GIS Environment for Simulation and Analysis of Landscape Processes

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Introduction

Efforts to balance economic development and environmental protection require new strategies for land use management based on better understanding of human impacts on landscape processes. Recent advances in the development of GIS technology, and in the availability of high resolution spatio-temporal data as well as exponential growth in computational power create conditions for building numerical simulation laboratories. In combination with field experiments, these laboratories can significantly enhance our understanding of landscapes as complex systems. To support the simulation and analysis of landscape processes, we have been developing methods, algorithms, and software tools that extend the capabilities of GIS beyond automatic mapping and that provide an environment for processing, analyzing, and communicating complex landscape phenomena in 3D space and time. Our methodological framework builds upon and extends our previous work (Mitasa et al. 1995a, Mitas et al., 1997), which is based on the representation of phenomena by multivariate functions (scalar or vector fields), and on the description of landscape processes by first principles equations which determine the configuration or evolution of corresponding fields.

In this paper we discuss some of the issues related to the application of GIS for landscape characterization and simulation, in particular, spatial interpolation and visualization, and their role in the development and communication of complex spatial models.

Spatial Interpolation and Topographic Analysis

Most inputs for distributed models of landscape processes are given by functions that depend on the position in 3D space and time. These multivariate scalar and vector fields represent quantities such as terrain, rainfall, temperatures, physical properties of soils, land cover, fluxes of matter, etc. While most of the field measurements are performed at sampling sites, often irregularly distributed in space and time, visualization, analysis and modeling within a GIS are often based on a raster representation (Figure 1). Reliable interpolation tools are therefore needed to support the preprocessing of data for landscape simulations. The underlying methods must satisfy several important demands: accuracy and predictive power, robustness and flexibility in describing various types of phenomena, smoothing for noisy data, d-dimensional formulation, direct estimation of derivatives (gradients, curvatures), applicability to large data sets, computational efficiency, and ease of use.

Currently it is difficult to find a method that fulfills all of these requirements for a wide range of
georeferenced data. Therefore, selecting an adequate method with appropriate parameters for a particular application is crucial. Different methods can produce quite different spatial representations (Figure 2), and in-depth knowledge of the phenomenon is needed to evaluate which one is the closest to reality. Unsuitable methods or inappropriate parameters can result in a distorted model of spatial distribution, leading to potentially wrong decisions based on misleading spatial information. An inappropriate interpolation can have even more profound an impact if the result is used as an input for simulations, where a small error or distortion can cause models to produce false spatial patterns (Mitas and Mitasova, in press).

Over the last few years we have developed a multivariate interpolation method (Mitas and Mitasova, 1988; Mitasova and Mitas, 1993; Mitasova et al., 1995a), which proved to be a valuable tool supporting the processing of data for creating spatio-temporal models of landscape phenomena and for preparing inputs for process-based landscape simulations. The method is called Regularized Spline with Tension (RST) and has been implemented within the GRASS GIS since 1993 (s.surf.tps, s.surf.rst), with regular updates and enhancements. The older, less general and also less robust version of the spline interpolation function published by Mitas and Mitasova (1988), has been implemented in ArcGrid and ArcView Spatial Analyst. Although the current implementation has several problems, after appropriate fixes it may become a useful alternative to other interpolation methods available to ArcGrid and ArcView users. RST is based on the minimization of a smoothness functional with variational parameters such as an anisotropic tension.

These can be used to change the character of the interpolant to properly represent the behavior of modeled phenomenon. The variational capabilities of the RST were very useful in our effort to produce high-quality digital terrain models, where we were able to eliminate many artificial features typical of numerous interpolation methods currently available (Mitasova et al., 1996; Mitasova et al., 1995a; Wood and Fisher, 1993). These artificial features, especially the waves along contours (Mitasova et al., 1996; Mitas and Mitasova, in press), or the peaks and pits around the data points (Figure 2, IDW, Kriging, Topogrid), make the use of standard interpolation methods problematic, especially for producing inputs for some highly sensitive models of landscape processes.

