US Army Corps
of Engineers
Construction Engineering
Research Laboratories

USACERL Interim Report 99/12
December 1998

Digital Terrain Modeling and Distributed Soil Erosion Simulation/Measurement for Minimizing Environmental Impacts of Military Training

by
Steven D. Warren

Because soil erosion and deposition have negative repercussions on military preparedness and the environment, the Strategic Environmental Research and Development Program (SERDP) has funded efforts to develop geographic information system (GIS) tools and methods to enhance the accuracy, spatial prediction, and visual representation of erosion and deposition on military lands. During Fiscal Year 1997, the CASC2D model was modified to include an upland erosion algorithm. The modified model produced accurate runoff hydrographs, but fell short in predicting sediment discharge. Part of the inaccuracy is attributable to channel erosion not taken into account by the current CASC2D model. The Unit Stream Power Erosion and Deposition (USPED) model was enhanced to include tangential curvature. The modification greatly improves the accuracy of erosion and deposition predictions in areas of convergent slopes. The process-based SIMulated Water Erosion (SIMWE) model was used to investigate the effects of rainfall excess, surface roughness, critical shear stress, detachment capacity, and transport capacity on erosion and deposition. Results of initial investigations conducted to determine if the SIMWE model could be used to predict the consequences of common erosion and sediment control practices were promising. Various GIS tools were developed to help in processing and visualization of distributed data.

SERDP
Strategic Environmental Research and Development Program
Improving Mission Readiness through Environmental Research

Executive Summary

Soil erosion and the consequent siltation of waterways have long been major environmental concerns on military installations. In recognition of the negative repercussions that soil erosion and deposition have on military preparedness and the environment, the Strategic Environmental Research and Development Program (SERDP) has funded a project entitled "Digital Terrain Modeling and Distributed Soil Erosion Simulation/Measurements for Minimizing Environmental Impacts of Military Training." The primary focus of the project is to develop geographic information system (GIS) tools and methods to enhance the accuracy of soil erosion and deposition modeling and to facilitate improved visual representation of erosion and deposition on military lands. There will be improved capability to estimate erosion/deposition potential as an input for choosing optimal land use management and rehabilitation programs. More accurate modeling of erosion and deposition will assist land managers and trainers in optimizing training schedules, delineating training areas, and monitoring changes over time. The models will also assist in maximizing availability of military lands with minimal impact to natural resources, especially to soil and vegetation. The overall net result of this research will be improved land management and reduced land maintenance costs.

To achieve maximum effectiveness in large areas of complex terrain, integration of erosion and deposition models with GIS is essential. Often, high resolution digital elevation models (DEMs) required by erosion/deposition models must be interpolated from coarser resolution DEMs, scattered point data, or topographic contours. For this project, a method of interpolation by regularized spline with tension was enhanced for the purpose of deriving high resolution DEMs. When compared with other methods of interpolation, the resulting DEM provides a much more accurate representation of the actual terrain. During Fiscal Year 1997, the interpolation method was further enhanced with a support tool that allows users to set different smoothing parameters for each given point, depending on the accuracy of the measurement. This capability supports the combination of data from various sources with different accuracies, with the resulting surfaces passing the closest to the most accurate data and allowing deviation from the less accurate data.

CASC2D is a 2-dimensional, physically based rainfall-runoff model that simulates spatially variable surface runoff. Early efforts under SERDP funding concentrated primarily on using the model to simulate watershed response to military training scenarios. During Fiscal Year 1997, an attempt was made to add an upland erosion algorithm to the model. In a test at the Goodwin Creek watershed in Mississippi, the improved CASC2D model produced remarkably accurate runoff hydrographs, but fell short in predicting sediment discharge. At least part of the inaccuracy is attributable to channel erosion that is not taken into account by the current CASC2D model.

The Universal Soil Loss Equation (USLE) and its revision (RUSLE) are the most widely accepted erosion models in the world. They are lumped-parameter semi-empirical models developed for agricultural fields. The models account for topography by the use of a parameter that incorporates only slope length and steepness. Such a simplistic approach cannot account for convergence and divergence of slope or for concavities, convexities, and other irregularities that affect erosion and deposition processes. With SERDP funding, the topographic parameter of these models has been replaced with an analog that incorporates the unit stream power theory and upslope contributing area rather than slope length. This new Unit Stream Power Erosion and Deposition (USPED) model is applicable to complex slope geometries. It accurately predicts greater erosion on slope shoulders than on downslope positions. Furthermore, by measuring the change in sediment transport capacity across a GIS grid cell, it also predicts sediment deposition. To more fully accommodate observed erosion and deposition patterns, a new 2-dimensional USPED was derived during FY97. When the results of the 1-dimensional and the 2-dimensional flow models are compared with the observed pattern of colluvial deposits, it is clear that the 1-dimensional model fails to predict deposition observed in areas where the profile curvature is close to zero but where there is a significant tangential concavity. It also underestimates erosion in areas with tangential convexity (shoulders). The prediction by the 2-dimensional flow model in these areas is in significantly better agreement with the observed pattern of deposition.

Over the past decade, several process-based models have been developed with the hope of replacing the older empirical models. While these models incorporate the impact of soil, cover, and management practices in great detail, the description of topography is overly simplified. To overcome these shortcomings, the SIMulated Water Erosion (SIMWE) model was developed with SERDP funding. The SIMWE model is based on the solution of the continuity equation, which describes the flow of sediment over the landscape, depending on a steady state water flow, detachment and transport capacities, and properties of soil and cover. It is a landscape scale, bivariate model of erosion and deposition by overland flow designed for spatially complex terrain, soil, and cover conditions. The underlying continuity equations are solved by Green's function Monte Carlo methods to provide the robustness necessary for spatially variable conditions and high resolutions. During Fiscal Year 1997, the SIMWE model was used to investigate the effects that rainfall excess, surface roughness, critical shear stress, detachment capacity and transport capacity have on erosion and deposition processes. Initial investigations were conducted to determine if the SIMWE model could be used to predict the consequences of common erosion and sediment control practices. The results were promising.

Simulation of landscape processes is more sensitive to noise and artifacts in landscape characterization data than the more traditional uses of GIS such as automatic map production or spatial analysis. There is a continuing effort to extend the GIS capabilities to support modeling and simulation of processes by implementing new, advanced methods and data structures. This project has focused on improving methods for multivariate spatial interpolation, topographic analysis and visualization, and on extending the data structures to support multivariate point and raster format.

Foreword

This study was sponsored by the Strategic Environmental Research and Development Program (SERDP) under SERDP Project No. CS-752, "Digital Terrain Modeling and Distributed Soil Erosion Simulation/Measurements for Minimizing Environmental Impacts of Military Training," and conducted under Work Unit EM8, "Terrain Modeling and Soil Erosion Simulation." The technical monitor was Dr. Femi A. Ayorinde, Conservation Program Manager. Mr. Bradley P. Smith is the Executive Director, SERDP.

The work was managed by the Resource Mitigation and Protection Division (LL-R) of the Land Management Laboratory (LL), U.S. Army Construction Engineering Research Laboratories (CERL). Significant portions of this research were performed by Dr. Helena Mitasova, Dr. Lubos Mitas, and Mr. William M. Brown from the Geographic Modeling and Systems Laboratory at the University of Illinois, Mr. Mark Jourdan of the Hydraulics Laboratory at the U.S. Army Engineer Waterways Experiment Station (WES), and Mr. Robert Larson of the Geotechnical Laboratory at WES. Large sections of this report have been excerpted from various reports and publications by all of the performers. The CERL principal investigator was Dr. Steven D. Warren. Robert E. Riggins is Chief, CECER-LL-R; Dr. John T. Bandy is Operations Chief, CECER-LL; and William D. Goran is the responsible Technical Director. The CERL editor was Gloria J. Wienke, Technical Resources.

Dr. Michael J. O'Connor is Director of CERL.

Contents

List of Figures

1 Introduction

Background

Soil erosion and the consequent siltation of waterways have long been major environmental concerns on military installations. Accelerated soil erosion results from and ultimately jeopardizes military training and testing. Among the research and development priorities for Department of Defense (DoD) lands, abatement of soil erosion ranks second only to threatened and endangered species concerns. It has been variously estimated that the cost to restore damaged Army lands to tolerable levels of soil erosion could range from $100M to $200M per year for as long as a decade. Annual maintenance costs to keep soil erosion at an acceptable level have been estimated around $40M using existing technology. In an era of declining budgets, the DoD simply cannot afford such expenditures. It is paramount that more cost-effective measures be developed to plan and implement erosion control.

Numerous erosion and sediment control technologies are readily available to military installations. These include revegetation, construction of earthen features such as sediment retention ponds and terraces, and the use of a wide variety of commercially available erosion control products. Unfortunately, it is not always clear which techniques to use, where they should be placed, how big they should be, or when the optimal time occurs for implementation. As a result, projects are often over- or under-engineered. In addition, land managers often address the symptoms of a problem (e.g., an area of intensive erosion) while failing to consider the ultimate source of the problem (e.g., the source of excessive runoff). Cost-effectiveness of land reclamation practices can be maximized as we better understand and model landscape processes that affect soil erosion. With adequate understanding and modeling capability, it is possible to intervene at the appropriate time and place and with the appropriate techniques to achieve maximum benefit with the least expenditure of human energy and financial resources.

Until recently, most approaches to erosion and sediment modeling relied on lumped-parameter semi-empirical relationships developed for agricultural lands. The most widely accepted and used model is the Universal Soil Loss Equation

(USLE)(Wischmeier and Smith 1978) and its Revised form (RUSLE) (Renard et al. 1997). These equations have the form

$$A=RxKxLSxCxP \quad [Eq\ 1]$$

where average annual soil loss (A), expressed in tons/ha/yr, is estimated as the product of factors representing rainfall erosivity (R), inherent soil erodibility (K), the length and steepness of slope (LS), plant cover (C), and conservation support practices (P). The RUSLE changes the technology used to evaluate the factors and adds data to extend the empirical relationships. While these models are helpful in predicting average annual soil erosion over relatively homogeneous parcels of land, they provide little insight into the landscape processes governing soil erosion, and are incapable of predicting erosion on complex terrain. In addition, they are incapable of predicting the extent or spatial distribution of sediment deposition.

Over the past decade, there has been a move to replace the empirical models with more complex process-based models such as the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing 1995). While still developmental and not widely accepted, these models have improved the understanding of erosional processes and provide the basis for dramatic improvements in the accuracy of erosion and sediment modeling.

A major drawback of existing empirical and process-based models has been the 1-dimensional (1D) approach used to derive them. Landscapes have generally been assumed to be homogeneous, planar features. Average erosion rates have been determined and assigned to entire hillslopes and watersheds, thus providing no information regarding the sources and sinks of eroded materials. Alternatively, complex landscapes have been computationally divided into a series of semi-homogeneous planes, and erosion has been calculated for each plane. Neither approach provides adequate spatially distributed information on erosion and deposition to effectively optimize erosion control efforts. Only through integration with a geographic information system (GIS) is it possible to model erosion, sediment transport, and sediment deposition in an environment that can account for heterogeneous landscapes (i.e., convergence, divergence, concavity and convexity of slopes, variable land uses and conditions, heterogeneous soil types, etc.).

Geographic information systems represent variability in terrain with a digital elevation model (DEM), where elevation is recorded for each pixel or grid cell in a map. DEMs are generally derived from scattered elevation data or topographic maps. Interpolation of elevation data from known points to all pixels in a map is generally required. While many methods of interpolation are available, some are more accurate than others. Given the importance of topography to erosion modeling, the best possible method should be used.

