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INTEGRATING GEOGRAPHIC INFORMATION SYSTEMS AND ENVIRONMENTAL SIMULATION MODELS: A STATUS REVIEW

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ABSTRACT

Geographic information systems (GIS) have emerged over the past decade as widely used software systems for input, storage, manipulation, and output of geographically referenced data. This chapter examines the status of GIS as a technology to support environmental simulation modeling in the atmospheric, hydrologic, and ecologic sciences. The status of GIS integration is reviewed, with emphasis on dynamic, physically-based modeling approaches that integrate the effects of different environmental processes across multiple scales. GIS is currently used to assemble and manage large spatial databases, to perform spatial and statistical analyses, and to produce effective visual representations of model results. The first steps have been taken toward more tightly linked approaches, including embedding modeling within the GIS. Integrated multidisciplinary modeling has created new opportunities for GIS, but has also exposed the weaknesses of the current generation of GIS technology, particularly in areas of functionality and data modeling. The final section of the chapter summarizes the current status of GIS in this field and suggests directions for future development.

INTRODUCTION

The 1980s saw extensive advances in geographic information systems (GIS), a technology now recognized as increasingly important to natural resource management and environmental assessment. GIS's are widely used to assemble and manage large spatial databases, perform analyses, and produce effective visual representations of management options.

Current GIS software packages range from expensive packages for scientific workstations to PC-based and public domain software. In general, they can be grouped into those that use a raster or pixel-based representation, and those that use vector- or coordinate-based representation of points, lines, and areas. Many vector-based GIS are constructed as hybrid systems connecting relational database management systems and graphical databases. Reviews of GIS technology can be found in introductory texts by Star and Estes (1990), Burrough (1986), and in the two-volume reference by Maguire, Goodchild, and Rhind (1991).

Simulation models are sophisticated tools for characterizing and understanding environmental patterns and processes, and estimating the effects of environmental change at local, regional, and global scales. Recent attention has focused on developing land surface process modules for atmospheric models, applying distributed parameter approaches for water flow and contaminant transport modeling in surface and groundwater systems, and extending simulation modeling to complex ecological systems at broader scales. Advanced research concepts for integrating various dynamic simulation models across multiple time and space scales, such as coupled-systems modeling or land-atmosphere interactions modeling, are rooted in global change research programs (ESSC, 1986, 1988; ICSU, 1986; IGBP, 1990; NRC, 1986, 1990).

The new generation of dynamic simulation models requires large amounts of diverse spatial data characterizing those dynamic land surface properties that exert fundamental controls over environmental processes (Steyaert, 1993). Some environmental processes exhibit strong spatial components such as dispersion, advection, slope runoff, and spatial interactions within ecosystems. Research on spatial complexity and heterogeneity within landscapes is a priority within a wide range of disciplines. Thus,

there is growing interest in the potential for integrating GIS technology and environmental simulation models in spatial database development, spatial processes, exploratory spatial analysis, and model output visualization.

This chapter reviews the status of the integration of GIS technology and environmental simulation models in the atmospheric, hydrologic, and ecologic sciences (for a more extensive perspective, see Goodchild, Parks, and Steyaert, 1993). The main focus is on dynamic, physically-based modeling of land-atmosphere interactions and water quality research. An attempt is made to illustrate how this interdisciplinary, multiscaled modeling approach has created new applications for GIS technology. The purpose of each type of dynamic simulation modeling application is described. Details on the modeling approach are followed by a discussion on the exact role of GIS in the modeling. In some cases, suggestions for enhancements to GIS technology are noted where the current capabilities fall short of what is needed.

ATMOSPHERIC MODELING AND GIS

The integration of atmospheric modeling and GIS technology is just beginning. One promising area involves spatial data handling and analysis support for land surface parameterizations, the land process modules of atmospheric general circulation models (GCM) and mesoscale meteorological models. The use of GIS technology in regional air quality and tropospheric chemistry models is also under study (Novak and Dennis, 1993). Such simulation modeling is complemented by the use of remote sensing and GIS technologies to examine land surface processes related to the energy balance, soil moisture budget, and radiative transfer. For example, process-oriented field experiments also provide the basis for the integration of atmospheric simulation models and remote sensing and GIS technologies to understand environmental processes, develop algorithms, and make regional extrapolations (NASA, 1991; Running, 1991b).

Land Surface Parameterizations for Atmospheric Modeling

Lee et al. (1993) reviewed the functions and data requirements for advanced land surface parameterizations such as the biosphere-atmosphere-transfer scheme (BATS) of Dickinson et al. (1986), Simple Biosphere model (SiB) of Sellers et al. (1986), and the Land-Ecosystem-Atmosphere-Feedback (LEAF) model (Lee, 1992). These land surface process models simulate interactions between the biosphere at the land surface and the free atmosphere and can include the exchanges of water and energy fluxes at time steps of seconds to hours (NRC, 1990).

The purpose of land surface parameterizations such as BATS, SiB, and LEAF is to determine as realistically as possible the exchanges of radiative, momentum, and sensible and latent heat fluxes between the land surface and the lower atmosphere. In determining these exchanges within each model grid cell, the models take into account atmospheric forcing (solar radiation, temperature, humidity, wind, and precipitation) and, in particular, the role of vegetation and other land surface properties. The models require detailed data on dynamic land surface characteristics such as albedo, surface roughness, and stomatal conductance, all of which control the fluxes.

