Multiscale Simulation of Land Use Impact on Soil Erosion and Deposition Patterns

Helena Mitasova*, Lubos Mitas and William M. Brown

ABSTRACT

Sustainable use of natural resources requires coordination of conservation efforts between a diverse group of individuals and agencies that view and manage the landscape at different scales, from field level by a farmer, to entire watersheds by state or federal agencies. To better support the multilevel management, we propose a methodology for erosion modeling at multiple scales and levels of complexity. Simple estimates are performed by the modified USLE and Unit Stream Power based model. More detailed simulations of land use impacts are supported by the process-based erosion model SIMWE (SIMulated Water Erosion). The SIMWE model is designed for spatially variable terrain, soil, and cover conditions enabling us to capture spatial aspects of watershed's internal behavior. The model is based on the Monte Carlo solution of bivariate water and sediment flow continuity equations, and supports modeling with spatially variable resolutions. We illustrate the outlined methodology by studies of land use impacts on erosion and deposition patterns in a Pilot Watershed in Illinois and experimental farm in Germany.

INTRODUCTION

Effective conservation of natural resources requires coordination of efforts between individual landowners and government agencies, involving planning and decision making at different scales and levels of detail. At a *regional scale*, watersheds are often represented as homogeneous units with terrain, soil, and cover conditions described by averaged values. The watershed-based models (SWAT: Arnold et al. 1993) simulate a broad spectrum of processes (surface and subsurface water flow, sediment and pollutant transport, etc.) with continuous time simulation. The results represent averages for entire watersheds/sub watersheds, so lower resolution (100-30m) raster or polygon data are sufficient. This approach supports management at a regional, level, which involves, for example, identification of watersheds with high risk composition of land use, or designation of watershed level conservation areas.

Landowner's level of management requires detailed spatial representation (10-1m resolution) and models capable to simulate effects of spatially variable land cover. This level of detail is necessary for implementation of conservation practices at the most effective locations, as well as for selecting the projects that save the most soil or benefit the most acres per dollar cost. The empirical models such as USLE, which have been used at this level for many years, are now being replaced by process-based models, such as WEPP (Flanagan and Nearing 1995).

The evaluation of the combined impact of locally implemented conservation practices on the entire watershed requires a multiscale approach, which links the high resolution, landowner level simulation with low resolution, regional simulation. Recent advances in Geographic Information Systems (GIS) technology and linkage of numerous models with GIS (Moore et al. 1993, Srinivasan and Arnold 1994) create a potential to develop tools for coordination of conservation efforts at a hierarchical system of management levels. However, advances in models, algorithms, and GIS tools are needed to fully support this approach. In this paper, we present a brief overview of our efforts in research and development of methodologies, which aim to fulfill some of the needs of the multiscale approach.

METHODS

The watershed models based on homogeneous spatial units have been described in detail in literature (Arnold et al., 1993), therefore, we focus on distributed modeling of erosion and deposition patterns for spatially variable conditions. Within the spatially continuous approach, model inputs and outputs are represented by multivariate functions discretized as grids. Flows of water and sediment are described as bivariate vector fields rather than commonly used systems of 1D flows (Moore et al., 1993). To support modeling at different levels of complexity we have developed a set of tools which range from modifications of relatively simple empirical models to a more complex, process-based approach (Fig. 1, not sent with manuscript). GIS technology is used to support the processing, analysis and visualization of the data and simulation results (Mitas et al., 1997).

Modified Universal Soil Loss Equation

The Universal Soil Loss Equation (USLE) is a well known empirical equation developed for the detachment capacity limited erosion in fields with negligible curvature and no deposition. To incorporate the impact of flow convergence, a replacement of the slope length by the