With an adequate DEM, various aspects of the hydrologic cycle can be modeled, including rainfall infiltration, runoff, soil detachment, sediment transport, and sediment deposition. Military land managers are required to make a variety of decisions related to short- and long-term planning of military training and testing operations, and the need for, timing, and placement of land reclamation activities. The most appropriate hydrologic model for one application may be insufficient or excessive for another application. Therefore, a variety of models should be available to meet the various data requirements. In addition, there is a great need to develop the capability within these models to predict the hydrologic consequences of various land reclamation practices.

No amount of text or numerical output can replace the value of a picture that illustrates the spatial distribution of erosion and deposition. Such depictions, as well as 3-dimensional visualization of soil profiles, watershed cross-sections, etc., can be invaluable for planning and placing erosion and sediment control projects. While multi-dimensional visualization is common for many applications, it has been problematic in natural resource GIS applications where data at a variety of scales may need to be combined (e.g., terrain surface features are generally mapped at a scale of meters; soil profile features are measured in centimeters). New algorithms for handling complex, multi-scale data are needed.

Military training and testing activities affect soils and vegetation. Changes in these parameters can have a great impact on the hydrologic cycle. Therefore, information about the impact of military operations on these parameters is essential. While the Land Condition Trend Analysis (LCTA) component of the Army's Integrated Training Area Management (ITAM) program has provided abundant information on the effects of military operations on vegetation, information regarding the impacts on soils is limited. There is a need to enhance this state of knowledge in order to adequately model the effects of military activities on the soil erosion process.

Technical Objectives

During Fiscal Year 1995 (FY95), the Strategic Environmental Research and Development Program (SERDP) began funding an effort to develop GIS tools and methods to enhance the accuracy, spatial prediction, and visual representation of erosion and deposition on military lands. The project incorporates the following parallel objectives to meet the information, modeling, and visualization shortfalls discussed above:

1. Develop multivariate spline interpolation methods to support terrain modeling and processing of field data.

2. Complete the CASC2D model as a distributed model of rainfall-runoff processes.

3. Further develop the unit stream power theory approach to the Universal Soil Loss Equation to improve prediction of erosion, add prediction of deposition, and allow application of the model in complex topography.

4. Develop a multi-dimensional application of the detachment/transport capacity theory approach to erosion and sediment prediction as contained in the Water Erosion Prediction Project.

5. Develop a vehicle-soil-climate interaction model based on field measurements of soil and hydrologic parameters.

6. Enhance visualization techniques supporting the design and communication of dynamic erosion and sediment transport model results.

7. Develop the capacity to incorporate erosion, runoff and sediment control practices into erosion/deposition models.

2 Prior Accomplishments

The primary focus of this report is to provide a detailed summary of FY 97 accomplishments for SERDP Project No. CS-752, Digital Terrain Modeling and Distributed Soil Erosion Simulation/Measurements for Minimizing Environmental Impacts of Military Training. However, in order to lay the groundwork for such discussion, a summary of accomplishments from previous fiscal years will be covered in this section.

Interpolation

To achieve maximum effectiveness in large areas of complex terrain, integration of erosion and deposition models with GIS is essential. A mathematical characterization of topography, at one level or another, is a fundamental requirement of nearly all such models. Within a GIS this is most effectively accomplished with the use of a digital elevation model (DEM). A DEM contains the elevation of each pixel or cell in the landscape. Our experience has shown that the optimal resolution (pixel size) for landscape level erosion and sediment modeling is in the range of 5 to 20 meters. Unfortunately, data with this resolution are not common. Instead, high resolution DEMs must be interpolated from coarser resolution DEMs, scattered point data, or topographic contours. Various techniques have been devised to interpolate and compute high resolution DEMs from the various data sources. Different computational methods, however, produce widely differing results.

For this project, a method of interpolation by regularized spline with tension (RST) (Mitasova and Mitas 1993, Mitasova and Hofierka 1993) was enhanced for the purpose of deriving high resolution DEMs. The method is based on the assumption that the approximation function should pass as closely as possible to the given data points and should be as smooth as possible. A tension parameter controls the distance over which a given point influences the resulting surface model and enables the user to tune the character of the resulting surface from a membrane to a thin plate. A smoothing parameter controls the deviation of the resulting surface from the individual data points, a procedure that is necessary for processing noisy data. Optimum parameters are found empirically by visual analysis or by minimizing the cross-validation error (Mitasova et al. 1995).

When compared with other methods of interpolation, the resulting DEM provides a much more accurate representation of the actual terrain (Figure 1).

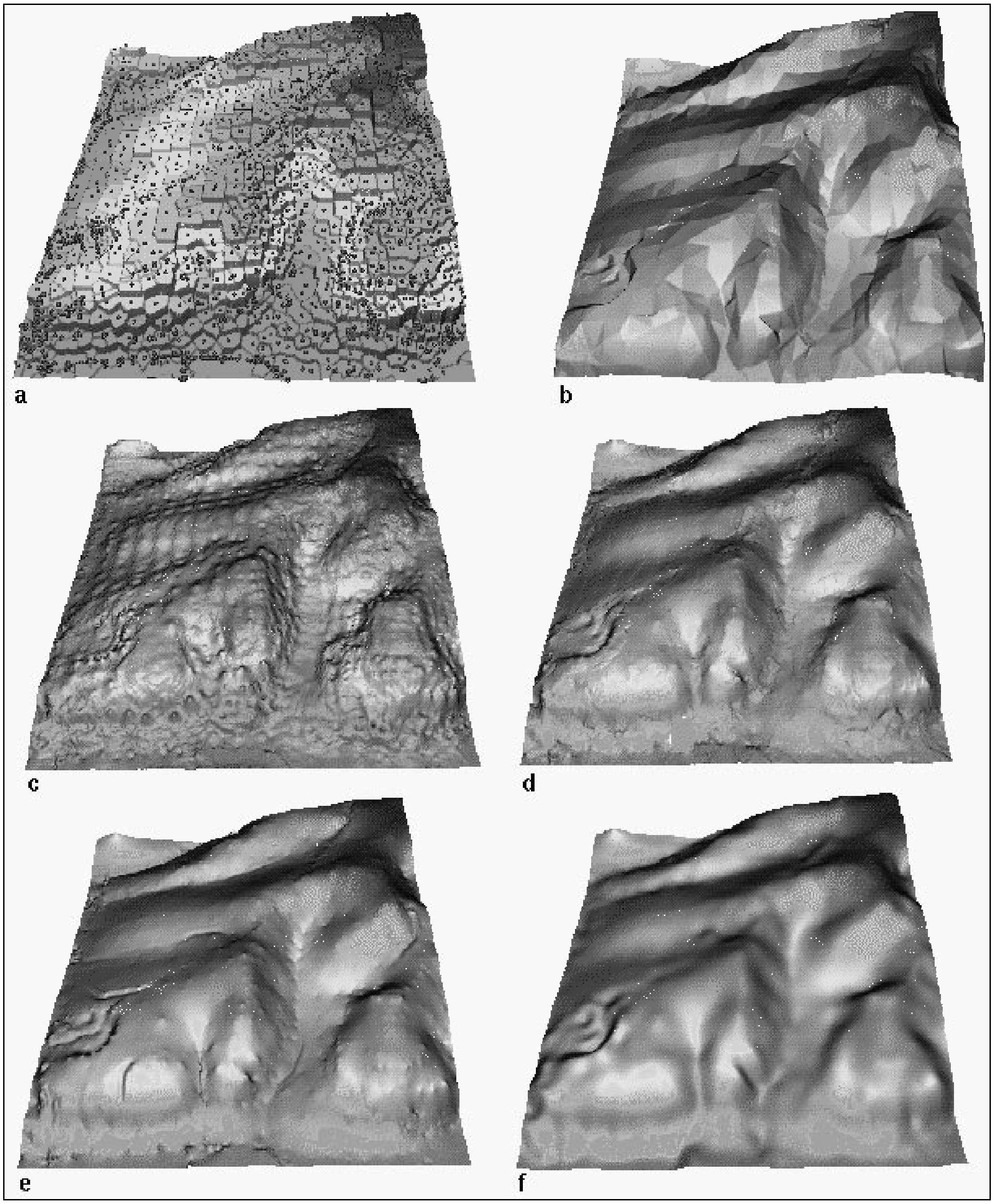

Figure 1. Interpolation of a digital elevation model (DEM) from scattered data points. Graphics represent (a) Voronoi polygons, (b) triangulated irregular network (TIN) based linear interpolation, (c) inverse distance weighting, (d) ordinary kriging, (e) spline with tension and stream enforcement, and (f) regularized spline with tension and smoothing. The data is from the Scheyern Experimental Farm, Germany, courtesy of Dr. Karl Auerswald.

CASC2D

Originally developed with funding from the Army Research Office (ARO), CASC2D is a 2-dimensional (2D) physically based rainfall-runoff model that simulates spatially variable surface runoff (Julien, Saghafian, and Ogden 1995). It is fully integrated with the Geographic Resources Analysis Support System (GRASS) GIS. The model uses the Green and Ampt method to model infiltration, a 2D diffusive wave formulation of the de St. Venant equations for overland flow, and a 1D solution of the diffusive wave formulation for channel flow routing. Outputs include runoff hydrographs and maps of infiltration depth, surface moisture, surface runoff depth, channel runoff depth, and rate of infiltration. Prior to FY97, SERDP-funded efforts concentrated primarily on the application of the model to simulate watershed response to military training scenarios (Doe, Saghafian, and Julien 1996).

Unit Stream Power Theory

The Universal Soil Loss Equation (USLE) and its revision (RUSLE) are the most widely accepted erosion models in the world. They are lumped-parameter semi-empirical models developed for agricultural fields. In their standard form, they are designed for homogeneous, rectangular farm fields. Topography is accounted for by the use of a parameter (LS) that takes into account only slope length and steepness. Such a simplistic approach cannot account for convergence and divergence of overland flow or for concavities, convexities, and other irregularities of slope that affect erosion and deposition processes on a local scale. By using the unit stream power theory to describe erosion processes, a physically based LS analog has been developed that has been shown to be equivalent to the traditional LS factor on planar surfaces (Moore and Burch 1986, Moore and Wilson 1992). The LS analog is conceptually easier to understand and is more readily applied in a GIS environment. And because it incorporates upslope contributing area rather than slope length, it has the added benefit of being applicable to complex slope geometries. This improved USLE/RUSLE has been dubbed the Unit Stream Power Erosion and Deposition (USPED) model. The USPED model, with the LS analog, accurately predicts greater erosion on slope shoulders than on downslope positions (Figure 2). Furthermore, by measuring the change in sediment transport capacity across a GIS grid cell, it also predicts sediment deposition (Moore and Wilson 1992, Mitasova et al. 1996).