The aggregation or "scaling-up" of these data within variable sized grid cells of atmospheric models is also a research issue involving the proper representation and parameterization of subgrid processes. For example, Skelly, Henderson-Sellers, and Pitman (1993) note that at least three distinct approaches to aggregation are used in simulation models: (1) determine the predominant land cover class within the model grid cell, (2) aggregate the land surface properties (roughness, etc.) by some weighted averaging approach, or (3) or aggregate the fluxes after running the model.

Given these types of data issues, Skelly, Henderson-Sellers, and Pitman (1993) suggested that GIS can assist in the manipulation of surface data for model input or for comparisons of model results. They see integration proceeding along two tracks: (1) utilizing the GIS as a data management, analysis, and display tool which is linked to the land surface parameterization, and (2) fully integrating the land surface parameterization into the GIS. They call for a "self-parameterizing" database in which the land surface data component is used to update the land surface parameterization within the atmospheric model automatically.

Lee (1992; personal communication, 1993), Smith et al. (1993), and Lakhtakia (personal communication; 1993) illustrate two approaches for spatial data handling and the tailoring of 1-km land cover characteristics data, such as described by Loveland et al. (1991), as input to the LEAF and BATS models, respectively. Lee (1992; personal communication, 1993) developed spatial data handling tools to ingest and process 1-km land cover data directly into the Colorado State University Regional Atmospheric Modeling System. These spatial data processing functions were used to change map projections, reclassify the land cover to the LEAF classification, aggregate the land cover to nested grids (10-km fine resolution and 40-km coarse resolution), and select the dominant land cover classes based on percentage composition within the grid cell (water, bare soil, and predominant vegetation type).

In contrast, Smith et al. (1993) and Lakhtakia (personal communication, 1993) used similar spatial data handling tools within the land analysis system (LAS) to prepare land data for the Pennsylvania State University/National Center for Atmospheric Research mesoscale model version 4 (MM4). LAS software was also used to build land data for a soil moisture module used to initialize the MM4 system.

Regional Air Quality and Acid Deposition Modeling

Novak and Dennis (1993) and Birth et al. (1990) discuss the potential role of GIS technology as related to regional air quality and acid deposition models, including the Environmental Protection Agency's Regional Acid Deposition Model (RADM), Regional Oxidant Model (ROM), Urban Airshed Model (UAM), and the Regional Lagrangian Model of Air Pollution (RELMAP). These models are used to investigate physical and chemical processes associated with air pollution and to develop strategies for emissions control. The users need spatial analysis tools to evaluate and interpret model predictions, as well as capabilities to analyze collectively a variety of model results.

Novak and Dennis (1993) describe a cooperative pilot project in the EPA to determine the use of the ARC/INFO[1] GIS software for air pollution research and assessment activities. The goals were to enhance database management, provide users (researchers and policy analysts) with transparent access to spatial data for a wide variety of models (RADM, ROM, UAM, and RELMAP), and take advantage of spatial display and analysis tools within the ARC/INFO GIS. They describe how a pilot interactive display and environmental analysis system in the ARC/INFO GIS was developed to permit end-users to study the relationships between measured and predicted air pollution, point and area source emissions, land use, and health effects.

The pilot study concluded that a GIS is an effective tool to estimate emissions inputs to air pollution models and to design emissions control strategies. However, Novak and Dennis (1993) note that GIS is limited in its ability to deal with temporal variability, finite difference calculations, three-dimensional analysis, and efficient data conversions. The study recommended improved GIS

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[1] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government or the authors.

functionality for animation of spatial fields, exploring three-dimensional fields, enhanced data manipulation (sorts), transparent interfaces with other software packages, and user friendliness.

Remote Sensing and GIS Technologies in Land Process Modeling

Although the future looks promising, GIS technology has made only modest inroads into studies involving remote sensing and land surface process research. In most cases, GIS-type functions in digital image processing systems or "home-grown" generic GIS are used. However, there appears to be a growing role for GIS technology in major field experiments such as the International Satellite Land Surface Climatology Project (ISLSCP) (see for example NASA, 1991).

Shih and Jordan (1992) analyzed Landsat thematic mapper (TM) mid-infrared (MIR) data and land use categories within a GIS to make qualitative estimates of surface soil moisture in central Florida. Image processing and GIS functions of the Earth Resources Laboratory Application Software were used in the study to classify the image (TM bands 2, 3, and 5), to georeference the classified image and the MIR band 7 image, to calibrate the MIR digital counts to in-band planetary albedo estimates, to aggregate land use classes according to band 7 albedo estimates, and to overlay the results for qualitative assessment of surface soil moisture categories.

Other examples include the use of remote sensing and GIS technologies to study land surface processes by Goodin, Yang, and Yang (1992) and Luval et al. (1990). The latter study used the aircraft-based thermal infrared multispectral sensor with GIS-type functions to study canopy temperatures, thermal response numbers, and evapotranspiration (ET) in the tropical forest regions of Costa Rica.