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*Helena Mitasova, Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, 1120 Jordan Hall, Raleigh, NC, USA; Lubos Mitas, Department of Physics, North Carolina State University, Raleigh, NC, USA; William M. Brown, Geographic Modeling Systems Laboratory, Department of Geography, 220 Davenport Hall, University of Illinois at Urbana-Champaign, Urbana. *Corresponding author: hmitaso@unity.ncsu.edu

upslope contributing area per unit contour width was suggested by Moore and Wilson (1992) and Desmet and Govers (1996). The modified LS factor at a point on a hillslope is:

$$LS(\mathbf{r}) = (m+1) [A(\mathbf{r}) / 22.13]^m [\sin \beta (\mathbf{r})^n / 0.0896] \quad (1)$$

where $A(\mathbf{r})$ is upslope contributing area per unit width, $\beta (\mathbf{r})$ is the steepest slope angle, $\mathbf{r}=(x,y)$, m and n are parameters dependent on the type of flow. We use the equation (1) as an approximate *LS* factor for estimation of soil loss using RUSLE, with the assumption that transport capacity exceeds detachment capacity everywhere and erosion and sediment transport is detachment capacity limited. Impact of replacing the slope length by upslope area is illustrated in Figure 1, which shows that the upslope area better describes the increased erosion in the areas of concentrated flow. However, both the standard and modified USLE equations can be properly applied only to areas experiencing net erosion, depositional areas should be identified and excluded.

Unit Stream Power based Erosion/Deposition model

The Unit Stream Power based Erosion/Deposition model (USPED) is a simple model which predicts the spatial distribution of erosion and deposition rates for transport capacity limited case of erosion process. For this case, the sediment flow rate $\mathbf{q}_s(\mathbf{r})$ is at the sediment transport capacity $T(\mathbf{r})$, (Julien and Simons, 1985)

$$|\mathbf{q}_s(\mathbf{r})| = T(\mathbf{r}) = K_t |\mathbf{q}(\mathbf{r})|^m [\sin\beta(\mathbf{r})]^n \quad (2)$$

where $\mathbf{q}(\mathbf{r})$ is the water flow, $K_t(\mathbf{r})$ is the soil transportability coefficient, m, n are constants dependent on the type of flow and soil properties. Steady state water flow can be approximated as a function of upslope contributing area $|\mathbf{q}(\mathbf{r})| = A(\mathbf{r}) i$, where i is spatially uniform rainfall intensity. Within the 2D flow formulation, water and sediment flow are represented as bivariate vector fields $\mathbf{q}(\mathbf{r})=\mathbf{q}(x,y)$, $\mathbf{q}_s(\mathbf{r})=\mathbf{q}_s(x,y)$ and net erosion and deposition rate is estimated as a *divergence* of the sediment flow (Mitas and Mitasova, 1998a):

$$D(\mathbf{r}) = \nabla . \mathbf{q}_s(\mathbf{r}) = \nabla . [T(\mathbf{r}) . \mathbf{s}(\mathbf{r})] =$$
$$K_t i\{ [\nabla A(\mathbf{r}) . \mathbf{s}(\mathbf{r})] \sin \beta (\mathbf{r}) - A(\mathbf{r}) [k_p(\mathbf{r}) + k_t(\mathbf{r})] \} \quad (3)$$

where $\mathbf{s}(\mathbf{r})$ is the unit vector in the steepest slope direction, $k_p(\mathbf{r})$ is the profile curvature (curvature in the direction of the steepest slope) and $k_t(\mathbf{r})$ is the tangential curvature (curvature in the direction perpendicular to the gradient). According to the equation (3), the erosion and deposition pattern is controlled by the change in the overland flow depth (first term) and by the local geometry of terrain (second term), including *both* profile and tangential curvatures (Fig. 2). The local acceleration of flow in both the gradient and tangential directions play therefore equally important roles in spatial distribution of erosion/deposition. When the results of the 1D flow and the 2D flow models (Fig. 2) are compared with the observed pattern of colluvial deposits (Mitas and Mitasova, 1998a), the 2D model correctly predicts deposition in heads of valleys and alluvial cones of deposition in hollow outlets (Fig. 2, not sent with manuscript). The model also predicts increased net erosion

on shoulders. Although the above analysis strictly applies to the case when $m = n = 1$, it is possible to derive similar expressions for $m, n > 1$, and the qualitative conclusions remain the same.