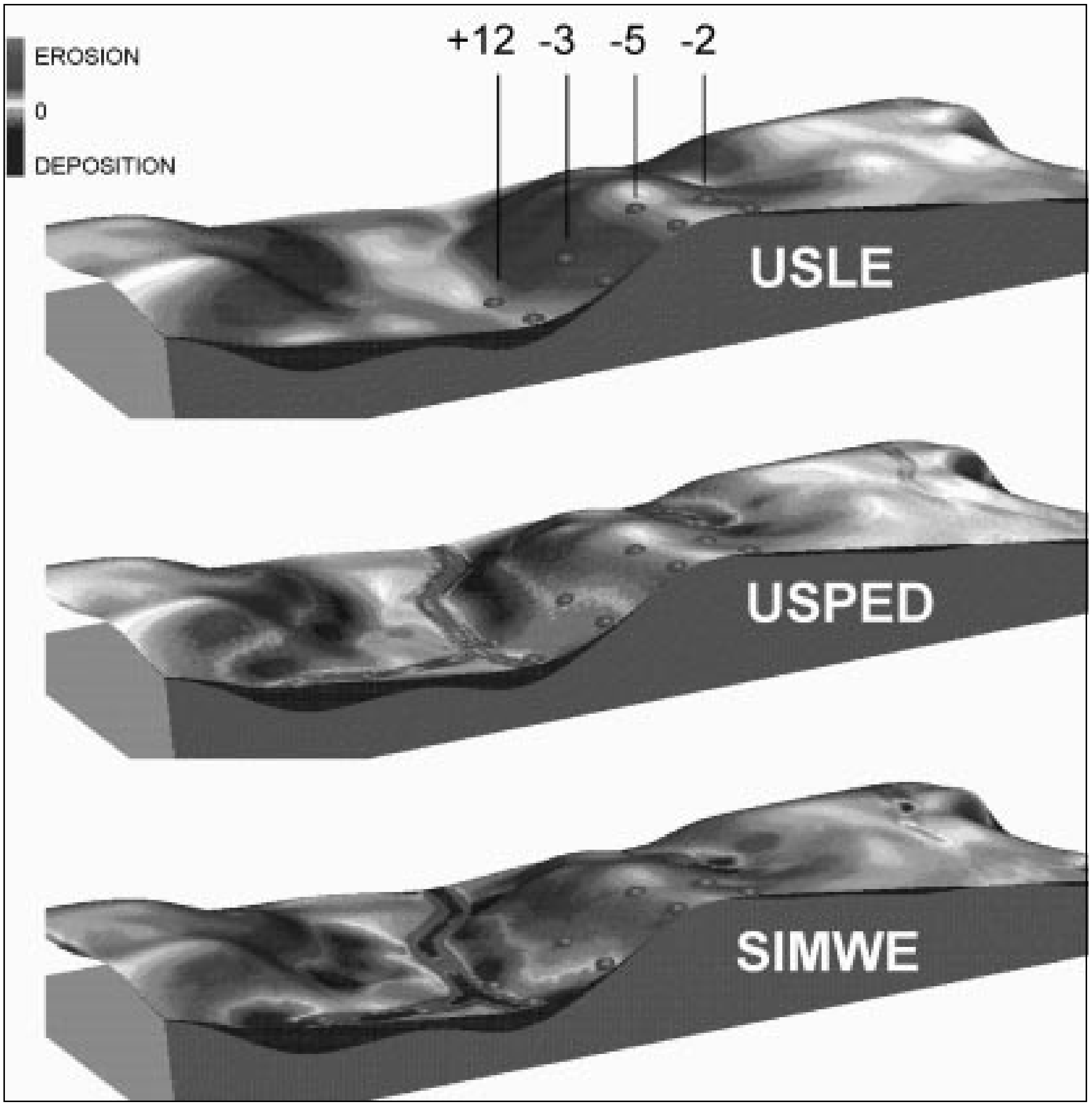

Figure 2. A comparison of the topographic potential for erosion and deposition for the traditional USLE, the unit stream power analog (USPED), and SIMWE. Soil samples were taken from the locations represented by the green dots. The samples were analyzed for cesuim-137 content as an index to erosion and deposition. Net loss or gain of cesium-137 (see numbers at the top) represent proportional levels of erosion and deposition, respectively. The blue band below each figure is an exaggerated depiction of relative sediment deposits as determined by soil cores. Data is from the Scheyern Experimental Farm, Germany, courtesy of Dr. Karl Auerswald.

Detachment/Transport Capacity Theory

Over the past decade, several process-based models have been developed with the hope of replacing the older empirical models. Foremost among these has been the WEPP model developed by the U.S. Department of Agriculture's Agricultural Research Service (Flanagan and Nearing 1995). WEPP is a field-scale erosion and deposition model based on 1D flow over hillslope segments. It relies heavily on detachment/transport capacity theory. While the model incorporates the impact of soil, cover, and management practices in great detail, the description of topography is very simplified. Hillslopes are divided into segments and the equation is solved for each segment. Results are given as statistical averages or integrals for entire hillslopes or small watersheds.

To overcome these shortcomings, the SIMulated Water Erosion (SIMWE) model was developed (Mitas, Brown, and Mitasova 1997). The SIMWE model is based on the solution of the continuity equation that describes the flow of sediment over the landscape, depending on a steady state water flow, detachment and transport capacities, and properties of soil and cover. It is a landscape-scale, bivariate model of erosion and deposition by overland flow designed for spatially complex terrain, soil, and cover conditions. The underlying continuity equations are solved by Green's function Monte Carlo methods to provide the robustness necessary for spatially variable conditions and high resolutions. When compared to the traditional USLE, SIMWE provides a much improved representation of erosion and deposition similar to the unit stream power enhancement to the USLE (Figure 2).

Visualization

Multidimensional dynamic visualization is beneficial both as a process of research and discovery and as a method of communicating measured or modeled geographic phenomena. Combinations of raster, vector, and point data can be displayed simultaneously to allow observers to study spatial relationships in 3-dimensional (3D) space. Visual analysis requires the ability to distort the spatial relationships by changing vertical scales, separating surfaces, and performing transformations on point or vector data. Visualization tools have been created to support the development and application of landscape process models based on spatial and temporal distribution of multiple parameters representing terrain, soil properties, rainfall, infiltration, cover, etc.

Before FY97, considerable effort was expended to enhance SG3d, the first advanced visualization program for GRASS. It was designed to be used with a Silicon Graphics IRIS workstation. SG4d is a version of SG3d that was enhanced to incorporate volume data. Development of the third-party libraries on which SG3d was dependent has been discontinued, so the project has been forced to seek alternatives.

To support modeling of infiltration processes and long-term effects of erosion, a 3D model of soil properties is needed. GIS capabilities to handle multidimensional data is therefore required. To this end, implementation and initial testing of a 3D grid data file format (g3d) for managing volumetric spatial data was completed. The storage format and programmer's interface allow random access to compressed floating point double precision 3D data with caching. It is fully integrated with GIS, using established database hierarchy for header and data files.

3 FY97 Progress

Interpolation

To gradually fulfill the requirements of spatial interpolation for GIS applications and simulations, the implementation of the RST method is periodically updated. During FY97 we developed a support tool for spatially variable smoothing. This allows users to set a different smoothing parameter for each given point, depending on the accuracy of the measurement. This capability supports the combination of data from various sources with different accuracies, with the resulting surfaces passing the closest to the most accurate data and allowing deviation from the less accurate data.

The Geographic Modeling and Systems Laboratory at the University of Illinois also tested the interpolation tools in ArcView Spatial Analyst and found a serious flaw in the implementation and application of splines used in the Spatial Analyst tutorial (ESRI 1997). The results of the analysis were provided to ESRI with a suggestion of how to fix the flawed implementation of interpolation. The problem is being fixed.

CASC2D

The CASC2D model was originally developed to predict the amount of runoff from a given rainfall event and its spatial and temporal distribution within a watershed. During FY97, an attempt was made to add an upland erosion algorithm to the model. The approach uses a modified sediment transport equation from Julien, Saghafian, and Ogden (1995):

[Eq 2]

$$q_s = 25500 q_o^{2.035} S_o^{1.664} \frac{K}{0.15} CP$$

where q_s is sediment discharge in tons/ms, q_o is runoff discharge (from the traditional CASC2D), S_o is slope, and K, C, and P are the soil erodibility, cover, and conservation practice parameters of the USLE, respectively.

The equation is calculated for each grid cell to determine available sediment. Available sediment is then routed from the grid cell to its downhill neighbors. Sediment transported out of a grid cell is assumed to come first from sediment already in suspension, second from previously deposited sediment, and lastly from the soil surface.

The model was tested on the Goodwin Creek watershed in northern Mississippi (Johnson et al. 1998). The watershed is divided into 14 nested subcatchments, each with a flow measuring flume at the drainage outlet. The drainage areas above the stream gaging stations range from 0.63 to 8.26 sq mi. Twenty-nine recording rain gages are located throughout the watershed. Historic rainfall, runoff, and sediment data from three storms were used to evaluate the upland erosion component of the CASC2D model. Runoff hydrographs predicted by CASC2D were remarkably accurate. The ratio of predicted to actual total runoff through the gaging stations fell within an acceptable range of 74 to 109 percent. However, the ratio of predicted to actual sediment discharge (tons/ac/yr) ranged from 4 to 156 percent. While promising, these results indicate that further development and calibration is needed on the erosion module. At least part of the difference can be attributed to channel erosion that is not taken into account by CASC2D.

Unit Stream Power Theory

The unit stream power erosion and deposition (USPED) model is a derivation of the USLE/RUSLE. It is a simple model that predicts the spatial distribution of erosion and deposition rates for a steady-state overland flow with uniform rainfall excess conditions where transport capacity is the limiting factor. USPED substitutes an analog for the slope length and steepness (LS) factor of the USLE. Sediment flow rate is approximated by sediment transport capacity which is, in turn, computed as a power function of slope, upslope area, and a transportability coefficient that is dependent on soil and cover. Net erosion and deposition are computed as changes in sediment flow rate from one grid cell to its adjacent downhill neighbors.

Within the original USPED model, water and sediment flow are modeled as 1D flow along a flow line generated over 3D terrain. The net erosion/deposition rate is computed as a change in the sediment flow rate along the flow line, approximated by a directional derivative of the sediment flow rate. For this univariate case, the net erosion/deposition rate D(x,y) is

$$D(x,y) = dT(x,y)/ds = K(x,y) \{[\text{grad } h(x,y) \bullet s(x,y)] \sin \beta(x,y) - h(x,y)\, k_p(x,y)\} \quad \text{[Eq 3]}$$

where T(x,y) is sediment transport capacity, K(x,y) is the transportability coefficient, h(x,y) is the water depth estimated from the upslope area, s(x,y) is the unit vector in the steepest slope direction, ß (x,y) is slope, and $k_p(x,y)$ is the profile curvature (terrain curvature in the direction of the steepest slope). This 1D flow-based formulation includes the impact of water flow, slope, and profile curvature. However, the impact of tangential curvature is incorporated only through the water flow term. The predicted pattern is in good agreement with field observations except at the heads of valleys where it predicts only erosion; soil maps and field experiments indicate that both erosion and deposition are occurring in those locations.

To more fully accommodate observed erosion and deposition patterns, a new 2D USPED was derived during FY97. Water and sediment flow are represented as a bivariate vector field q(x,y), $q_s(x,y)$. Net erosion/deposition rate is estimated as a divergence of the sediment flow. Assuming uniform rainfall, soil and cover conditions, and a transport capacity limiting case with sediment flow close to sediment transport capacity, the net erosion/deposition can be written as:

$$D(x,y) = \text{div } q_s(x,y) = K(x,y)\{[\text{grad } h(x,y) \bullet s(x,y)] \sin \beta(x,y) - h(x,y)\, [k_p(x,y) + k_t(x,y)]\} \quad \text{[Eq 4]}$$

where $k_t(x,y)$ is the tangential curvature (curvature in the direction perpendicular to the gradient). Topographic parameters s(x,y), $k_p(x,y)$, $k_t(x,y)$ are computed from the first and second order derivatives of the terrain surface, approximated by the regularized spline with tension. The spatial distribution of erosion/deposition is controlled by the change in the overland flow depth and by the local terrain geometry, including both profile and tangential curvatures. The equation thus demonstrates that the local acceleration of flow in both the gradient and tangential directions play equally important roles in the spatial distribution of erosion/deposition. The impact of the tangential curvature $k_t(x,y)$ is, therefore, twofold. First, it influences the water depth through its control of water flow convergence/divergence, with tangential concavity leading to a rapid increase in water depth and an increase in the potential for erosion. Second, it causes a local change in sediment flow velocity, with tangential concavity creating potential for deposition. The interplay between the magnitude of water flow change and both terrain curvatures determines whether erosion or deposition will occur.

When the results of the 1D and the 2D flow models are compared with the observed pattern of colluvial deposits (Figure 3), it is clear that the 1D model fails to predict deposition observed in areas where the profile curvature is close to zero but where there is a significant tangential concavity. It also underestimates erosion in areas with tangential convexity (shoulders). The prediction by the 2D flow model in these areas is in significantly better agreement with the observed pattern of deposition.