As part of a regional approach to estimate forest ET, Running et al. (1989) developed a simple GIS to integrate topographic, soils, vegetation, and climate data for forested regions of western Montana. Key data input for each grid cell also included satellite-derived estimates of leaf area index, daily microclimatic data estimated from in situ and satellite data, soil water capacity, and water equivalent snowpack data to estimate snowmelt runoff. Daily ET estimates were mapped for the region based on output from FOREST-BGC (biogeochemical cycles), a forest ecosystem simulation model. Further details on this coupled systems modeling approach are provided in the section on ecological modeling.

HYDROLOGIC MODELING AND GIS

There has been significant progress in the integration of GIS technology with hydrologic modeling in the fields of precipitation-runoff modeling for watersheds, including distributed parameter approaches, surface water quality modeling, and groundwater flow and contaminant transport modeling. Following some overview comments on the nature of hydrologic modeling, the status of GIS technology and model integration is summarized in terms of each of these three subject areas.

Maidment (1993) summarizes the basic elements of hydrologic modeling and examines the foundation for linking GIS technology and hydrologic modeling. He suggests that a GIS can add spatial specificity in the modeling and address regional and continental scale problems not yet resolved in hydrology. According to Maidment, a hydrologic model may be defined as the mathematical representation of the flow of water and its constituents on some part of the land surface or subsurface environment. He summarizes the challenge of modeling in three parts. First, the modeling of water flow is concerned with the disposition of rainfall in terms of runoff, infiltration, groundwater recharge, evaporation, and water storage. Second, the hydraulics of flow are considered based on the discharge of water at a particular point. These include flow velocity and water surface elevation in a channel, or

the Darcy flux and piezometric head in an aquifer. Third, transport issues related to water quality and pollutant flows are considered.

Maidment defines the spatial components of hydrologic modeling as watersheds (such as lumped models, linked-lumped models, or distributed parameter models), pipes and stream channels concerned with channel roughness, aquifers (groundwater flow and transport), and lakes and estuaries. He categorizes models according to a taxonomy based on five sources of variation: time, three space dimensions, and randomness. In contrast, Moore et al. (1993) define six model structures for surface-subsurface models using a topographic approach, including lumped models, hydrologic response units (HRU), grid-based models, triangulated irregular networks (TIN)-based models, contour-based models, and two- or three-dimensional groundwater models.

Maidment (1993) suggests that contemporary links between GIS and hydrologic modeling include hydrologic assessment, hydrologic parameter determination, hydrologic modeling in a GIS, and linking a GIS and hydrologic models. These types of linkages are illustrated in subsequent discussions. For example, hydrologic assessment is illustrated by several types of water quality models. Watershed analysis tools and other approaches for hydrologic parameterization are noted. Dynamic models are linked to a GIS, mainly in terms of model input and output. There are now some excellent examples of tightly coupled GIS-model integration and there are realistic prospects for examples of hydrologic modeling within GIS. According to Maidment, the new frontiers in hydrologic modeling with GIS include research on spatially distributed watershed properties, partial area flow, surface water-groundwater interaction, and regional and global hydrology.

Distributed Parameter Watershed Modeling

Traditional watershed modeling by the lumped-model approach is complemented by the distributed parameter approach. In lumped-systems modeling as described by Maidment (1993), the spatial properties of the watershed are averaged without consideration of the effects of location of land characteristics or topological relationships within the watershed or stream network. In contrast, the distributed parameter modeling approach uses detailed digital terrain data and, in come cases, soils, land cover, and other spatial data in the modeling of hydrologic processes, and explicitly considers spatial location of each spatial unit within the watershed.

Rewerts (1992) and Engel, Srinavasan, and Rewerts (1993) review the benefits of distributed parameter modeling relative to the simple lumped approach (in the context of surface flow and pollution modeling in a distributed parameter mode). They note that nonpoint pollution source modeling is concerned with the movement of pesticides and nutrients, as well as soil erosion. Distributed parameter models incorporate the variability in landscape features that controls hydrologic flow and transport processes (topography, soils, and land use), and therefore, are potentially a more realistic modeling approach. Engel, Srinavasan, and Rewerts (1993) also note that distributed parameter modeling accounts for all parts of the watershed simultaneously and incorporates spatial and temporal variability due to landscape attributes. They note that a third advantage of distributed modeling is that the results of "plot-size" research can be extrapolated to the watershed scale.

Much of distributed parameter modeling is now using GIS technology to perform watershed drainage system analysis (Band, 1986; Jenson and Domingue, 1988), to develop various types of HRUs such as those defined by Leavesley and Stannard (1990), or to conduct research on basic runoff-infiltration processes such as in the concept of representative elemental areas described by Wood, Sivapalan, and Beven (1990). For example, Band (1986) and Jenson and Domingue (1988) developed procedures to determine watershed drainage systems, including drainage boundaries, subbasins, and stream network divides, based on the analysis of digital elevation models (DEM). Gandoy-Bernasconi

and Palacois-Velez (1990) developed similar procedures for analyzing DEMs represented by TINs. Vieux (1988, 1991) and Smith and Brilly (1992) review the use of these algorithms in hydrological modeling.