Soil and cover parameters similar to those used in USLE or WEPP were not developed for the USPED model. Therefore we use the USLE factors to include relative impact of soil and cover on sediment transport capacity and $m=1.0-1.6$, $n=1.3$ to obtain the results comparable with erosion rates estimated by USLE (see Mitasova et al., 1999). Lower values of m apply for prevailing sheet erosion, higher values are used for prevailing rill erosion. Caution should be used when interpreting the results because the USLE parameters were developed for different conditions and to obtain correct quantitative predictions new parameters need to be developed (Foster 1990).

Process-based simulation of water erosion

SIMulation of Water Erosion model (SIMWE) is based upon the description of water flow and sediment transport by first principles equations (Foster and Meyer, 1972; Bennet, 1974). The model is described by Mitas and Mitasova (1998a), here we briefly present its principles.

Overland water flow. A 2D shallow water flow is described by the bivariate form of continuity equation (Julien et al., 1995):

$$\partial h(\mathbf{r}, t) / \partial t = i (\mathbf{r}, t) - \nabla.\mathbf{q}(\mathbf{r}, t) \quad (4)$$

where $h(\mathbf{r}, t)$ is water depth, t is time, $i(\mathbf{r}, t)$ is rainfall excess, $\mathbf{q}(\mathbf{r}, t)$ is water flow, $\mathbf{r}=(x,y)$. The continuity equation is coupled with the momentum conservation equation and the hydraulic radius is approximated by the normal flow depth. The system of equations is closed using the Manning's relation. In this paper we assume that the solution for a steady state, provides an adequate estimate of water depth for the land management applications. In addition, we assume that the flow is close to the kinematic wave approximation, but we include a diffusion-like term to incorporate the impact of diffusive wave effects (Mitasova and Mitas, 1998a).

Sediment flow. The sediment transport by overland flow is described by the continuity of sediment mass (Haan et al., 1994) with the bivarite formulation given as

$$\partial [\rho c(\mathbf{r}, t) h(\mathbf{r}, t)] / \partial t + \nabla.\mathbf{q}_s(\mathbf{r}, t) =$$
$$\text{sources -sinks} = D(\mathbf{r}, t) \quad (5)$$

where $\mathbf{q}_s(\mathbf{r},t)$ is the sediment flow rate per unit width, $c(\mathbf{r},t)$ is sediment concentration, ρ is mass per sediment particle, and $D(\mathbf{r}, t)$ is the net erosion or deposition rate. For shallow, gradually varied flow the storage term can be neglected leading to a steady state form of the equation (5). The sources and sinks term $D(\mathbf{r})$ is derived from the following relation between the sediment transport capacity $T(\mathbf{r})$ and the actual sediment flow rate $|\mathbf{q}_s(\mathbf{r})|$ (Foster and Meyer, 1972)

$$D(\mathbf{r}) = \sigma(\mathbf{r}) [T(\mathbf{r}) - |\mathbf{q}_s(\mathbf{r})|] \quad (6)$$

where $\sigma(\mathbf{r})$ is the first order reaction term which is obtained from the following relationship (Foster and Meyer, 1972):

$$D(\mathbf{r})/D_c(\mathbf{r}) + |\mathbf{q}_s(\mathbf{r})| / T(\mathbf{r}) = 1 \quad (7)$$

where $D_c(\mathbf{r})$ is detachment capacity. Different sediment transport capacity and detachment capacity equations can be

implemented, depending on the prevailing type of flow. We have used functions of shear stress (Foster and Meyer, 1972) and stream power (Nearing et al.1997) in our applications. Our experience indicates that a more general transport capacity equation is needed to reflect the changes in type of flow over the landscape.

The impact of model parameters on the resulting erosion/deposition is described by Mitas and Mitasova (1998a). It is possible to show that for $\sigma(\mathbf{r}) \rightarrow 0$ the erosion is detachment capacity limited and the SIMWE model predicts erosion pattern close to modified USLE. For $\sigma(\mathbf{r}) \rightarrow \infty$ erosion is transport capacity limited and SIMWE predicts pattern close to the USPED model.