Because the RST method has a d-dimensional formulation (Mitasova et al., 1995a) it was implemented also as a volume and volume-time interpolation function for computation of 3D and 4D models of landscape phenomena measured in 3D space and time, such as the concentration of chemicals or soil properties. Because the landscape characterization data

<table>
<thead>
<tr>
<th>phenomenon (field)</th>
<th>point data</th>
<th>3D dynamic map</th>
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<tbody>
<tr>
<td>elevation: $z = f(x,y)$</td>
<td><img src="image1" alt="Elevation Map" /></td>
<td><img src="image2" alt="Elevation 3D Map" /></td>
</tr>
<tr>
<td>precipitation: $p_i = f_i(x,y)$; $i = 1, ..., 12$</td>
<td><img src="image3" alt="Precipitation Map" /></td>
<td><img src="image4" alt="Precipitation 3D Map" /></td>
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<tr>
<td>soil horizons: $z_i = f_i(x,y)$; $i = 1, ..., 5$</td>
<td><img src="image5" alt="Soil Horizons Map" /></td>
<td><img src="image6" alt="Soil Horizons 3D Map" /></td>
</tr>
<tr>
<td>land cover: $z + h_i = f_i(x,y)$; $i = 1, ..., 12$</td>
<td><img src="image7" alt="Land Cover Map" /></td>
<td><img src="image8" alt="Land Cover 3D Map" /></td>
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<tr>
<td>soil particle size (% clay): $c = f(x,y,z)$</td>
<td><img src="image9" alt="Particle Size Map" /></td>
<td><img src="image10" alt="Particle Size 3D Map" /></td>
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<tr>
<td>conc. of chemicals in water: $w = f(x,y,z,t)$</td>
<td><img src="image11" alt="Chemical Concentration Map" /></td>
<td><img src="image12" alt="Chemical Concentration 3D Map" /></td>
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have different properties and distributions in horizontal/vertical/temporal dimensions, anisotropic tension or rescaling is used in vertical and temporal directions to ensure the numerical stability of interpolation.

To gradually fulfill the requirements of spatial interpolation for GIS applications, we are periodically improving the implementation of the RST method with the most recent enhancements including the support for spatially variable smoothing, which 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. The resulting surfaces pass the closest to the most accurate data and are allowed to deviate more from the data that are measured less accurately.

Besides multivariate interpolation, the RST method was also designed to support the analysis of the geometry of interpolated surfaces and volumes by computation of slope, aspect and different types of curvatures using derivatives of the RST function (Mitasova and Hofierka, 1993; Mitasova et al., 1995a). These parameters are often needed as inputs for landscape process models; therefore, their reliable estimation is crucial for successful simulations. Within our approach the computation of topographic parameters is performed simultaneously with interpolation, leading to increased reliability and consistency in their estimation.

Another class of topographic parameters, such as upslope contributing area or slope length, is based on flow-tracing. We have developed a vector-grid algorithm for relatively fast and simple estimation of these parameters (Mitasova et al., 1996) and implemented it in GRASS GIS as r.flow. For more complex applications we have developed a physics-based approach using Monte Carlo solution of water flow continuity equation within an erosion simulation tool SIMWE (Mitas and Mitasova, 1997). The process-based approach helps to resolve some problems of geometry-based approaches, such as dispersal flow, overflowing pits, or split streams.

**Visualization**

Advanced visualization tools supporting visual analysis and communication of complex 3D spatio-temporal data significantly enhance the efficiency of the development and applications of
landscape process models. While a wide selection of computing platforms and software solutions is available for creating sophisticated dynamic 3D visual models (Raper, 1989; Hibbard et al., 1994; Stephan, 1995), there are still only a few examples of full integration of such visualization capabilities within a single GIS providing seamless sharing of data or object types. Implementation of the landscape simulation concepts described in the introduction has stimulated, indeed demanded, integration of GIS and computer cartography with scientific visualization (Brown and Gerdes, 1992; Brown and Astley, 1995). To provide insight into spatial and spatiotemporal relations of studied phenomena, the cartographic models are created within a GIS, using multiple dynamic surfaces and isosurfaces, together with draped raster, vector, and point data in an appropriate projection of 3D space. Visual exploration and analysis of data are facilitated by interactive manipulations of visualization environment parameters such as viewing position, z-scale, cutting planes for profiles and fence diagrams, light position, and brightness. Dynamic cartographic models are developed by animating the sequences of images created by changing the viewing parameters or by displaying evolving series of data (Brown et al., 1995; Mitas et al., 1997). Interactive query capabilities, whereby original attributes are retrieved directly from the GIS database, facilitate the modeling process. Integration within the GIS encourages greater use of all available data due to the ease of data access and manipulation. Such integration also stimulates an interdisciplinary research involving specialists from various disciplines who use GIS to perform different tasks on the same data sets.