Detachment/Transport Capacity Theory

During FY97, the various parameters of the SIMWE model were examined to determine how variability in natural phenomena and properties influence the erosion process.

Impact of Spatially Uniform Parameters in Complex Terrain

Meyer and Wischmeier (1969) presented an erosion model based on principles later formulated as a closed form erosion equation by Foster and Meyer (1972) and used in the WEPP, CREAMS, and numerous other models (Hong and Mostaghimi 1995; Haan, Barfield, and Hayes 1994) including SIMWE. They formulated the model for a 1D complex profile and analyzed its behavior for various combinations of parameters, thus elucidating the impacts of different terrain, rainfall, soil, and cover properties on distribution of erosion and deposition rates along a profile. SIMWE extends the capability of the model from a 1D complex profile to a terrain represented by a bivariate (2D) function in 3D space.

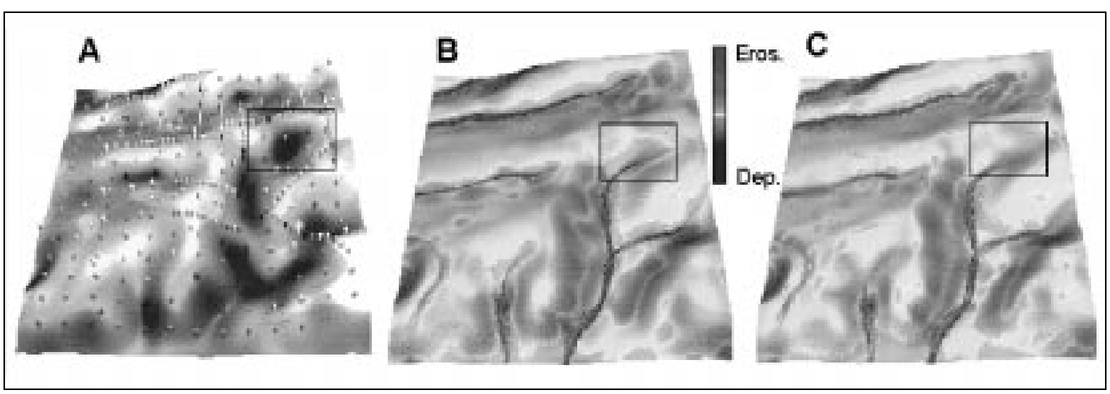

Figure 3. A comparison of measured colluvial deposits. Graphics show (A) with predicted erosion and deposition applying to USPED with 2D (B) vs. 1D (C) flow, i.e., with and without incorporation of the tangential curvature, respectively.

The following examples represent a generalization of SIMWE on a 2D complex profile. In each example the baseline situation is a rainfall intensity of 36mm/hr, fully saturated soils (i.e., no infiltration of rainfall into the soil), rough surface (e.g., dense grass with Manning's n = 0.1), sandy soil (negligible critical shear stress, low detachability [K_t] and low transportability [K_d], [K_t = K_d = 0.0003]). The examples illustrate how the magnitude and pattern of erosion/deposition rates change due to changes in individual parameters.

Rainfall Excess. Rainfall excess is estimated as rainfall intensity minus infiltration rate. In other words, it is the amount of water available for runoff. Rainfall excess influences the magnitude of erosion/deposition rates. With increasing rainfall excess, erosion and deposition rates both increase. However, the spatial pattern of erosion and deposition does not change (Figure 4).

Surface Roughness. Surface roughness is expressed in terms of Manning's n coefficient, where low coefficients indicate minimal roughness and high coefficients indicate significant roughness. Surface roughness influences water and sediment flow velocities. Manning's n depends on vegetation cover as well as the soil surface. Its values have been derived experimentally and are available from the literature and the WEPP users manual (Flanagan and Livingston 1995). Changes in surface roughness alter erosion and deposition patterns. In this example, deposition for smooth surfaces (n=0.01) is predicted only on about 14 percent of the total area, while deposition for rough surfaces (n=0.1) is closer to 24 percent of total area (Figure 5).

Critical Shear Stress. This parameter represents the resistance of a soil to the shearing forces of water flow. It depends on soil and cover properties. Typical values are available from the WEPP manual (Flanagan and Nearing 1995). If the shear stress of flowing water at the given location is lower than the critical shear stress of the soil, no soil is detached. As a result, this parameter affects the erosion/deposition pattern (Figure 6). With all other parameters being held

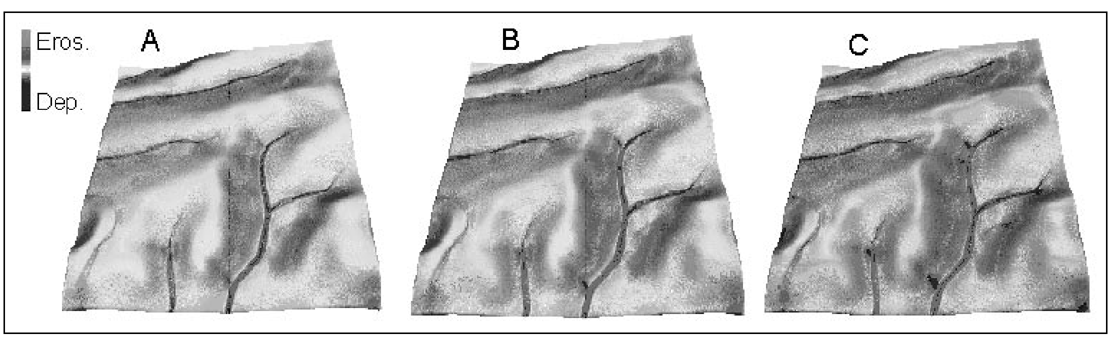

Figure 4. Effect of increasing rainfall excess. Graphics show an increase from 36 mm/hr (A) to 72 mm/hr (B) to114 mm/hr (C).

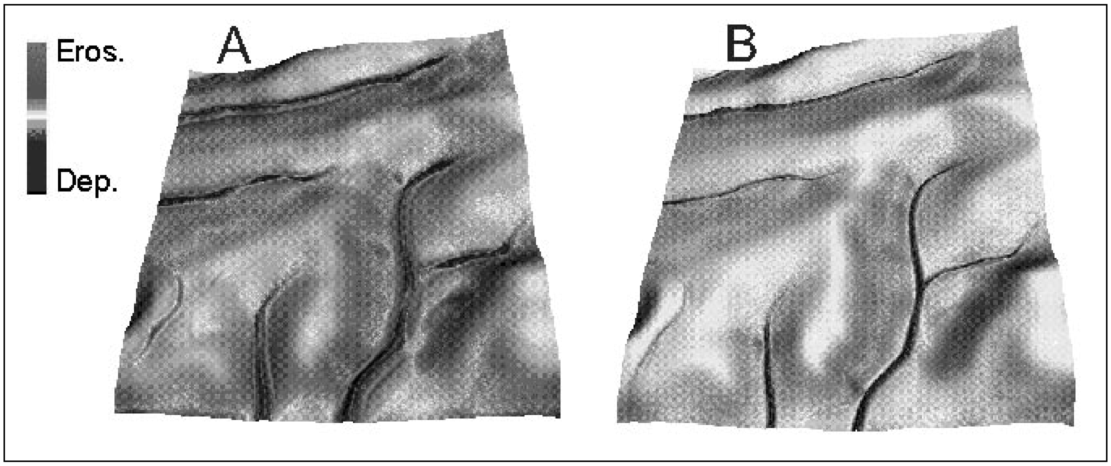

Figure 5. The effect of increasing surface roughness on erosion and deposition. Graphics show Manning's N=0.01 (smooth, A) and 0.10 (rough, B).

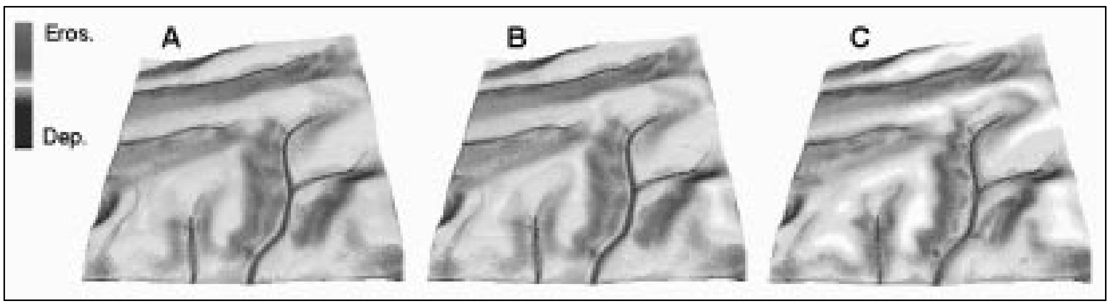

Figure 6. Changing patterns of the intensity and spatial distribution of erosion and deposition. Graphics show change resulting from increasing the critical shear stress of the soil from 1 (A) to 3 (B) to 7 (C).

equal, an increase in the critical shear stress of the soil will reduce the spatial extent of erosion. However, it has the potential to increase the magnitude of erosion rates on steeper hillslopes and in areas with concentrated flow because water with fewer suspended sediments has higher potential to transport sediment.

Erodibility and Transportability. Soil erodibility, represented by a detachment capacity coefficient (K_d), is a measure of the susceptibility of soil to detachment by water flow (Flanagan and Nearing 1995). It is often defined as the increase in soil detachment per unit increase in shear stress of clear water flow. Soil transportability, represented by a transport capacity coefficient (K_t), is a measure of the ability of a soil to be transported by water flow. It depends on soil properties, but can also be influenced by vegetation. This coefficient is not directly measured and is not provided in WEPP. Rather, it is estimated indirectly, which makes proper determination of this parameter problematic. However, the parameter can be derived, at least for some types of soils, using the published values of the first order reaction coefficient or using the procedure suggested by Finkner et al. (1989).

Simulations show that changes in soil erodibility (K_d) can markedly alter the spatial pattern of erosion and deposition (Figure 7). However, the impact on the magnitude of the in-stream sediment load may be small. This illustrates the fact that measuring sediment load in the watershed outlet does not provide adequate information to understand the erosion processes on hillslopes. Thus, the use of in-stream sediment concentration to determine appropriate erosion protection measures can be problematic.

Simulations also show that soil transportability has a profound impact on the erosion process by influencing both the spatial distribution and the magnitude of sediment flow and erosion/deposition (Figure 7). Recently, other researchers have begun to more fully recognize the importance of transport capacity for overland flow erosion (Govers 1991; Guy, Rudra, and Dickinson 1991; Nearing et al. 1997).

It is important to note that detachment capacity and transport capacity do not act independently; they are interrelated and it is the interaction that controls the pattern and magnitude of erosion. Any change in detachment capacity or transport capacity necessarily alters the ratio between the two coefficients. This leads to the change in the character of the erosion process. Where the detachment capacity of the soil is significantly lower than transportability (e.g., clayey soil), soil erosion is limited by the detachment capacity; where detachment capacity is significantly greater than transportability (e.g., sandy soil), soil erosion is limited by the transport capacity of runoff. Figure 7 illustrates this phenomenon.