Multiscale Green's Function Monte Carlo solution of continuity equations

As a robust and flexible alternative to finite difference or finite element methods for solving the equations (4), (5) we have proposed to use a stochastic approach based on Green's function Monte Carlo method (Mitas and Mitasova, 1998a,b). Within this approach, the equations are interpreted as a representation of stochastic processes with diffusion and drift components (Fokker-Planck equations) and the actual simulation of the underlying process is carried out utilizing stochastic methods (Gardiner, 1985). To obtain the solution, the number of sampling points, distributed according to the source, is generated. The sampling points are then propagated according to the Green's function and the averaging of path samples provides an estimation of the actual solution (water depth, sediment concentration) with a statistical accuracy that is inversely proportional to the square root of the number of samples. The solution is described in more detail in Mitas and Mitasova (1998a), and illustrated by animations in Mitas et al. (1997) and Mitasova and Mitas (2000). To support detailed simulations of local land use impacts within larger watersheds we have reformulated the solution for accommodation of *spatially variable accuracy and resolution* (Mitas and Mitasova, 1998b). The implementation uses multi-pass simulations, starting from a low resolution for the entire watershed and continuing with linked-in simulations performed at higher resolutions within sub areas where more detailed data are available and their use is necessary due to the complexity of terrain and land use configuration. Example of water depth simulation at 10m resolution with embedded 2m-resolution grid is given in Fig. 3. More detailed explanation of this simulation including several animations illustrating the principles of path sampling are presented by Mitasova and Mitas (2000) at http://skagit.meas.ncsu.edu/~helena/gmslab/gisc00/duality.html.

The equations (4), (5) describe the water and sediment flow at a scale equal or larger than an average distance between rills and therefore the presented approach allows us to perform simulations at variable spatial resolutions from one to hundred meters.

Application examples

Pilot Watershed in Illinois. To illustrate the combination of regional and landscape scale modeling for evaluation of various conservation strategies we use an example of a 91 square miles watershed in Illinois which serves as a demonstration area for the Illinois Department of
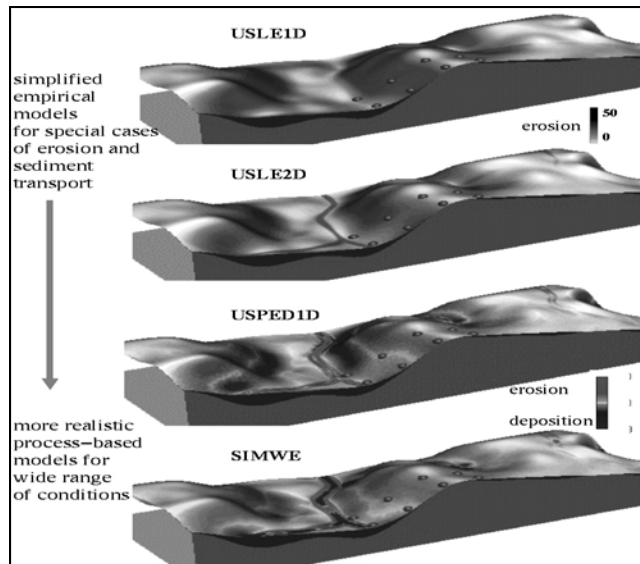

Fig. 1. Set of distributed erosion models with increasing complexity: a) USLE based on slope-length, b) modified USLE using upslope area, c) USPED erosion and deposition, d) SIMWE erosion and deposition. The results of each model represented by a color map are draped over a 3D terrain model with depth of colluvial deposits shown in the crossection. Spheres show location of sampling sites where crop yields, soil properties and other measurements were taken.
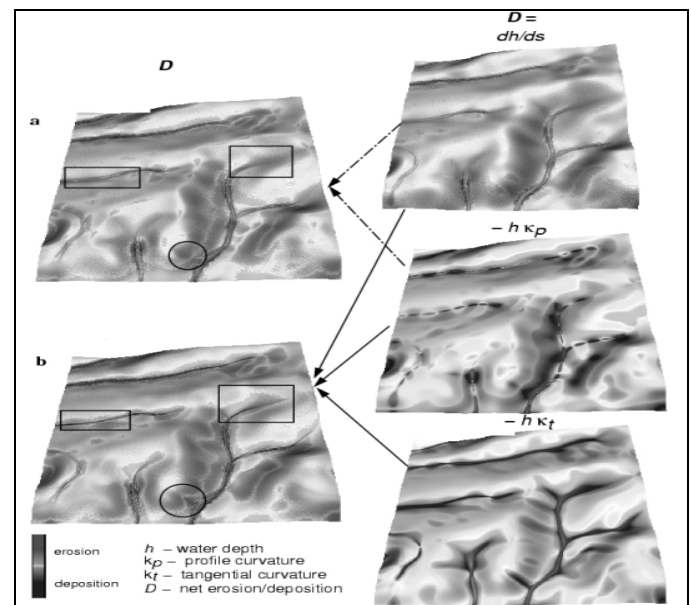

