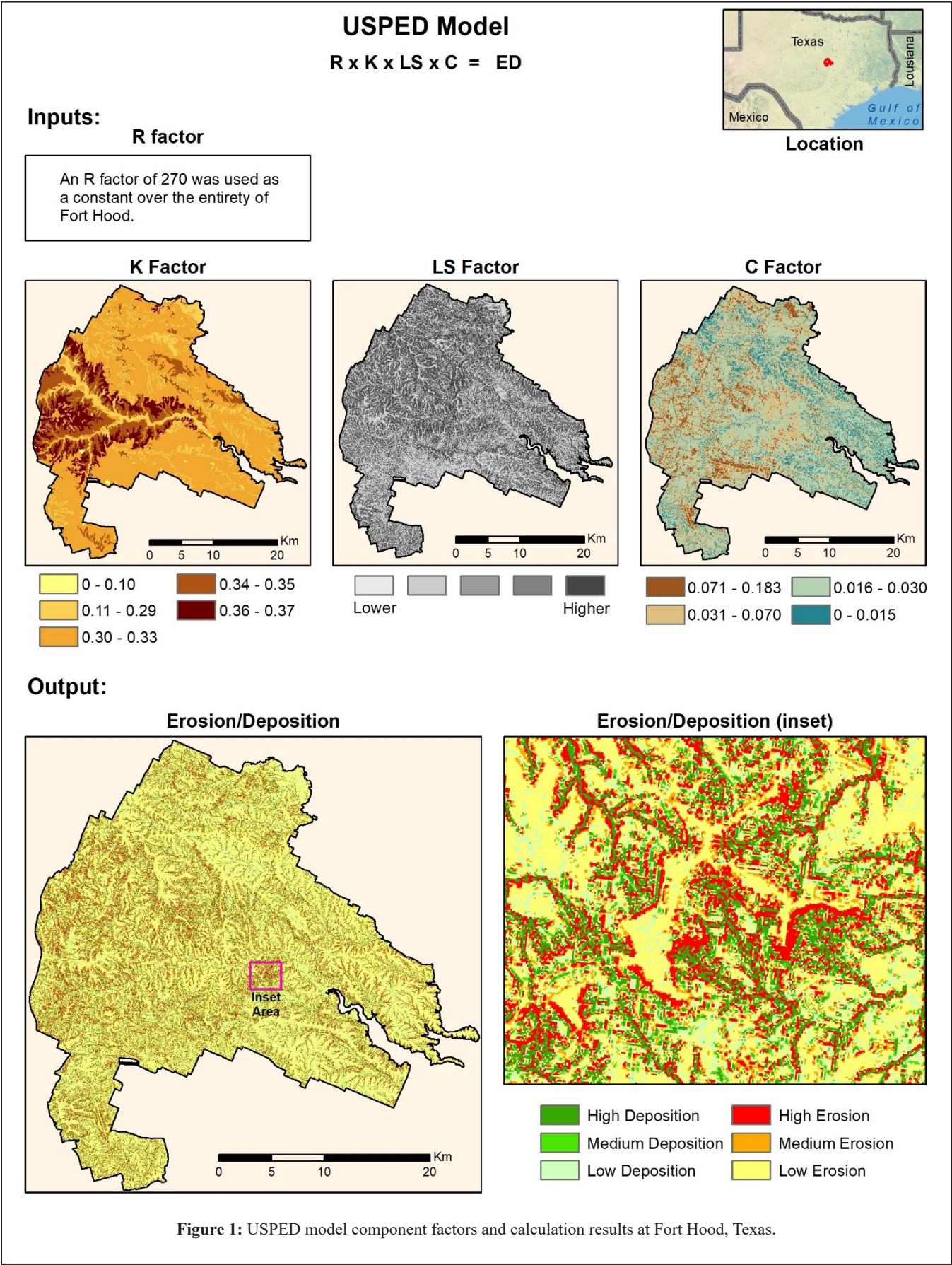
Discussion

Evaluation of the accuracy of erosion models has been historically limited by the lack of long-term measured soil erosion [26]. Furthermore, comparisons have been primarily made only

a watershed that affect sediment transport, but suffers from both spatial and temporal variability [27,28]. The use of an SDR is merely a performance factor that can vary seasonally and can produce erroneous results [29].

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% 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 errors. We fully acknowledge that table 1 may not completely 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.

The level of accuracy of the USPED model was similar to comparisons of soil erosion produced by measuring levels of ¹³⁷Cesium in the soil [25], suggesting that erosion estimation, by whatever means, will not likely produce estimates with significantly greater accuracy. One must recall that the USPED, as are all USLE-based models, is only a model. As a model, it is unrealistic to expect accuracies beyond about 80%. While the USPED and USLE components are designed to represent 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 from year to year based on the parameters that feed their calculation.

In the quest to produce more accurate erosion prediction, predictive models have become more complex. However, there is minimal evidence that highly complex models significantly outperform simpler ones [30-32]. The USPED model is a relatively simple soil erosion and sediment model that takes advantage of modern technologies such as remote sensing and digital elevation models to produce spatially distributed estimates of soil erosion and sediment deposition that accurately approximate visual observations of the same parameters most of the time. Such distributed estimates replace the need to make meticulous spatially distributed measurements in order to adequately combat those processes.

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