Use of visualization at different stages of the development and analysis of a complex erosion model is described in detail by Mitas et al. (1997), including the animations published on a CD-ROM and the World Wide Web. The animations were used to illustrate the stochastic method of the continuity equation solution, the impact of the change in model parameters on the results, comparison with field data, and computer aided erosion prevention design. The use of dynamic cartographic models for visual analysis of multivariate landscape phenomena characterized by sets of discrete sampling points and by interpolated surfaces/hypersurfaces is also illustrated by the examples in Figure 1.

The efficiency and suitability of visualization tools for exploring multivariate land characterization data are ensured by a high level of interactivity and by a combination of advanced visualization capabilities with the traditional spatial query and analysis functions of a GIS (Brown et al., 1995; Brown and Astley, 1995). In an effort to expand some of the interactive visualization capabilities to users accessing the cartographic models on the World Wide Web, a simple translator of georeferenced raster data to Virtual Reality Modeling Language (VRML) formatted files has been developed. This translator, implemented in the GRASS GIS as a command p.vrml (Brown, 1996), can be used to output the models of landscape phenomena stored in a GIS database as VRML formatted files, enabling sharing of surface visualizations on the Web.

Applications

We illustrate the methods we've presented using an example of 3D modeling of soil properties and erosion simulations using the SIMWE model (Mitas and Mitasova, 1997) at an experimental farm.

Volume Modeling of Soil Properties

To test the possibilities of creating 3D models of soil properties within a GIS we computed a series of spatial models from comprehensive soil survey data for an experimental farm at Scheyern, Germany (Auerswald et al., 1996). Soil properties (from data provided through the courtesy of Dr. Auerswald) were measured in 3D space up to 1.2m depth, and they included results of chemical analysis (pH, nitrates, phosphates, potassium, organic matter, etc.), soil texture analysis, and qualitative information for each sample. Using these data, it was possible to derive additional information and parameters such as the depth of colloidal deposits and hydraulic conductivity needed for erosion simulations.

From the point of view of spatial modeling, a special challenge for representation and visualization of soil data was posed by the fact that the vertical spatial vari-
ability requires much higher resolutions than the resolutions used for the representation of phenomena in a horizontal plane. We have investigated two approaches to 3D modeling of the measured soil properties (Brown et al., 1997). The first approach is based on bivariate interpolation of soil properties for each horizon and 3D representation by multiple horizon surfaces with color representing the distribution of modeled soil property (Mitasova et al., 1995b, Brown et al., 1997). The second approach is based on trivariate interpolation of point data to a 3D raster map with 2m horizontal and 0.1m vertical resolution using the RST method (Figure 3) and on volume visualization using isosurfaces, animated cross-sections or fence diagrams. To visualize vertical relationships with sufficient detail, we have used 100 times relative exaggeration of depths for both cases.

The results are illustrated by volume models of organic carbon, hydraulic conductivity, and soil reaction (pH) combined with contours (Figure 3). We have found that if the proper tools are available, the full 3D model is more appropriate than the representation based on multiple surfaces as it incorporates the vertical relationships into interpolation and allows for more efficient visual analysis.

**Distributed Process-Based Erosion Simulations**

We illustrate the GIS-supported erosion modeling, using the same study area as in the previous example. As an input for erosion simulations we have interpolated a 2m-resolution DEM from measured elevation data using the RST method and prepared raster maps representing the existing and simulated soil and cover conditions. The simulations were performed by SIMWE, a landscape-scale bivariate model of erosion, sediment transport, and deposition by overland flow designed for spatially complex terrain, soil, and cover conditions (Mitas et al., 1997). The underlying continuity equations are solved by Green's function Monte Carlo method, to provide the robustness necessary for spatially variable conditions and high resolutions. Results of simulations for the traditional land use (Figure 4a) were then compared to data indicating the location of erosion/deposition, in particular, depths of colluvial deposits and linear erosion features digitized from aerial photographs (Mitas and Mitasova, forthcoming).