The growth of vegetation reduces both K_d and K_t. The resulting erosion/-deposition pattern depends on the interaction between the rates of change. If both K_d and K_t change at the same rate, the spatial distribution of erosion/deposition stays the same. If vegetative growth reduces K_d faster than

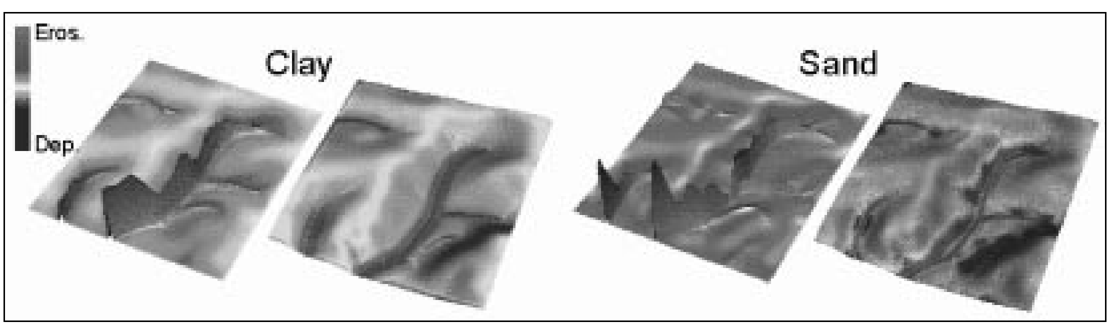

Figure 7. The effect of soil type on sediment flux and erosion/deposition patterns. Clayey soils are difficult to detach (low detachment capacity) but easy to transport (high transport capacity); sandy soils have high detachment capacity but low transport capacity. Left graphic in each pair shows sediment flux; right graphic shows erosion/deposition patterns.

K_t, the erosion/deposition process changes from a transport capacity limited case toward a detachment capacity limited case. The interrelation between the parameters is an open research question and there is a lack of systematic experimental and theoretical/modeling work in this area.

Transport and Detachment Capacity Equations

These simulations (Mitas and Mitasova 1998), as well as work reported by others (e.g., Govers 1991; Guy, Rudra, and Dickinson 1991; Nearing et al. 1997), indicate that the transport capacity equation used in the WEPP model is probably not general enough for use in complex terrain. Similar suggestions have been made regarding the detachment equation used in WEPP (Bjorneberg, Aase, and Trout 1997). To address this issue we tested both the power law shear stress relations (Julien and Simon 1985) with different power exponents and the new stream power based relation suggested by Nearing et al. (1997) as alternatives to the WEPP transport capacity equation.

Julien and Simon (1985) analyzed the existing sediment transport equations and presented an equation in a general form:

$$q_s = p\, q^m \sin ß^n\, i^d\, (1 - t_0 / t)^e \qquad \text{[Eq 5]}$$

where q_s is the sediment flux, q is the water flux, ß is the slope angle, i is the rainfall intensity, t_0 and t are the critical shear stress and shear stress respectively, and p, m, n, d, and e are experimental or physically based coefficients. WEPP uses this equation with m=n=1.5. We tested it for values of m=0.6 through 2.0. Willgoose, Bras, and Rodriguez-Iturbo (1989) showed that the parameter m depends on the type of flow and channel geometry, thus indicating that in complex terrain and cover conditions this coefficient should be spatially variable depending on the type of flow in a particular area. When m is large, water flow has a great effect on erosion patterns; when m is small, terrain has a more profound effect.

For modeling erosion in a rill, Nearing et al. (1997) presented an improved fit to several sets of experimental data by relating sediment load q_s to stream power o:

$$\log q_s = A + \{B \exp (C + D \log o) / [1 + \exp (C + D \log o)]\} \qquad \text{[Eq 6]}$$

with the constants A = -34.47, B = 38.61, C = 0.845, D=0.412.

Based on experimental conditions, it was suggested that this equation could be a reasonable estimation of the sediment transport capacity. The equation can be rewritten to the following form (Mitas and Mitasova 1997):

$$T(r) = | q_s(x,y) | = a_0 \exp [-\{ b / \{1 + [o(x,y) / o_0]^d \}\}] \qquad \text{[Eq 7]}$$

where a_0=1380, b=88.90, d=0.179, o_0=8.89.$10^{-6,}$ and o is the stream power.

This form of the equation allows us to define a physical interpretation of the constants, as a_0 represents a saturated sediment load for infinitely large stream power, o_0 is a "reference" stream power, and b=88.90 and d=0.179 are dimensionless exponents.

Strictly speaking, the choice of the constants corresponds to the experimental results used in the fit and could be different in other cases (e.g., an effective transport capacity coefficient analogous to the one in the Julien and Simon equation (Equation 5) has to be included for different covers, etc). The Mitas and Mitasova equation (Equation 7) differs from the Julien and Simon equation in that the effect of flow velocity is incorporated directly into transport capacity via the stream power. For complex terrain and cover conditions, flow velocity can change dramatically with varying location, so one can expect differences in predicted patterns of erosion/deposition by using the latter equation as the sediment transport capacity.

The general pattern of erosion and deposition predicted by using the stream power based equation for transport capacity was similar to the patterns obtained from the shear stress based equation (Figure 8). However, there were significant quantitative differences as well as more dramatic spatial variability in the erosion regimes due to the variability of the first order reaction coefficient. Preliminary results indicate that the stream power based equation is significantly different from the sheer stress equation and deserves further investigation and experimental testing, especially for different types of soils and larger sizes of experimental plots.

Visualization

Simulation of landscape processes is more sensitive to noise and artifacts in landscape characterization data than the more traditional uses of GIS such as automatic map production or spatial analysis. The efficiency of simulations depends on digital data representation; representation by polygons, commonly used for mapping, is less efficient for process simulations. Also, the models often

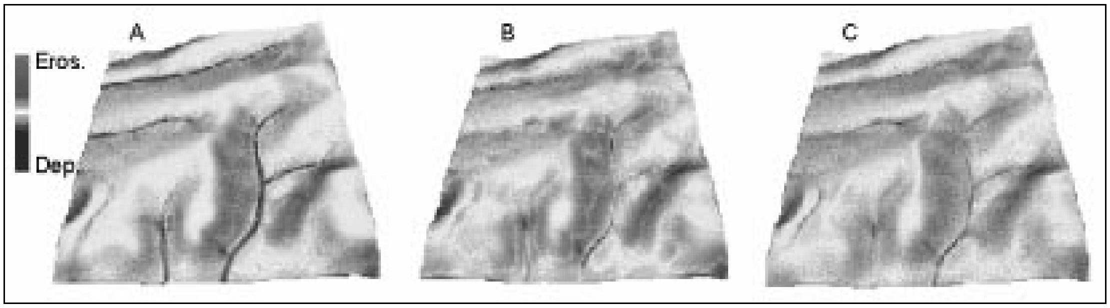

Figure 8. Erosion and deposition as a result of using different equations. Graphics represent the Julien and Simon equation with m=1.5 (A) and m=0.6 (B), and the Mitas and Mitasova equation (C).

include complex spatial and spatio-temporal relationships, and their understanding requires more sophisticated graphical representations than the standard 2D maps. Therefore, there is a continuing effort to extend the GIS capabilities to support modeling and simulation of processes by implementing new, advanced methods and data structures. This effort focused on improving methods for multivariate spatial interpolation, topographic analysis, and visualization, and extending the data structures to support multivariate point and raster format. Some of these improved capabilities will be available within the new GRASS releases in cooperation with the Baylor University GRASS Research Group (http://www.baylor.edu/~grass/).

From the point of view of spatial modeling, the representation and visualization of soil data poses a significant challenge. The spatial variability of soil properties in a vertical profile requires resolutions much higher than those used for the representation of the same phenomena in a horizontal plane (i.e., centimeters versus meters). Using data from a comprehensive soil survey from the Scheyern Experimental Farm, we investigated two primary approaches to creating a 3D model of soil properties: (1) sorting the data by horizons, interpolating a 2D raster map for each horizon at 2m resolution, and creating a multiple surfaces model; and (2) interpolating the 3D data to a 3D raster map with 2m horizontal and 0.1m vertical resolution using the trivariate implementation of the RST method (Figure 9). The full 3D model is more appropriate than the representation based on multiple surfaces, as it incorporates the vertical relationships into the interpolation and allows more efficient visual analysis. The 3D spatial model of organic carbon shows the highest concentrations in the area with long-term grass cover. However, as expected, the amount of organic carbon rapidly decreases with depth. The values for hydraulic conductivity were derived from information on particle size distribution for each sample. The interpolated 3D raster map, together with a DEM, can be used as an input for a 3D infiltration model, enhancing the realism of hydrologic simulations. The pH model shows greater spatial variability in the vertical direction, with areas of low pH (high acidity) located primarily in grassy areas.

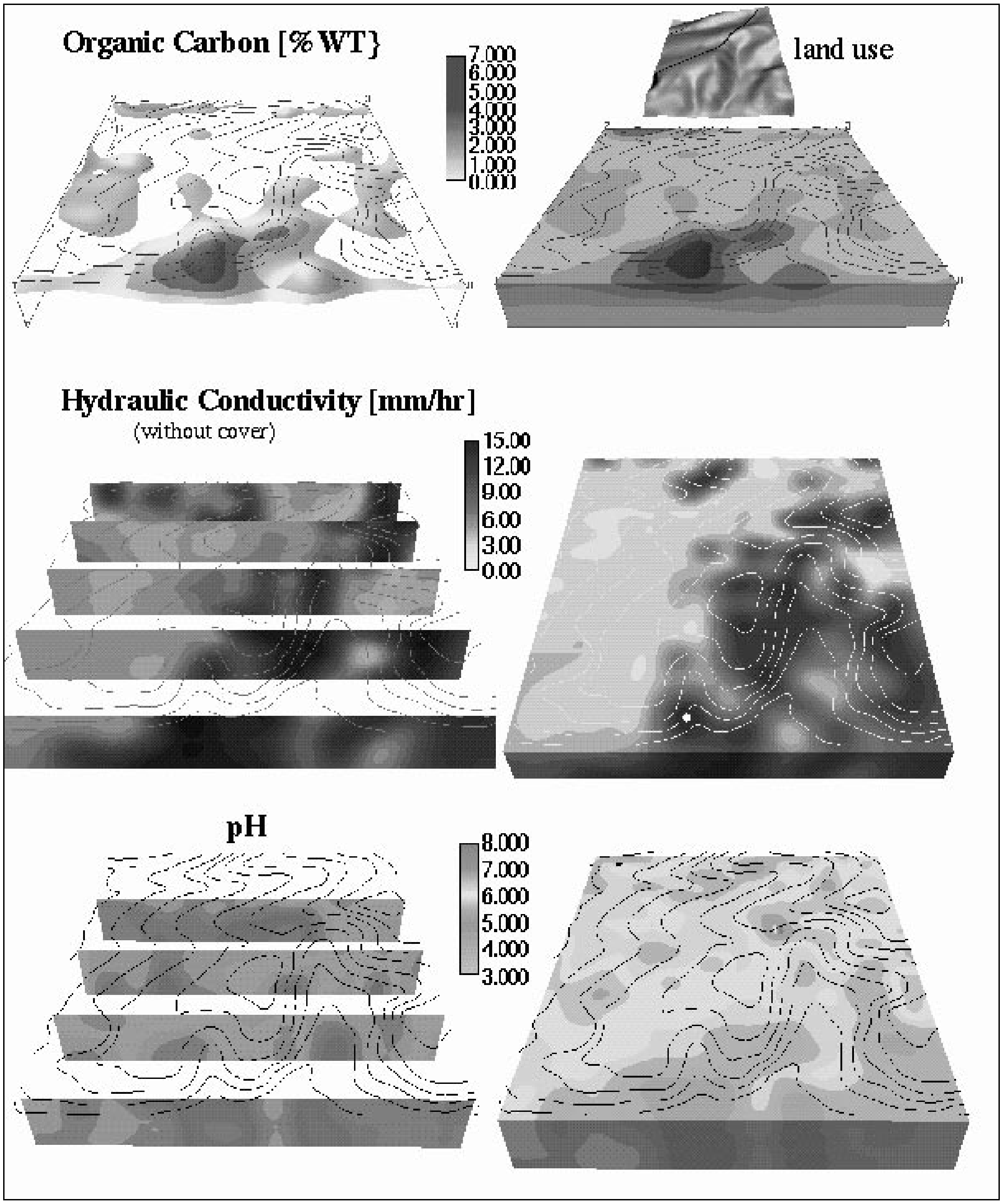

Figure 9. Three-dimensional visualization of soil organic matter content, hydraulic conductivity, and pH. The vertical profile has been exaggerated 100x to facilitate visualization. The small

insert labeled "land use" shows cultural practices at the time the data were collected; the brown areas represent cultivated areas while the green areas are grassed.