Fig. 2. The difference between erosion and deposition patterns computed based on a) 1D sediment flow - equation includes impact of water depth change and profile curvature, b) 2D sediment flow - equation includes additional term with tangential curvature. The net erosion and deposition as well as the spatial pattern of the terms in the equation used to compute it are draped as color maps over the 3D view of terrain model.
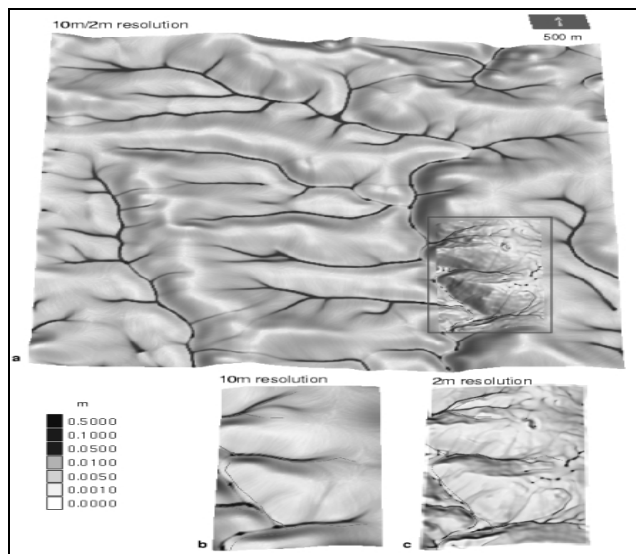
Fig. 3. Multiscale water depth simulation using path sampling applied to nested grids: a) 10m resolution with embedded 2m resolution water depth pattern, b) c) comparison of results from 10m and 2m resolution simulations for the embedded subarea. The high-resolution result shows greater number of concentrated flow areas than can be captured at the lower resolution.
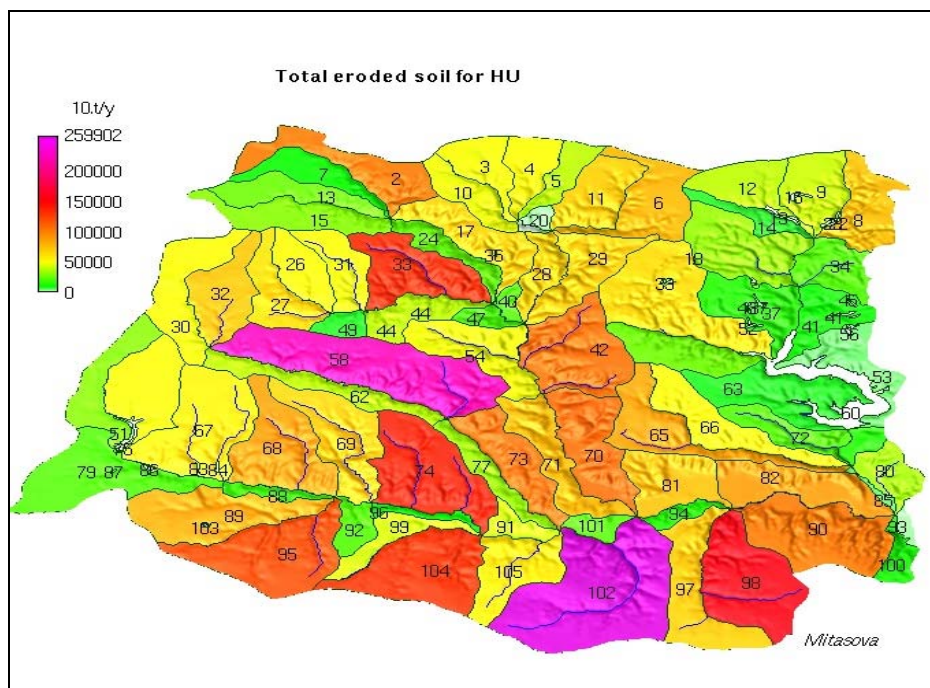