After proper calibration, the SIMWE model can be used for analyzing and designing the place-
ment of selected erosion protection measures based on land cover, as illustrated by the following simple example. First, we used the model to identify locations with the highest erosion risk, assuming a uniform land use. Then, the protective grass cover was distributed to the high risk areas while preserving the extent of grass cover at the original 30% of the area (Figures 4a and 4c). We performed a simulation with the new land use to evaluate its effectiveness. The results demonstrate that the new design has a potential to dramatically reduce soil loss and sediment loads in the ephemeral streams when compared with the traditional land use. The crest in sediment flow in the valley disappears and is replaced by light deposition within the grassway, while the maximum and total rates of erosion are significantly reduced. It is interesting to note that the land use design obtained by this rather simple computational procedure, using only the elevation data, had several common features with the sustainable land use design proposed and implemented in 1993 at the farm, based on extensive experimental work (Auerswald et al., 1996). A simplified version of that land use design, along with prediction of water and sediment flows and net erosion/deposition is presented in Figure 4b. It uses a significantly higher proportion of permanent grass cover and fallow leading to higher water depths and further reduction of soil loss. However, there is a higher price paid in the form of reduced agricultural area.

Conclusions

The approach and examples presented in this paper illustrate several aspects of advanced GIS application to landscape characterization and process simulation. Implementation of the multivariate fields concept for landscape characterization in a GIS and development of appropriate tools, such as multivariate RST interpolation and visualization, increase the efficiency of input preparation as well as analysis and presentation of complex simulation results. This approach further supports the move from profile and/or polygon-based models, to more realistic 3D dynamic simulations based on multivariate fields and description of processes by first principles equations.
References


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Biographies

Helena Mitasova, Ph.D., worked as a Research Scientist at the Department of Physical Geography and Cartography at Comenius University, Bratislava, before coming to the Illinois Natural History Survey as a visiting researcher in 1990. From 1991 to 1995 she was involved in the development of software for surface modeling, analysis, and visualization for GRASS GIS at the U.S. Army Construction Engineering Research Laboratories in Champaign, Illinois. Currently, she is a research associate in the Department of Geography, Geographic Modeling and Systems Laboratory, working on erosion simulations and 3D dynamic GIS.

Lubos Mitas, Ph.D., came to the Department of Physics at the University of Illinois at Urbana-Champaign in 1990 from the Institute of Physics in Bratislava, Czechoslovakia. Since 1992 he has been working at the National Center for Supercomputing Applications as a Research Scientist on quantum Monte Carlo methods for electronic structure of molecules and solids. In addition to his work in physics he has been developing the interpolation methods for geo-scientific applications since 1985. Recently, he has developed methods and programs for process-based erosion simulations. His interpolation methods have been implemented in several commercial and public-domain GISs, such as GRASS, ArcGrid, and ArcView.

William M. Brown graduated from the University of Illinois, Urbana-Champaign in 1981 with a B.S. in biology and received an A.A.S. in Visualization Computer Graphics from Parkland College, Champaign, in 1992. He completed an internship at the National Center for Supercomputing Applications in 1991. He worked as a research programmer for the Modeling and Visualization Group, Spatial Analysis and Systems Team, at the U.S. Army Construction Engineering Research Laboratories from 1991 to 1995. Currently he is in the Department of Geography, Geographic Modeling and Systems Laboratory, working on multidimensional dynamic visualization for GIS.

Steven Warren received his Ph.D. in Watershed Management from Texas A&M University in 1985. Since then, he has worked at the U.S. Army Construction Engineering Research Laboratories in Champaign, Illinois, where he is currently a Principal Investigator in the Resource Mitigation and Protection Division. Dr. Warren assisted in the development of the U.S. Army’s Land Condition-Trend Analysis program. As part of that effort, he integrated the Universal Soil Loss Equation with satellite imagery, ground-truthed data, and the Geographical Resources Analysis Support System to produce an erosion-based land capability classification system. Dr. Warren continues to work in the area of soil erosion modeling and prediction, but has expanded his efforts to include research into rehabilitation of severely damaged military training lands. This work includes an investigation into the biology and function of crypto-gamic soil crusts as they relate to soil stability in arid and semiarid regions. Dr. Warren is a Certified Professional Soil Erosion and Sediment Control Specialist and a member of the Soil and Water Conservation Society.