Simulation of the Impact of Erosion, Runoff, and Sediment Control Practices

During FY97, we investigated the possibility of using the SIMWE model to analyze and design the placement of vegetation for erosion control. Using the Scheyern Experimental Farm in Germany as the case study, we investigated the implications of altering the spatial distribution of land cover. At the time of original collaboration with the Scheyern Experimental Farm, approximately 21 percent of the study area was planted in grass; the remainder was cultivated This land use resulted in severe erosion when a large storm event occurred during the time when the agricultural fields were bare. As a result, the farm implemented some "best management practices" in an attempt to curb the erosion. The practices consisted of planting wide-grassed buffers at the valley bottom. The new scenario consisted of 41 percent grassed areas, with the remainder under cultivation. The hydrologic consequences of the two scenarios, as predicted by SIMWE, are shown in Figure 10 (A and B).

Using SIMWE, we attempted to optimize the placement of grassed areas in the watershed. First, we used the model to identify locations with the highest erosion risk, assuming a uniform land use. Then, a protective grass cover was distributed to the high risk areas. The predicted results of this strategy are shown in Figure 10C. By strategically placing only 19 percent grass cover, the model shows that virtually all sediment was eliminated from the stream channel. Although significant erosion was still evident with the "optimized" design, the results demonstrate the potential to use the SIMWE model to dramatically reduce soil loss and sediment loads in the ephemeral streams, while minimizing management input and maximizing agricultural production. We found that the effectiveness of this design depends on differences in roughness; a combination of very smooth bare soil and a very dense grassed waterway resulted in predictions of higher erosion along the borders of the grassed waterway.

We also tested the capabilities of the SIMWE model to simulate water flow and erosion processes in the presence of runoff and erosion control structures such as terraces and ponds. Such structures create significant topographic discontinuities. To create these topographic discontinuities, we modified the terrain surface to represent a simplified pond (depression) and a terrace (discontinuity-fault and a small flat area with zero gradient). Tests were conducted using a hypothetical case of uniform soil and vegetative cover. The SIMWE algorithm was robust enough to simulate the water and sediment flow even for this complex situation, as illustrated by Figure 11. Water and sediment accumulated within the pond and the terrace. The results are encouraging, and allow us to target the simulation of more complex and realistic structures in the future.

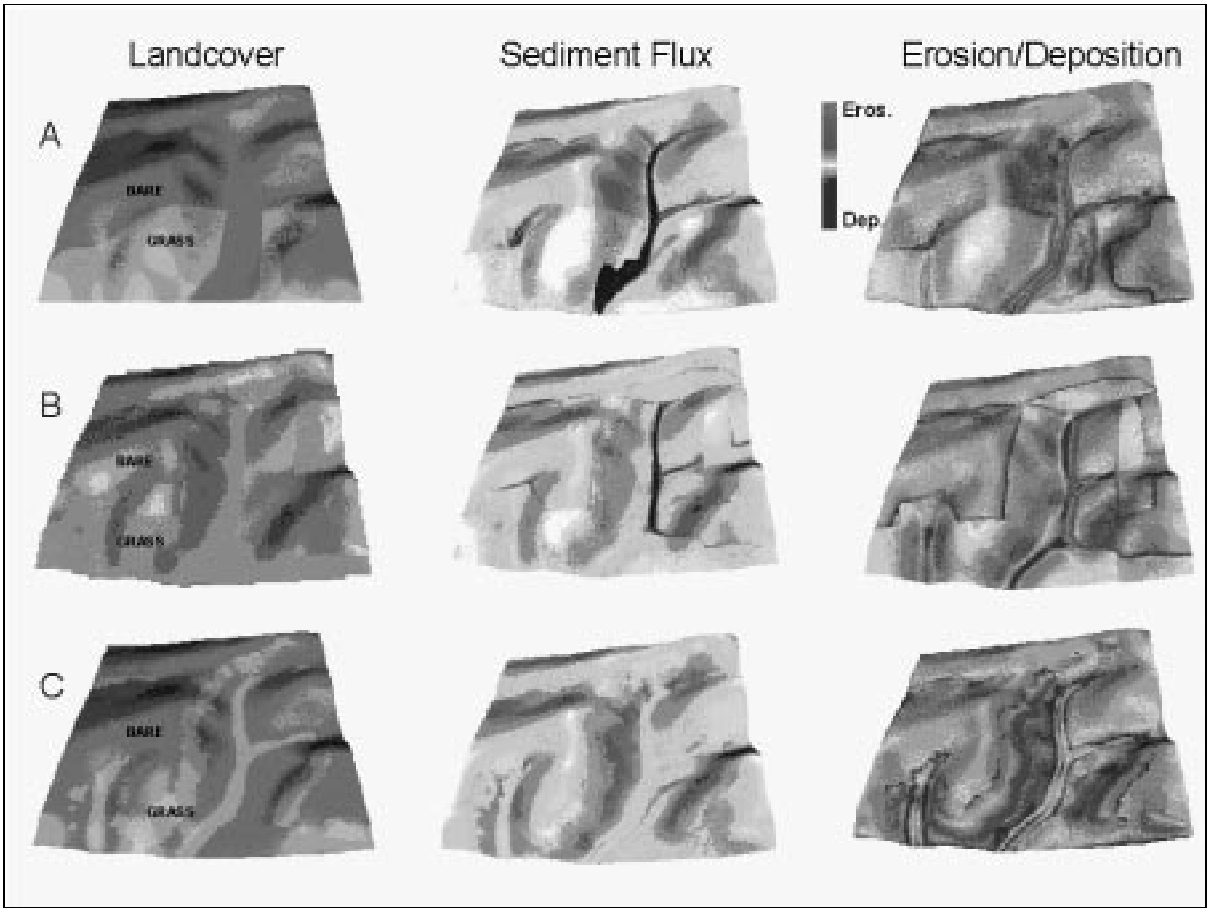

Figure 10. Estimates of sediment flux and spatial patterns of erosion and deposition predicted by SIMWE. Graphics represent the original distribution of grass (green) vs. cultivated area (brown) at the Scheyern Experimental Farm (A), the new design (B), and the design optimized by SIMWE (C).

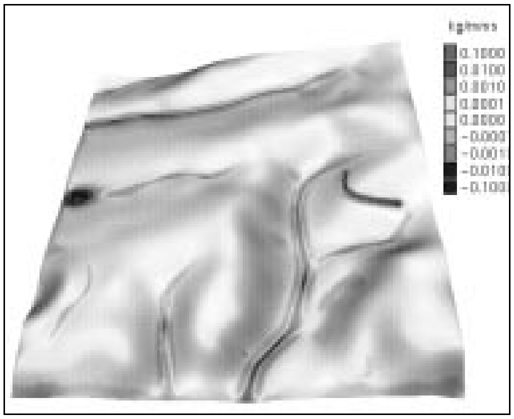

Figure 11. Impact of terrain structures on water and sediment flow and net erosion/depostion under uniform conditions. A sediment retention basin has been simulated near the left margin of the figure. The simulation shows significant deposition in the basin. A simulated terrace is seen as the crescent shape near the right side of the figure. Note that deposition occurs above the terrace, but erosion occurs on the downslope side of the terrace.

4 Applications

One of the goals of this project is to develop methods and tools for erosion risk assessment and erosion prevention in support of military installations. This task poses a special challenge because military installations often occupy large areas with terrains much more complex than typical agricultural regions for which most of the traditional erosion modeling tools were developed. In addition, the manner in which military installations are used often creates a mosaic of relatively well preserved natural areas intermingled with landscapes exposed to high intensity disturbance. The principles of process-based erosion modeling developed for agriculture lands have to be significantly enhanced and new approaches have to be developed to meet this challenge. This section will demonstrate some of those methodologies with examples from Fort Irwin, CA and Fort McCoy, WI.

Fort Irwin

To illustrate the issues associated with simulations for large areas, we used an example of a mountainous region at Fort Irwin, CA. The standard 30-m DEM available for the entire study area (3000 square km) represents 4 million grid cells, a challenging data set for the current process-based simulation tools and workstations. Unfortunately, the 30-m resolution is only adequate for rough identification of high erosion risk areas. To capture such features as roadways, a 5-m resolution is preferred. Such a data set would contain 121 million grid cells; simulations would be prohibitively expensive, if not impossible, with current computational resources. It is clear that for such a large area, modeling at different scales and resolutions is needed, depending on the importance and complexity of the watersheds. The aim of the following illustration is to demonstrate potential strategies for using standard 30-m elevation data for erosion simulations in a large area. Climate, soil, and cover properties will vary dramatically in nature but are held constant in this example.

Digital Elevation Model and Topographic Analysis

Topographic parameters serve as inputs to erosion models, but they are also useful for evaluating the quality of a DEM and identifying possible noise and systematic errors as illustrated by the following example of terrain with draped tangential curvature. Tangential curvature for the standard 30-m DEM shows acceptable structure in the mountainous area, while significant noise and systematic errors (stripes) are present in the lowland (Figure 12A). After smoothing and resampling to a 10-m resolution using the RST interpolation method, the noise is reduced (density of striping is reduced) and the major topographic features become more visible (Figure 12B). These images clearly demonstrate that the need for precision and accuracy is spatially variable, with flatter areas much more sensitive than mountains. Note how the artificial structure in flat areas continuously transforms into the real terrain structure in mountains. This is an especially troublesome phenomenon if a DEM is to be used for simulations, as the artificial structure can be mistaken for the real topographic feature.

USPED

To illustrate the impact of smoothing and resampling on erosion modeling with the USPED model, we computed the topographic potential for net erosion/ deposition at three resolutions. The differences in detail that can be achieved at various resolutions are demonstrated as color maps draped over the 10-m resolution DEM for a 36 sq km area (Figure 13). While the 10-m resolution does not improve the accuracy of the original elevation model, the smoothing reduces the noise and the higher resolution facilitates a better description of terrain geometry, thus leading to more realistic results of erosion model. The USPED model is very sensitive to artifacts in a DEM as it is a function of second order derivatives (curvatures) of the elevation surface (Mitasova et al. 1997).

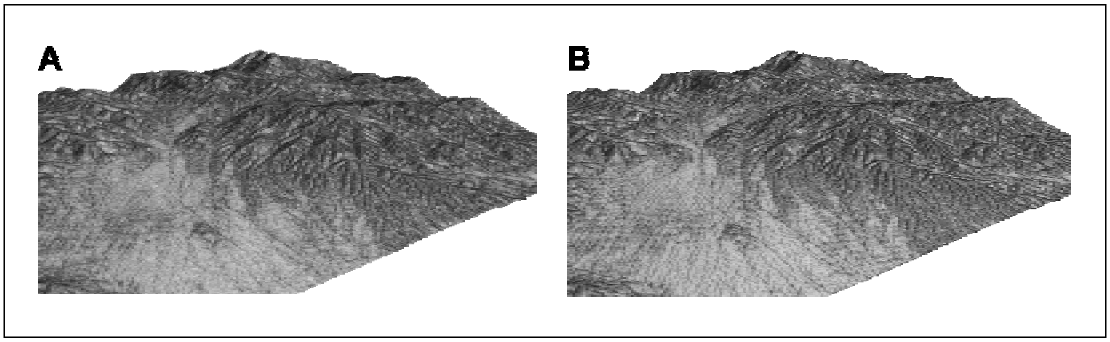

Figure 12. Terrain with draped tangential curvature using the original 30-m DEM (A) and with a resampled 10-m DEM with smoothing (B).