Fig. 4. Total soil loss (soil detachment in tons/year) estimated for each hydrologic unit from 30m resolution data by modified USLE. The units with ID# 102, 58, 99 and 33 were identified as high risk. The numbers are relative because no calibration or validation based on observed rates was done. The hydrologic units are courtesy Dr. Borah (Borah et al. 2000) and were delineated for a dynamic watershed simulation model.
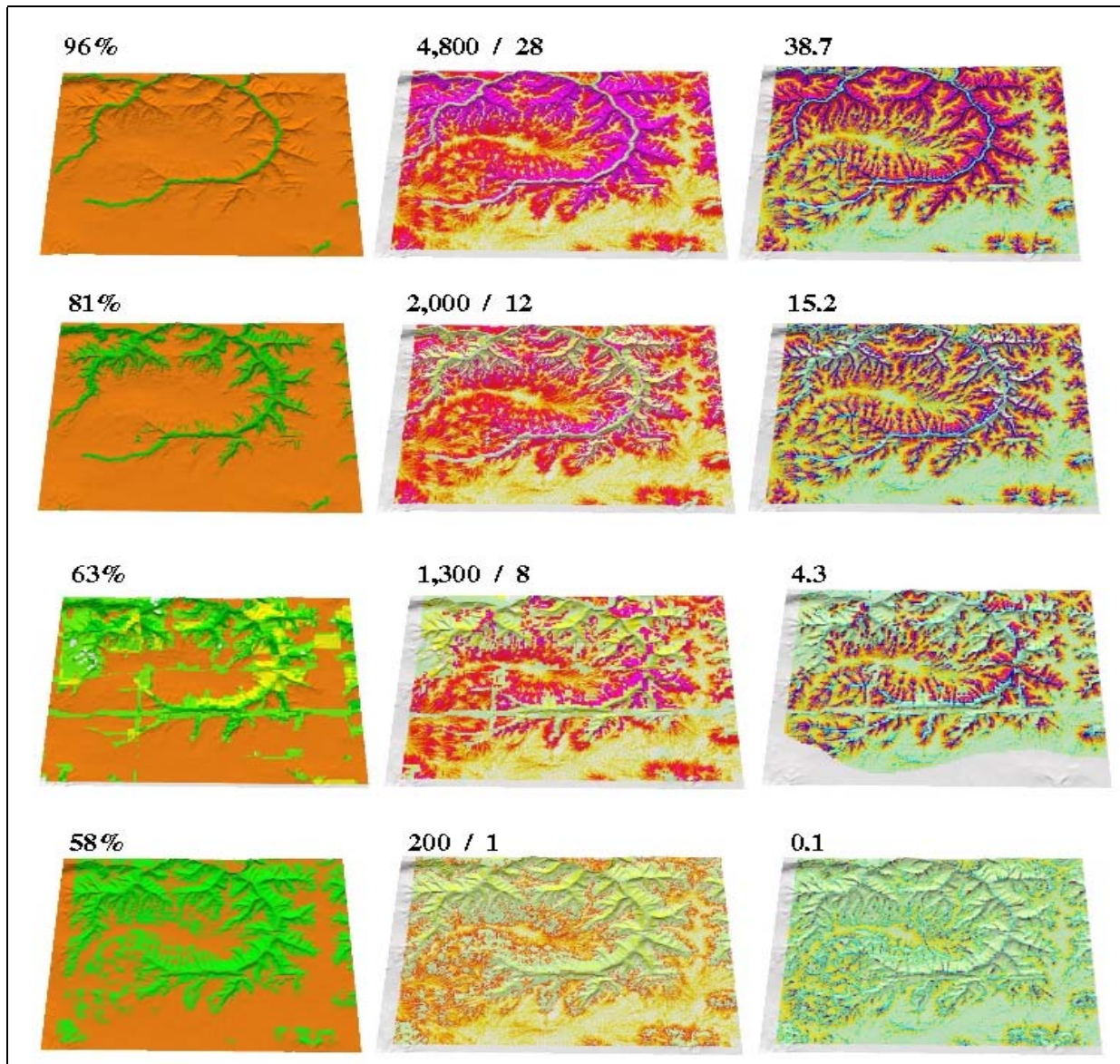
Fig. 5. Soil detachment and net erosion/deposition modeled at 10m resolution for various conservation strategies: a) stream buffer, b) combination of a stream buffer with protection of steep slopes, c) current land use, d) conservation areas at locations with potential soil detachment greater than 10 ton/(acre.year). The numbers representing total [t/y] and average [t/ac.y] soil detachment estimated by modified USLE, and amount of eroded soil that could not be deposited within the landscape [t/y] estimated by USPED are relative because no calibration or validation based on observed data was done. The percentages represent portion of land used for agriculture.