A modified version of Band's algorithm is incorporated into the Geographic Resource Analysis Support System (GRASS) GIS (GRASS, 1988), while the Jenson and Domingue algorithm is the basis for such analysis tools within the ARC/INFO GIS (ESRI, 1991). Vieux and Kang (1990) describe a set of terrain analysis tools for the GRASS GIS called GRASS Waterworks. These GIS tools, coupled with standard GIS functions for boolean searches and overlay operations, form the basis of much contemporary hydrological modeling with GIS.

Hay et al. (1993) describe how a GIS is used in a coupled-systems modeling approach to assess the sensitivity of water resources of the Gunnison River Basin to climatic variability, including potential climatic change scenarios (see also Leavesley, Branson, and Hay, 1992). The output of nested general circulation and mesoscale models is linked to an orographic-precipitation model that provides the precipitation input for a precipitation-runoff modeling system (PRMS), a distributed parameter watershed model (Leavesley et al. 1983). The output of PRMS is used in a downstream flow accounting and routing system to estimate total discharge of the pilot test basin. The GIS is used to manage, manipulate, and analyze the topographic, soils, vegetation, climate, and derived land surface characteristics data that help to determine the behavior of major processes within this coupled systems approach. Such processes include the amount and spatial variability of precipitation through snow accumulation in the orographic-precipitation model, watershed processes (snow melt, evapotranspiration, infiltration, and runoff), and stream flow routing (Hay et al., 1993). For example, the GIS is used to define elevation grids of various grid cell sizes and then characterize terrain statistics in each cell for use in orographic-precipitation modeling. The GIS is also used to assess the effects of slope, aspect (wind orientation), and elevation as a function of scale on modeled precipitation. The gridded model precipitation estimates are then routed to either HRUs or a second grid for PRMS modeling.

GIS is used by the PRMS modeler to define HRU boundaries, estimate parameters in HRUs (or grid cells), and verify the model results. To illustrate, Leavesley and Stannard (1990) developed procedures for characterizing HRUs based on terrain statistics (elevation, slope, and aspect), soil and vegetation types, and rainfall distribution. The watershed delineation tools of Jenson and Domingue (1988) and standard overlay capabilities of GIS are used to define HRUs from these land data. GIS is also used to define basin characteristics in HRUs for estimation of subsystem processes in the PRMS: for example, rainfall interception of vegetation based on vegetation type and density; infiltration based on soil type and slope; ET based on vegetation type, soil type, slope, aspect, and elevation; surface runoff based on vegetation type and density, slope, and soil type; and channel flow as a function of slope and stream length (Hay et al., 1993). In the case of ET calculations, GIS is used to obtain TIN-based statistics of terrain, aspect, and elevation within each model grid cell as a basis for area weighting solar radiation estimates for more realistic estimates of ET. Finally, PRMS estimates of snow cover are validated against satellite-derived estimates based on comparison in the GIS.

Gao, Sorooshian, and Goodrich (1993) report on the integration of GRASS GIS with a physically based distributed parameter precipitation-runoff model for watershed analysis. The model consists of coupled modules for separate hydrologic processes including rainfall intensity, vegetation canopy interception, infiltration, surface lateral flow given saturated soil conditions, channel flow, and subsurface flow. A rectangular grid is used for horizontal discretization with vertical discretization for soil layers. One purpose of the modeling system is to examine the spatial and temporal variability of hydrological processes, determine controlling factors, and investigate scale effects. The GRASS GIS is used by the system to extract model input parameters by grid cell from the spatial database and to visualize model results. GRASS overlay capabilities are used with UNIX system programming macros

to retrieve and edit basin characteristics within individual watershed boundaries. The realtime visualization of model results is accomplished by special UNIX shell programs that extract hydrographs and spatial output, such as overland flow intensity, as the model is executing. One UNIX shell runs the model and another shell counts the lines in the model output until the spatial domain is filled, and then pipes the results to GRASS for display. Gao, Sorooshian, and Goodrich (1993) indicate that this dynamic linkage between the GIS and the numerical modeling system facilitates error analysis, sensitivity checks, model calibration and validation, and investigation of multiscale hydrologic processes. The GRASS GIS is also used for generalization of spatial data.

Other examples of distributed parameter modeling of precipitation-runoff processes in watersheds with some type of GIS interface are described by Smith and Brilly (1992), Johnson (1989), Neumann and Schultz (1989), Vieux (1991), and Drayton, Wilde, and Harris (1992). In each of these, a GIS is used to define model parameters based on spatial analysis of terrain, soils, and land cover data with varied approaches to the integration of the model and GIS. In the work of Neumann and Schultz (1989), a prototype modeling system is described in which remote sensing and GIS technologies are simply used for model parameterization.

Surface Water Quality Modeling

Both qualitative and quantitative approaches address the nonpoint pollution source modeling problem. The traditional qualitative approach with a GIS involves weighted compositing and overlay (Burrough, 1986). Quantitative approaches usually involve some type of distributed parameter modeling. Each of these approaches is illustrated in the following section.

In an example of the weighted compositing index approach, Blaszczynski (1992) described how the revised universal soil loss equation (RUSLE) is interfaced with a GIS to derive a soil erosion potential map for rangelands. The RUSLE is empirically based and is derived by the product of various factors related to rainfall and runoff, soil erodability, terrain slope length and steepness, land cover and management, and support practice. These factors are derived in a raster GIS based on the analysis of various spatial data input on terrain, soil survey, and land use.