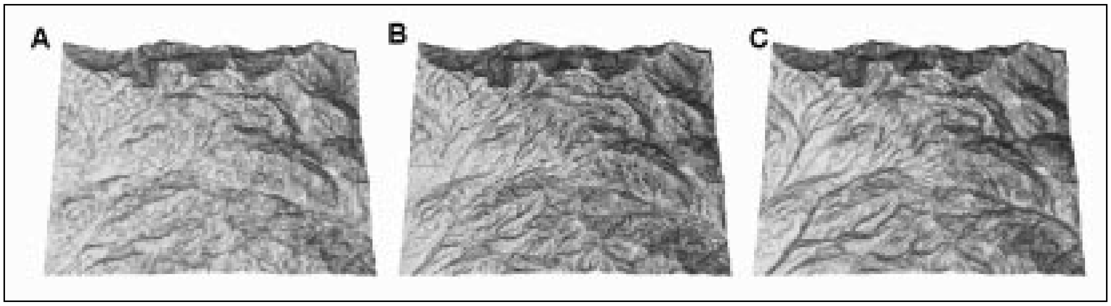

Figure 13. The topographic potential for net erosion and deposition as predicted by the USPED model using DEM resolutions of 90 (A), 30 (B), and 10 m (C).

SIMWE

Incorporating a 10-m resolution DEM with smoothing, we used the SIMWE model to calculate sediment flow rates and net erosion/deposition for a 36 sq km area (Figure 14). SIMWE calculates sediment flow rates by solving the continuity of mass equation. The results show high sediment flow rates in the centers of valleys with dispersal of sediment flow in some. Net erosion/deposition rates were estimated for a regime where sediment transport is a limiting factor. The erosion/deposition results of the SIMWE model compare well with the results of the USPED model at the same resolution.

Fort McCoy

Using the USPED model to estimate the topographic potential for erosion and deposition, we compared the results of a standard 30-m resolution DEM (1-m vertical resolution) with a 10-m resolution DEM (0.1-m vertical resolution) for an area at Fort McCoy, WI (Figure 15). The 10-m DEM was derived from the 30-m DEM by resampling and smoothing. With the 30-m DEM, the USPED model adequately predicts areas of high potential for soil erosion, especially in hilly areas and along streams. It also shows that a significant portion of the material eroded from hillslopes is deposited before it reaches the main streams. However, the map created with the 30-m DEM inadequately predicted zones of high erosion due to concentrated flow in valleys. In addition, there are artificial waves of erosion and deposition along the 1-m contours in flatter areas. The artificial waves are due primarily to the inadequacy of the 1-m vertical resolution with the 30-m DEM.

When the 10-m resolution DEM was used with the USPED model, high erosion continued to be evident in the hilly areas and along main streams; deposition is predicted in concave areas (Figure 15B). However, unlike the map derived with 30-m elevation data, the 10-m resolution DEM map also indicates high erosion in areas with concentrated flow that could reach the main streams. The artificial pattern of erosion/deposition along contours is not present.

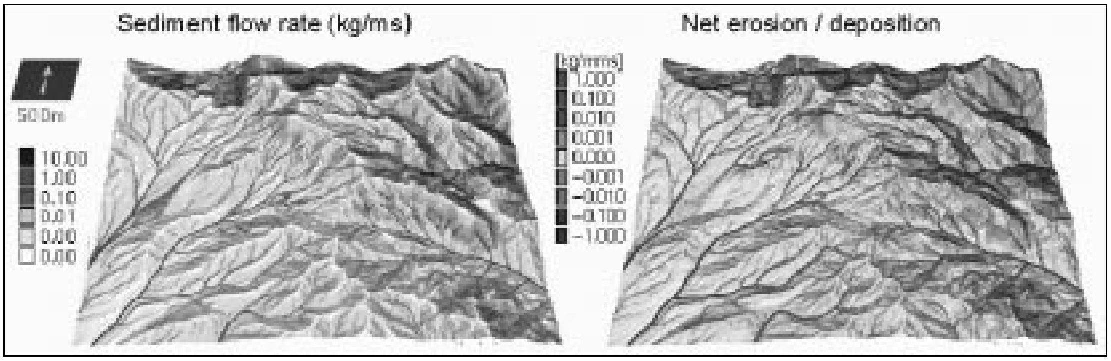

Figure 14. Sediment flow rate and net erosion/deposition as predicted by the SIMWE model using a 30-m resolution DEM resampled and smoothed to 10-m resolution.

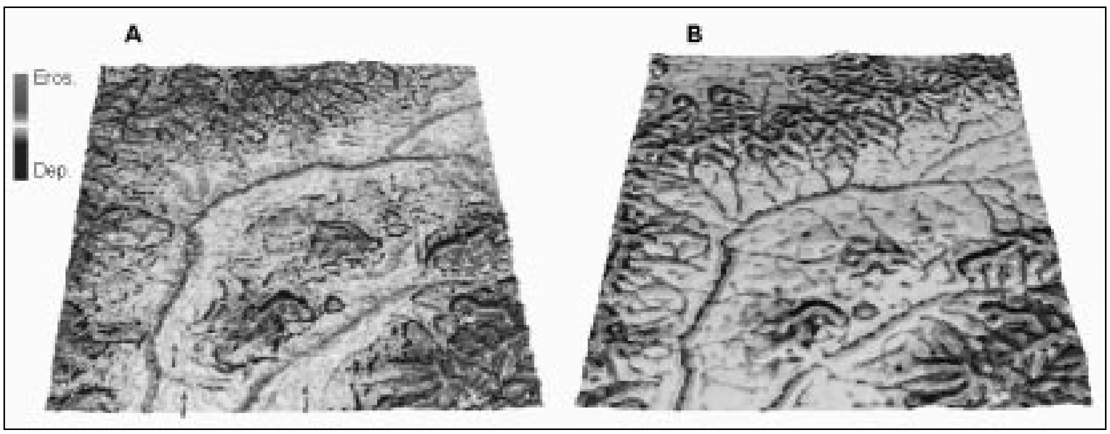

Figure 15. Topographic potential for erosion and deposition as predicted by the USPED model using a 30-m resolution DEM (A) and a 10-m resolution DEM (B) created by resampling and smoothing the 30-m DEM.

5 Summary and Future Improvements

The CASC2D, USPED, and SIMWE models represent significant advances in runoff, erosion, sediment routing, and sediment deposition modeling. This document illustrates the application of several aspects of advanced GIS methods and tools for landscape characterization and process simulation. We demonstrated the importance of a proper choice of interpolation method when preparing the input data for simulations. Replacing geometry-based algorithms by physics-based models improves the flow-related topographic analysis. The extension of GIS to three dimensions allows the creation of spatial models that capture the distribution of phenomena in 3D space. However, anisotropic scaling and resolution are also needed to create meaningful models.

Implementation of the concept of multivariate fields for landscape characterization and development of appropriate supporting tools increase the efficiency of data preparation, analysis, and presentation of simulation results. This approach further supports the move from profile and/or polygon-based models, to full 3D dynamic simulations based on multivariate fields.

The stochastic method of solving the first principles equations using the Green's function Monte Carlo technique provides a valuable research tool with much needed robustness and flexibility. It enables the investigation of several important issues such as erosion/deposition regimes, forms of sediment transport capacity, and different land use scenarios in a complex landscape. Using the bivariate formulation, we have theoretically elucidated the observed relationships between patterns of erosion/deposition and the terrain shape in the transport capacity limited regime. In particular, we have shown the relationship of terrain profile and tangential curvatures with observed patterns and have demonstrated that both curvatures are equally important for proper description and understanding of erosion in 3D space.

A suggestion of Nearing et al. (1997) that sediment loads from rills may be more strongly influenced by a sediment transport than by soil detachment, in general, agrees with our results. This seems to be true especially in complex terrain conditions where transport capacity changes significantly due to variations in terrain shape and cover, thus significantly affecting the distribution and amplitude of the water flow. Our calculations and analyses also suggest that sediment transport capacity plays a more important role than anticipated by the previous research, which focused on erodibility as the key control quantity. Obviously, a subtle and spatially variable interplay between erodibility and transport capacity can influence the processes in a profound way. We believe that this complexity clearly points toward the importance of the high accuracy-high resolution 2D simulations as one of the most promising research areas.

Fiscal year 1998 is the last year of funding for this project. During FY98, we will continue to make improvements to CASC2D, USPED, SIMWE, and the visualization capability. In addition, we will focus effort on validating each of the models with data from military installations. Efforts will be expended to extract vehicle-soil-climate relationships from existing databases at the U.S. Army Engineer Waterways Experiment Station; additional data will also be collected. Recognizing the need to make the new generation models available to others, we will attempt to provide a “cookbook” that will lead potential users through the appropriate steps of solving the models with the Geographic Resources Analysis Support System (GRASS) and Arc Info geographic information systems.

The products resulting from this project will improve the capability to generate accurate digital elevation models and perform topographic analyses for various terrain-related applications. There will be improved capability to estimate erosion/deposition potential as an input for choosing optimal land use management and rehabilitation programs. Modeling of erosion and deposition will help land managers and trainers optimize the training schedules, delineate training areas, and monitor changes over time. The models will also help maximize the availability of military lands with minimal impact to natural resources, especially to soil and vegetation. The overall net result of this research will be improved land management and reduced land maintenance costs.

References

Bjorneberg, D. L., J.K. Aase, and T.J. Trout. 1997. "WEPP model erosion evaluation under furrow irrigation." American Society of Agricultural Engineers Paper No. 972115, Minneapolis, MN. ASAE, St. Joseph, MI.

Doe, W.W., B. Saghafian, and P.Y. Julien. 1996. "Land-use impact on watershed response: the integration of two-dimensional hydrological modelling and geographical information systems." *Hydrological Processes* 10:1503-1511.

ESRI. 1997. *ArcView Spatial Analyst*. Environmental Systems Research Institute, Redlands, California.

Finkner, S.C, M.A. Nearing, G.R. Foster, and J.E. Gilley. 1989. "A simplified equation for modeling sediment transport capacity." *Transactions of the American Society of Agricultural Engineers* 32:1545-1550.

Flanagan, D.C. and S.J. Livingston, editors. 1995. *WEPP User Summary, USDA-Water Erosion Predition Project (WEPP).* National Soil Erosion Research Laboratory Report No. 11. U.S. Department of Agriculture, Agricultural Research Service, West Lafayette, IN.

Flanagan, D.C. and M.A. Nearing, editors. 1995. *Technical Documentation, USDA-Water Erosion Prediction Project (WEPP).* National Soil Erosion Research Laboratory Report No. 10. US Department of Agriculture, Agricultural Research Service, West Lafayette, IN.

Foster, G.R., and L.D. Meyer. 1972. "A closed-form erosion equation for upland areas." Pages 12.1 - 12.19. In: H.W. Shen (ed), *Sedimentation: Symposium to Honor Prof. H.A. Einstein*, Colorado State University, Ft. Collins, CO.

Govers, G. 1991. "Rill erosion on arable land in central Belgium: rates, controls and predictability." *Catena* 18:133-155.

Guy, B.T., R.P. Rudra, and W.T. Dickinson. 1991. "Process-oriented research on soil erosion and overland flow." Pages 225-242. In: A.J. Parsons and A.D. Abrahams (eds), Overland Flow Hydraulics and Mechanics. Chapman and Hall, New York.

Haan, C.T., B.J. Barfield, and J.C. Hayes. 1994. *Design Hydrology and Sedimentology for Small Catchments*. Academic Press.

Hong, S. and S. Mostaghimi. 1995. "Evaluation of selected management practices for nonpoint source pollution control using a two-dimensional simulation model." Presented as American Society of Agricultural Engineers Paper No. 952700, Chicago, IL. ASAE, St. Joseph, MI.