Natural Resources Pilot Watershed Program. To identify sub watersheds with high erosion risk, soil detachment was computed by the modified USLE using 30 m resolution elevation and land cover data and integrating the detachment estimate for each hydrologic unit. The flow routing program was specially designed to cut-off computation of upslope area when terrain flattens to avoid overestimation of topographic factor at this scale. The sub watersheds identified as high potential sources of sediment were then analyzed and various conservation strategies were explored using spatially distributed approach (modified USLE and USPED) applied to 10m resolution data (Fig. 5). The soil detachment and net erosion/deposition for the current land use were compared with estimates for various conservation strategies such as stream buffers, combination of stream buffers with protection of steep slopes and conservation areas aimed at elimination of soil detachment greater than a given threshold. The analysis has shown that widening of stream buffers did not have a significant effect on reduction of erosion although deposition was shifted farther from the stream. Combination of protection of steep slopes with narrower buffer seems to be more effective and is close to the current state. However, this strategy leaves out small but important areas in headwaters and areas with concentrated flow, which can contribute significantly to

sediment loads. By redesigning the land use so that these areas identified as high risk by both the modified USLE and USPED models are added to the conservation, the proportion of agriculture to conservation remains almost the same but the reduction in soil loss is substantial (Fig. 5).

Experimental farm. We illustrate the land owner level modeling using the data from Scheyern experimental farm (data courtesy K. Auerswald TUM, Germany). Figure 6 illustrates the simulation of grassed waterway impact using the SIMWE model.
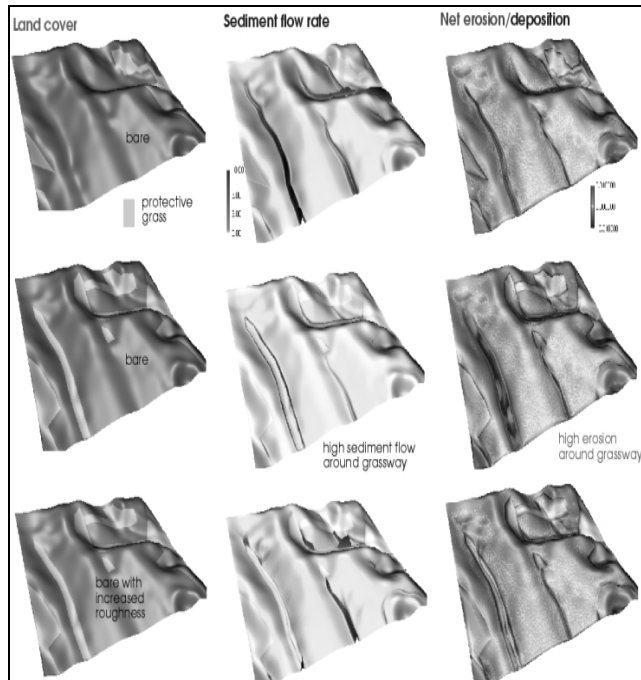