There is significant progress in the integration of GIS technology with physically based approaches for nonpoint pollution source water quality modeling as evidenced by the reviews of Rewerts (1992), Engel, Srinivasan, and Rewerts (1993), and Vieux (1991). Water quality and quantity modeling involving nonpoint sources of pollutants are dependent on spatially distributed attributes of a catchment or watershed. The heterogeneous spatial distributions of soil, land cover, land use, and topography determine the type of contaminant and affect key hydrological processes such as runoff and infiltration that determine the fate of the contaminant during overland flow, infiltration, and deep percolation into groundwater sources.

Engel, Srinivasan, and Rewerts (1992) describe the integration of the GRASS GIS with two watershed nonpoint pollution source models, the agricultural nonpoint source pollution (AgNPS) model (Young et al., 1987), and the areal nonpoint source watershed environmental response simulation (ANSWERS) model (Beasley, 1977; Beasley and Huggins, 1982). Both AgNPS and ANSWERS are distributed parameter models designed to identify nonpoint pollution source problems within agricultural watersheds. The models are typically implemented in the context of a decision support system to evaluate the effectiveness of erosion and chemical runoff movement techniques (Engel, Srinivasan, and Rewerts, 1992). These models deal with runoff, erosion, and chemical movement as individual processes. The models are run in a raster-based mode in which the watershed is divided into a set of regular grid cells. Although the data input requirements are quite large (for example, 21 input parameters for each grid cell in AgNPS), runoff characteristics and transport processes of sediments and

nutrients are simulated for each cell and routed to its outlet. Thus, upland pollution sources can be identified.

Rewerts (1992) and Engel, Srinivasan, and Rewerts (1993) discuss a modular toolbox approach consisting of various GIS tools to assist in data development and analysis requirements of the AgNPS and ANSWERS models. Separate modules are developed for hydrologic, erosion, and chemical movement processes. They cite several advantages of this modular approach including the ability to use modules with other distributed parameter models, the ease in updating or replacing modules, and the creation of a variety of modules based on different assumptions for process level modeling.

Needham and Vieux (1989) and Donovan (1991) describe the use of ARC/INFO to generate input files for the AgNPS model. The GIS is used to overlay the AgNPS grid cell structure with ARC/INFO coverages of topographic, soils, land use, and other map-based data. The AgNPS input parameters are determined in the GIS by using an area weighted analysis. The INFO files are exported as ASCII files for conversion to the AgNPS format.

Groundwater Flow and Contaminant Transport Modeling

An example of total GIS model integration is illustrated by the DRASTIC groundwater vulnerability model for state-wide assessment as described by Rundquist et al. (1991). This qualitative model requires the estimation of several hydrogeologic parameters that determine the name of the model: Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity. Each parameter is assigned an overall relative weight, and a rating for each possible categorical value of the parameter. For example, as illustrated by Rundquist et al. (1991), depth to water is assigned a weight of 5, and soil media has an overall weight of 2 in threat to groundwater vulnerability. The range of soils include thin or absent (rating of 10) to nonaggregated clay (rating of 1). The DRASTIC model index is calculated as the summation of the products of weights and ratings for each parameter. Rundquist et al. (1991) describe how the ERDAS GIS was used to estimate each model parameter from map data inputs and then calculate the index as a weighted composite.

Harris et al. (1993) report on the integration of the ARC/INFO GIS with groundwater flow and contaminant transport models for the analysis of the San Gabriel basin groundwater system. In this tightly coupled approach, an integrated system of pre- and post-processing programs was developed to facilitate data flow between the GIS and the CFEST (coupled fluid, energy, and solute transport) groundwater flow model. In general, the GIS was used to develop and calibrate the CFEST model, build and manage a large spatial database, and perform comparative analysis of model output. Specifically, the initial runs were based on the U.S. Geological Survey MODFLOW program (McDonald and Harbaugh, 1988), and the first task for the GIS was to convert MODFLOW input files to the CFEST format. GIS overlay capabilities were used to transfer model information from the orthogonal, regular MODFLOW grid to the irregular finite element grid of the CFEST model. GIS query and spatial analysis tools were used in the conceptual model development of the CFEST implementation. The GIS was also used to update and manage the extensive input files during iterative calibration runs with the CFEST model to simulate historical conditions based on observations. The GIS managed a large and diverse spatial database, which included data on water quality, well characteristics, land use, topography, geology, institutional and political boundaries, and contaminant analysis (Harris et al., 1993). The GIS also managed CFEST model input layers (grids, boundary conditions, and elemental and nodal properties) and model simulation output (water heads, contaminant concentrations, and flow vectors).

In a second approach to integration, Hake and Cuhadaroglu (1993) describe the development of a menu-driven interface between the Intergraph GIS and the MODFLOW groundwater model. In

this case, the interface was developed within the Intergraph MGE (Modular GIS Environment) Environmental Resource Management Applications (ERMA) software to simplify data input, analysis, and display. The GIS-model integration generated the model grid, automatically transformed coordinates, extracted data from the database, and provided overlay capabilities. The interface code features an impressive set of menus to invoke MODFLOW, define the grid, select various options to configure the simulation, define the output, run the model, and display output for analysis.