Johnson, B.E., P.Y. Julien, D.K. Molnar and C.C. Watson. 1998. "The two-dimensional upland erosion model CASC2D-SED." *Water Resources Research* (submitted).

Julien, P.Y., B. Saghafian, and F. L. Ogden. 1995. "Raster-based hydrologic modeling of spatially varied surface runoff." *Water Resources Bulletin* 31:523-536.

Julien, P.Y. and D.B. Simon. 1985. "Sediment transport capacity of overland flow." *Transactions of the American Society of Agricultural Engineers* 28:755-762.

Meyer, L.D. and W.H. Wischmeier. 1969. "Mathematical simulation of the process of soil erosion by water." *Transactions of the American Society of Agricultural Engineers* 12:754-758.

Mitas, L., W.M. Brown, and H. Mitasova. 1997. "Role of dynamic cartography in simulation of landscape processes based on multi-variate field," *Computers and Geosciences* 23:437-446. (http://www.elsevier.nl/inoa/homepage/miss/cageo/mitas/mitas.htm)

Mitas, L. and H. Mitasova. 1997. "Green's function Monte Carlo approach to erosion modeling in complex terrain." Presented as American Society of Agricultural Engineers Paper No.973066, Aug 10-14, Minneapolis, MN. ASAE, St. Joseph, MI

Mitas, L. and H. Mitasova. 1998. "Distributed soil erosion simulation for effective erosion prevention." *Water Resources Research* 34:505-516.

Mitasova, H., W.M. Brown, L. Mitas, and S.D. Warren. 1997. "Multi-dimensional GIS environment for simulation and analysis of landscape processes." Presented as American Society of Agricultural Engineers Paper No. 973034, Aug 10-14, Minneapolis, MN. ASAE, St. Joseph, MI.

Mitasova, H. and J. Hofierka. 1993. "Interpolation by regularized spline with tension: II. Application to terrain modeling and surface geometry analysis." *Mathematical Geology* 25:657-669.

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

Mitasova, H. and L. Mitas. 1993. "Interpolation by regularized spline with tension: I. Theory and implementation." *Mathematical Geology* 25:641-55.

Mitasova, H., L. Mitas, W.M. Brown, D.P. Gerdes, I. Kosinovsky, and T. Baker. 1995. "Modeling spatially and temporally distributed phenomena: new methods and tools for GRASS GIS." *International Journal of Geographical Information Systems* 9:443-446.

Moore, I.D. and G.J. Burch. 1986. "Physical basis of the length-slope factor in the Universal Soil Loss Equation." *Soil Science 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., L.D. Norton, D.A. Bulgakov, G.A. Larionov, L.T. West, and K.M. Dontsova. 1997. "Hydraulics and erosion in eroding rills." *Water Resources Research* 33:865-876.

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

Willgoose, G.R., R.L. Bras, and I. Rodriguez-Iturbe. 1989. A physically based channel network and catchment evolution model. Massachussetts Institute of Technology Technical Report No. 322. Cambridge, MA.

Wischmeier, W.H. and D.D. Smith. 1978. *Predicting rainfall erosion losses: a guide to conservation planning.* U.S. Department of Agriculture, Agriculture Handbook 537.

Appendix: List of Publications

The following list of publications and presentations are all products of this SERDP project.

Peer-reviewed Publications

1. Mitas, L. and H. Mitasova. 1998. "Distributed soil erosion simulation for effective erosion prevention." *Water Resources Research* 34:505-516.

2. Mitas L., W.M. Brown, and H. Mitasova. 1997. "Role of dynamic cartography in simulations of landscape processes based on multi-variate fields." *Computers and Geosciences* 23:437-446. (http://www.elsevier.nl/inca/homepage/miss/cageo/mitas/mitas.htm)

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

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

5. Mitasova, H., L. Mitas, W.M. Brown, D.P. Gerdes, and I. Kosinovsky. 1995. "Modeling spatially and temporally distributed phenomena: New methods and tools for GRASS GIS." *International Journal of Geographical Information Systems* 9:443-446.

6. Saghafian, B., P. Y. Julien, and F. L. Ogden. 1995. "Similarity in catchment response 1. Stationary rainstorms." *Water Resources Research* 31:1533-1541.

7. Julien, P.Y., B. Saghafian, and F.L. Ogden. 1995. "Raster-based hydrologic modeling for spatially-varied surface runoff." *Water Resources Bulletin* 31:523-536.

8. Mitasova, H., W.M. Brown, and J. Hofierka. 1994. "Multidimensional dynamic cartography." *Kartograficke listy (Cartographic Letters*) 2:37-50.

Chapters in Books

1. Mitas, L. and H. Mitasova. 1998. "Spatial Interpolation." In: P.Longley, M.F. Goodchild, D.J. Maguire, D.W. Rhind (eds.), John Wiley & Sons, Chichester, West Sussex, UK (in press).

2. Saghafian, B. 1996. "Implementation of a Distributed Hydrologic Model within GRASS." Pages 205-208. In: M.F Goodchild, L.T. Steyaert and B.O. Parks (eds), *GIS and Environmental Modeling: Progress and Research Issues*. GIS World, Inc., Ft. Collins, CO.

3. Mitasova, H., L. Mitas, W.M. Brown, D.P. Gerdes, I. Kosinovsky, and T. Baker. 1996. "Modeling spatially and temporally distributed phenomena: New methods and tools for Open GIS." Pages 345-352. In: M.F. Goodchild, L.T. Steyaert, and B.O. Parks (eds.), *GIS and Environmental Modeling: Progress and Research Issues*, GIS World, Inc., Ft. Collins, CO.

Proceedings, Reports, and Other Publications

1. Mitas, L. and Mitasova, H. 1997. Green's function Monte Carlo approach to erosion modeling in complex terrain. Paper 973066. American Society of Agricultural Engineers annual meeting. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659.

2. Mitasova, H., W M Brown, L. Mitas, and S.D. Warren. 1997. Multi-dimensional GIS environment for simulation and analysis of landscape processes. Paper 973034. American Society of Agricultural Engineers annual meeting. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659.

3. Mitas, L., H. Mitasova, W.M. Brown, and M. Astley. 1996. Interacting fields approach for evolving spatial phenomena: application to erosion simulation for optimized land use. In: M.F. Goodchild, L.T. Steyaert and B.O. Parks (eds), Proceedings of the III International Conference on Integration of Environmental Modeling and GIS. Santa Fe, NM. National Center for Geographic Information and Analysis, Santa Barbara, CA. Available on CDROM and WWW.

4. Brown,W.M., M. Astley, T. Baker, and H. Mitasova. 1995. GRASS as an integrated GIS and visualization environment for spatio-temporal modeling. Pages 89-99. In: Proc. Auto-Carto XII, February 12 - March 2, Charlotte, NC. American Congress on Surveying and Mapping and American Society for Photogrammetry and Remote Sensing.

Professional Presentations

1. Johnson, B.E., P.Y. Julien, and C.C. Watson. 1998. Development of a storm-event based two-dimensional upland erosion model (CASC2D-SED). First Federal Interagency Hydrologic Modeling Conference, April 21 - April 25, Las Vegas, NV.

2. Mitas, L., H. Mitasova, and W.M. Brown. 1997. Multi-variate fields and process based landscape simulations: Application to erosion modeling and land use optimization. Illinois GIS Association Conference, April 15-16, Champaign, IL.

3. Warren, S.D. and W.D. Goran. 1997. Erosion and sediment modeling. Department of Defense Environmental Security Modeling and Simulation Technical Workshop, Mar 19, Washington, DC.

4. Mitas, L., H. Mitasova, and W.M. Brown. 1996. Multi-variate fields and process based landscape simulations: Application to erosion modeling and land use optimization. Geographic Modeling Systems (GMS) Lab and USACERL GIS Colloquium Series, December 18, Champaign, IL.

5. Mitas, L., H. Mitasova, W. Brown, and M. Astley. 1996. Interacting fields approach for evolving spatial phenomena: application to erosion simulation for optimized land use. Third International Conference on Integration of Environmental Modeling and GIS, January 21-25, Santa Fe, NM.

6. Mitas, L., H. Mitasova, and S.D. Warren. 1996. Distributed, process-based erosion simulations for optimization of land rehabilitation measures. 5th Annual Land Rehabilitation and Maintenance Workshop, August 26-29, LaCrosse, WI.

7. Warren, S.D., K Auerswald, H. Mitasova, and L. Mitas. 1996. Advanced tools for predicting soil erosion and deposition. Second International Congress of the European Society of Soil Conservation, Sep 1-7, Munich, Germany.

8. Warren, S.D., L. Mitas, and H. Mitasova. 1996. Terrain modeling and soil erosion simulation. Second Annual Strategic Environmental Research and Development Program Symposium, Nov 20-22, Vienna, VA.

9. Mitasova, H., L. Mitas, and W.M. Brown. 1995. Digital elevation modeling and soil erosion simulation. First Annual Strategic Environmental Research and Development Program Symposium, April 12-14, Washington DC.

10. Mitasova, H., L. Mitas, W.M. Brown, S.D. Warren, and K. Auerswald. 1995. Multidimensional GIS tools for spatially distributed phenomena: Application to soil erosion prediction. American Society of Agricultural Engineers Annual Meeting, June 18-23, Chicago, IL.

11. Brown,W.M., M. Astley, T. Baker, and H. Mitasova. 1995. GRASS as an integrated GIS and visualization environment for spatio-temporal modeling. Auto-Carto 12, February 27 - March 2, Charlotte, NC. American Congress on Surveying and Mapping and American Society for Photogrammetry and Remote Sensing.

12. Saghafian, B. and F. L. Ogden. 1994. Two-dimensional hydrologic modeling CASC2D workshop. Memphis State University, Memphis, TN. June 9-10.

13. Ogden, F.L., B. Saghafian, and W. F. Krajewski. 1994. GIS-based channel extraction and smoothing algorithm for distributed hydrologic modeling. Annual American Society of Civil Engineers National Conference on Hydraulic Engineering, Buffalo, NY.

14. Kosinovsky, I., H. Mitasova, and D.P. Gerdes. 1994. Library for Multidimensional Surface Modeling and Analysis in GRASS. 9th Annual GRASS/GIS Conference, Reston, VA.

15. Brown, W.M. 1994. Multi-Dimensional Visualization using GRASS. 9th Annual GRASS/GIS Conference, Reston, VA.

16. Mitasova, H., L. Mitas, and I. Kosinovsky. 1994. Surface modeling. USDA, Soil Conservation Service, Midwest GIS meeting, Champaign, IL.

17. Mitasova, H. 1994. Surface modeling: Analysis and visualization with applications to environmental modeling. Lectures at the National Center for Geographic Information and Analysis, March 9-11, Santa Barbara, CA.

Trade Journal Articles

1. Mitasova, H., L. Mitas, W.M. Brown, and S.D. Warren. 1997. "GIS environment for simulation and analysis of landscape processes." *Mapnotes* 15:7-14. Illinois GIS Association.

Papers Under Review and in Preparation

1. Warren, S.D., H. Mitasova, K. Auerswald, and M.G. Hohmann. "A comparison of methods to determine slope steepness from digital elevation data." *Catena* (in preparation).

2. Ogden, F.L. and B. Saghafian. "Fully integrated distributed hydrologic modeling with GIS." *Journal of Hydrology* (submitted).

3. Johnson, B.E., P.Y. Julien, D.K. Molnar, and C.C. Watson. "The two-dimensional upland erosion model CASC2D-SED" (submitted).

USACERL DISTRIBUTION

Chief of Engineers
ATTN: CEHEC-IM-LH (2)
ATTN: CEHEC-IM-LP (2)
ATTN: CECC-R
ATTN: CERD-L
ATTN: CERD-M

Center for Ecol. Mgmt of Military Lands (3)
Fort Collins, CO 80523

Defense Tech Info Center 22304
ATTN: DTIC-O (2)

SERDP (6)

18
8/98