Fig. 6. Simulation of impact of a grassed waterway: land cover, sediment flow and net erosion/deposition a) before installation, b) with roughness in bare soil area 10x lower than in grass, c) with roughness in bare soil area 2x lower than in grass. The sediment flow is visualized as a colored surface draped over 3D terrain to highlight higher sediment flow rates in the areas of concentrated flow and around the grass way (b). Net erosion/deposition rates are draped over 3D terrain as color map. The simulations were performed using the SIMWE model at 2m resolutions. Data are courtesy Dr. Auerswald.

For bare soil conditions, an area with concentrated flow has high sediment flow and net erosion rates (Fig. 6a). With a grassed waterway, the sediment flow and net erosion is reduced, however, higher sediment flow and net erosion develops around the grassed waterway if the roughness of bare soil is about 10x smaller than in the grass (Fig. 6b). If the roughness in the bare field is only 2x smaller the erosion around the grass way disappears and there is prevailing deposition (Fig. 6c). Second example (Fig. 7) illustrates analysis of different land use alternatives and use of computer aided land use design to find effective spatial distribution of preventive grass cover (Fig. 7c, see also Mitasova and Mitas 1998a).
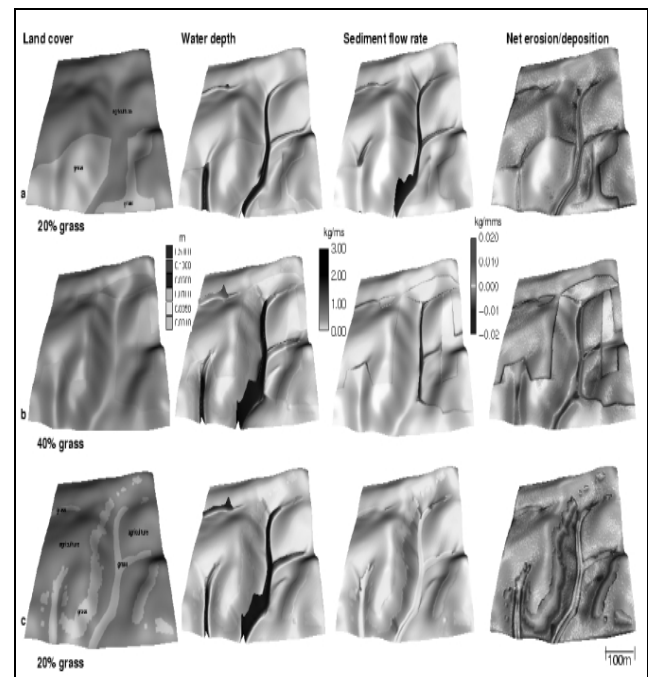

Fig. 7. Evaluation of impact of different land use alternatives on steady state water depth, sediment flow and net erosion/deposition pattern: a) original land use, b) empirically designed land use with increased proportion of grass cover, c) computer aided design for the same proportion of grass area as the original land use, but changed spatial pattern with grass located in areas which were identified by the model as high risk (concentrated flow areas and upper, convex parts of the hillslope). The new designs result in dramatic decrease in sediment delivery from the farm. Water depth and sediment flow rates are displayed as a surface draped over elevation surface to highlight the differences in the concentrated flow areas. Data are courtesy Dr. Auerswald.

CONCLUSION AND FUTURE DIRECTIONS

GIS and distributed erosion models based on 2D flow bring new insights into sediment transport processes in complex landscapes. With adequate calibration and field-testing they can become a powerful tool supporting multilevel management of conservation efforts. In the future, the multiscale approach can be extended to include a wider range of scales with simulation of processes appropriate for each scale. The land use design can become more effective by using optimization procedures for finding the land use patterns, which provide the most benefit for the invested resources.

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