ECOLOGICAL MODELING AND GIS

This section focuses on the growing use of GIS technology and dynamic simulation modeling in terrestrial ecological research. The focus is limited to examples pertaining to the land-atmosphere interactions modeling paradigm as formulated by the NRC (1990) and the IGBP (1990) and those discussed by Schimel, Kittel, and Parton (1991) and Hall, Strebel, and Sellers (1988). Johnston (1993) reviews the use of GIS as a research tool within the fields of community and population ecological research, and Hunsaker et al. (1993) give a general review of GIS in the fields of freshwater and marine ecological modeling.

In general, recent developments in physiologically based ecosystem dynamics simulation models, forest succession models, landscape ecology, and exploratory spatial analysis of disturbance patterns have created a promising foundation for GIS within these areas of ecological research. The following two sections summarize the status of GIS technology and ecological model integration in this context. The first section examines the role of a GIS as a tool to support dynamic simulation models operating at daily to monthly time steps for ecosystem dynamics, rangeland, and crop simulations. The second section focuses on forest succession modeling, typically characterized by annual model time steps. The use of a GIS in disturbance modeling is also examined.

Ecosystem Dynamics, Rangeland, and Crop Simulation Modeling

Examples of ecological models that fall in the land-atmosphere interactions paradigm include the regional hydro-ecological simulation system (RHESSys) recently described by Running, Nemani, and Band (1992), the CENTURY model discussed by Burke et al. (1990) and Schimel, Kittel, and Parton (1991), and various forest stand or ecological succession models (see for example Nisbet and Botkin, 1993). The first two examples and other physiologically based approaches for rangeland and crop simulation are described in this section. The ecological succession models illustrate processes operating over longer time scales and are discussed in the next section.

GIS technology is used to support the extrapolation of plot level information to regional scales. For example, Running (1991a), Running, Nemani, and Band (1992) and Nemani et al. (1993) describe the RHESSys as an integrated modeling system in which a physiologically based forest ecosystem model (FOREST-BGC) (Running et al., 1989) is used to extrapolate forest plot information to the regional and continental levels. The RHESSys is a coupled-system model that links hydrological, ecological, and microclimatological models with remote sensing, soils, and climate data. The model is designed to simulate and map water, carbon, and nutrient fluxes at various spatial scales. The simple or generic GIS approach discussed by Running et al. (1989) is replaced by a polygon-based approach for geographic information processing as discussed by Running (1991a) and Band et al. (1991). Topographic analysis tools developed by Band (1986) define a template consisting of hillslopes, stream channels, and subwatersheds that characterize the landscape structure. Polygons representing hillslopes and watersheds stratify leaf area index, microclimate data, and soil water capacity into relatively

homogeneous landscape units for model input. Spatial aggregation and scaling-up are achieved by defining landscape templates of differing spatial resolutions.

The ARC/INFO GIS was coupled with the CENTURY ecosystem model to simulate the spatial variability of grasslands biogeochemistry (Burke et al., 1990; Schimel and Burke, 1993). The GIS built regional climate and soils databases to drive the CENTURY model. Contoured maps of mean annual total precipitation and mean annual temperature were derived from monthly weather station data. The regional soil texture map was derived from county level data. These three ARC/INFO coverages were overlaid to define unique polygons for the model simulation. The GIS was used to map the CENTURY output including soil organic carbon, annual aboveground net primary production, net nitrogen mineralization, and nitrogen oxide fluxes (Burke et al., 1990).

GIS technology is contributing to rangeland production and agricultural crop simulation research. Hanson and Baker (1993) illustrate a GIS as a database manager for the simulation, production, and utilization of rangelands (SPUR) model. The GIS integrates climate, soils, hydrological, plant, animal, and terrain data for input, as appropriate, to the SPUR subsystem process modules for hydrology, plants, livestock, wildlife, insects, and economics. The SPUR model is currently used in combination with GIS and remote sensing technologies to understand the spatial patterns and interactions caused by processes within rangeland ecosystems. Hanson and Baker (1993) suggest that a GIS can assist in the parameterization, execution, and validation of models such as SPUR. This would contribute to the extrapolation of point data on soils, climate, plants, and experimental plot results to larger scales, for example, pastures, ranches, landscapes, and regions.

The potential role of remote sensing and GIS technologies to enhance crop simulations for small agricultural fields in the heterogeneous landscape environment of central South Carolina was demonstrated by Narumalani and Carbone (1993). Land cover was classified according to scrub/shrub, forest, wetland forest, wetland marsh, water, urban, and agricultural land categories based on analysis of SPOT multispectral images and National Aerial Photography Program photographs. Agricultural and nonagricultural land use regions were brought into an ARC/INFO GIS along with daily weather, soils, and other data sets needed by a physiologically based soybean growth model. Although the analysis was constrained by available weather data and the accuracy of the image classification, the method does illustrate how spatial data in a GIS permitted aggregation of crop simulation results by running the model on the desired land use parcel and ignoring the non-agricultural lands. This type of study is relevant to the integration of simulation models with GIS and remote sensing technologies to routinely assess or monitor changing agricultural conditions throughout the growing season.

As an example of realtime monitoring functions, Kessell (1990) and Kessell and Beck (1991) describe the role of a generic GIS that was developed in Australia for forest fire modeling as part of an overall modeling system for natural resource management. The purpose is to assess fire hazard and potential, as well as provide a realtime fire monitoring tool. The software and hardware package has had many variations over the years and is called the geographical information and modeling system (GIMS). The system has individual modules for vegetation structure and floristics for each grid cell as a function of other GIMS data layers (such as elevation, slope, aspect, and soil type), flammable fuel conditions, fire behavior, and fire area and perimeter growth over time. There are also modules for natural resource management including animal habitat, catchment protection, and resource allocation.

Ecological Succession and Landscape Disturbance Modeling

Ecological succession modeling and the study of landscape structure and disturbance patterns are two promising areas for GIS technology (Nisbet and Botkin, 1993; Polzer et al., 1991; Lowell, 1991; Kessell, 1990; Silveira, Richardson, and Kitchens, 1992; Baker, Egbert, and Frazier, 1991). The

following examples illustrate the current status and likely directions of GIS in this type of research, particularly considering heterogenous landscapes.

Nisbet and Botkin (1993) discuss how a GIS can display results of forest growth models such as JABOWA (Botkin, Janak, and Wallis, 1972) and FORET (Shugart and West, 1977). However, they also suggest that an expanded role for GIS could result from inclusion of potential spatial interactions, which could affect forest regeneration, growth, and mortality processes in the model. They suggested that conditions in adjacent cells, such as biomass levels or site heterogeneity, could be factors in the life cycle process.

Smith and Urban (1988) used a roving window of influence to keep track of biomass and leaf area within adjacent cells in a JABOWA-like model. Similarly, Woodby (1991) used the JABOWA-II model to consider extinction probabilities of trees as a function of site heterogeneity and the proximity of trees to surrounding landscape. Model simulations of up to 1,000 years showed a dependency on patch size, spatial variation of soil characteristics, and occurrence of disturbances. The results suggested the importance of spatial interactions due to variability in soil quality, soil moisture availability, patch size, and disturbance regime.

Based on these results, Nisbet and Botkin (1993) suggest that a suite of JABOWA-like forest growth models could be run in a GIS environment at the landscape scale to explore various hypotheses on the role of spatial interactions. They suggest that other complex spatial interactions could include the transport of materials (for example, by wind, water, and biological vectors), windshed effects, and pollution plume effects, and call for either an advanced modeling language to execute ecological models in a GIS or system calls to model subroutines from within the GIS.

Polzer et al. (1991) developed a software link between the PC ARC/INFO GIS and the ZELIG forest growth model (Urban, 1990). The GIS built and managed the spatial database and analyzed and visualized model results. The link involved using the GIS to parameterize the model input based on the GIS data structure, converting this structure to the model input format, and reformatting the model output back to the GIS data structure following the model simulations. The link was accomplished through the dBASE programming language, although the conversion of multiple files was cumbersome. This case study demonstrates the need for transparent data conversion routines between the GIS and the external dynamic simulation software.

The role of disturbances as a factor in ecological succession is a major research topic in landscape ecology. Baker et al. (1991), Lowell (1991), and Silveira, Richardson, and Kitchens (1992) illustrate three different approaches for modeling landscape disturbance, in each case with some GIS contribution. For example, Baker et al. (1991) describe the DISPATCH (DISturbance PATCH) simulation model that was developed as a theoretical framework to study disturbance and landscape interactions under global change scenarios. The model was designed to simulate repeated disturbances over time scales of hundreds of years, to simulate the effects of environmental variability or landscape structure on disturbance initiation and spread, and to provide information on quantitative changes in landscape structure. The components of the model include algorithms to generate climatic and disturbance regimes, five GIS map layers (vegetation type, patch age, elevation, slope, and aspect), a disturbance probability map based on grid cell conditions, and spatial data tools for structural analysis of patches. As noted by the authors, however, the limitations of the model include the inability to validate long-term simulations (usually a limitation) and realistically simulate disturbances such as fires or floods and the need for an extensive data set to calibrate the model.

Both Lowell (1991) and Silveira, Richardson, and Kitchens (1992) used historical data sets with separate types of landscape disturbance models and a GIS for case study analysis of ecological succession. Lowell (1991) used discriminant function analysis (DFA) to analyze the spatial and temporal distributional changes associated with long-term ecological succession within a central

Missouri wildlife research refuge. He concluded that the DFA does provide a useful framework for modeling spatiotemporal changes in the landscape patterns for this study area, which was farmed up until 1937 when human intervention was halted (except some grazing until the early 1960s) and the land was permitted to undergo natural ecological succession. He also suggests that the DFA is a parametric statistical tool for use in a GIS in ways that are entirely consistent with traditional overlay approaches that could have been used to analyze the central Missouri data. Specifically, the DFA provides a GIS with a means to develop temporal models that can be applied spatially.

Silveira, Richardson, and Kitchens (1992) used qualitative modeling and analysis approaches entirely in an ERDAS GIS to investigate possible landscape and disturbance relationships in the Everglades ecosystem over time. The model was designed to simulate disturbance due to fire damage and postdisturbance vegetation succession. The modeling approach was rule-based, that is, the ERDAS GISMO module was provided rules on fire behavior, successional rates, and other relationships that were based on the literature.

Landscape ecologists and other researchers have made large strides in developing GIS techniques and exploratory spatial data analysis tools to investigate complex landscape structure including disturbance patterns (Johnston, 1993; Johnston, 1992; Michener et al., 1992; Baker and Cai, 1992; Rossi et al., 1992; Walker and Belbin, 1990; and Hall et al., 1991). For example, Johnston (1993) discusses the use of GIS techniques in combination with satellite image analysis to detect ecotones in vegetation patterns and to estimate forest successional rates over time based on the analysis of disturbance patterns within multitemporal satellite scenes. Baker and Cai (1992) developed GRASS GIS tools called r.le, which are designed to analyze more than 60 measures of landscape structure (for example, distance, size, shape, diversity, and texture). Rossi et al. (1992) discuss the application of advanced geostatistical tools for interpreting ecological spatial dependance.

DISCUSSION, AND DIRECTIONS FOR GIS

This chapter has reviewed a wide variety of GIS applications involving atmospheric, hydrologic, and ecologic sciences. Applications have been found to fall into several broad categories. First, GIS is used as a preprocessor of data, making use of its functions for projection change, resampling, generalization, windowing and other data extraction tasks, map digitizing, and editing. Reformatting is often needed to meet the requirements of simulation packages. Second, GIS is used for storage of data, since the database management facilities of GIS keep track automatically of many housekeeping functions, such as simple documentation, and provide a uniform mode of access. Third, GIS is used for statistical analysis of data and model results, often in combination with standard packages for statistics or geostatistics. Fourth, GIS is used for visualization, particularly for presenting results of simulations in map form, often in combination with other data. These functions are all available in the current range of GIS products, and in most of these areas, functions are currently available to meet most needs.

Current GIS differ widely in the methods used to represent geographic features and patterns, and in the functions supported by each package. The choice of an appropriate GIS to support simulation modeling is often complex, requiring substantial technical knowledge on the part of the user. Some modelers use commercial packages with proprietary data formats such as ARC/INFO, while others use open public domain systems such as GRASS. In general, the current generation of GIS is considered difficult to use, in part because of the wide range and cumbersome nature of user interfaces.

GIS developers have been relatively slow to incorporate some of the more sophisticated forms of spatial analysis needed by environmental simulation modelers. For example, despite the importance of spatial interpolation to resampling of data, few packages offer the sophisticated methods of interpolation of geostatistics. Methods of spatial interpolation that allow the user to include a

sophisticated knowledge of interpolated phenomenon are also poorly developed. For example, it is not easy to find spatial interpolation algorithms in conventional GIS products that allow researchers to include discontinuities, or weight observations by quality.

Many researchers have used a GIS as a convenient source of functions for the display and mapping of data and results. Mapping software code can be complex, especially where functions must be included to mimic the skill of a trained cartographer in tasks such as positioning labels or where displays require the merger of many different types of information. Scientists with simple display requirements may find it more convenient to write their own code or make use of the increasing sophistication of scientific visualization packages like AVS (application visualization system) or Khoros rather than a GIS.

Goodchild, Haining, and Wise (1992) review the various forms of coupling that are possible when GIS technology and environmental models are used together. Loose coupling combines the capabilities of separate modules for GIS functions and environmental simulation by transferring simple files, often in ASCII format. Many GIS accept a wide range of input and output formats, but in many cases it is necessary to write a short piece of code as a bridge between the two modules. Loose coupling is effective for preprocessing data or displaying results, but may require the investment of substantial resources to build the necessary bridges. Tight coupling allows the two modules to run simultaneously and to share a common database. Because data formats and definitions must be shared, tight coupling is uncommon, although much more convenient for the researcher. Opportunities for tight coupling will increase as GIS data formats become more widely known, particularly through the use of open GIS toolboxes such as GRASS (1988), which allows the researcher access to source code. The development of the Spatial Data Transfer Standard (now adopted as Federal Information Processing Standard 173) will facilitate the development of tightly coupled GIS modeling systems.

Most of the applications reviewed in this chapter fall into one or more of the approaches for integration just described. Only a few use the GIS directly as the modeling environment, writing the simulation as a series of GIS commands rather than in a common source language. At present, such embedding of the model in a GIS is practical only in the case of finite difference models that can take advantage of the functionality of raster GIS for cell-based modeling, and the range of such raster capabilities falls short of the range needed for environmental simulation (Goodchild, 1993). Kemp (1992) argues that an ideal modeling language for environmental simulation would allow the modeler to ignore the details of the spatial representation of the model's variables. However, practical realization of this possibility is still in the future.

Several areas of successful integration of GIS technology and environmental simulation models have been described in this chapter, but advanced GIS tools are needed for further progress. Some of these capabilities such as efficient data conversion algorithms, exploratory spatial data analysis tools, and a modeling language have been highlighted. The software development community is just beginning to address these needs (for an extensive review of GIS development directions see Maguire, Goodchild, and Rhind, 1991), as well as other requirements such as temporal and three-dimensional data analysis capabilities that are typical of most dynamic simulation models. Hierarchical GIS is needed for regional extrapolations and other types of multiscale analysis. Object oriented approaches are just beginning to appear in the literature, especially for hydrologic modeling. An understanding of the underlying environmental processes and modeling approaches is a necessary requirement for the development of GIS tools in each of these areas.

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