GEOGRAPHIC INFORMATION SCIENCE AND SYSTEMS FOR

ENVIRONMENTAL MANAGEMENT

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ABSTRACT

The geographic context is essential both for environmental research, and for policy-

oriented environmental management. Geographic information systems are as a result

increasingly important computing applications in this domain, and an understanding of

the underlying principles of geographic information science is increasingly essential to

sound scientific practice. The review begins by defining terms. Four major sections

follow, dealing with advances in GIS analysis and modeling; in the supply of geographic

data for GIS; in software design; and in GIS representation. GIS-based modeling is

constrained in part by architecture, but a number of recent products show promise, and

GIS continues to support modeling through the coupling of software. The GIS data

supply has benefited from a range of new satellite-based sensors, and from developments

in ground-based sensor networks. GIS software design is being revolutionized by two

developments in the information technology mainstream: the trend to component-based

software, and object-oriented data modeling. Advances in GIS representation focus

largely on time, the third spatial dimension, and uncertainty. References are provided to

the more important and recent literature. The concluding section identifies three

significant and current trends: towards increasing interoperability of data and services;

increasing mobility of information technology; and increasing capabilities for dynamic

simulation.

KEY WORDS: geographic information system, geographic information science,

representation, metadata, simulation modeling

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1. INTRODUCTION

We normally define the environment to include the surface and near-surface of the Earth; that is, the biosphere, the upper parts of the lithosphere, and the lower parts of the atmosphere. Some facts about this domain are universally true, at any point in space and time: examples include general facts about the fluvial processes by which flowing water modifies landforms, or general facts about the behaviors of certain species. The discovery of such general facts is of course the major focus of much scientific activity. But other facts are specific in space, and often also specific in time. For example, the elevation of Mt Everest refers specifically to a small point on the Nepal–Tibet border, and undergoes changes through time due to the continued uplift of the Himalayas (and also to improvements in measurement techniques). We commonly use the terms *geographic* and *geospatial* to describe collections of such facts about specific places in the environment, and *spatiotemporal* to describe collections of facts about specific places at specific times (*spatial* is commonly defined as a generalization of *geographic* to any space, including outer space, or the space of the human body). Geographic facts are in themselves not as valuable and significant as general facts, but they are essential if general facts are to be extracted through the study of specific areas, or applied in specific areas to provide the boundary conditions and parameters that are needed in order to forecast, to evaluate planning options, or to design new structures.

Clearly a high proportion of the data needed for environmental management are geographic (for the purposes of this review the term will be used synonymously with

geospatial, and will include the possibility of temporal variation). Maps and atlases contain large quantities of geographic data, and geographic data can also be found scattered through books, journal articles, and many other media. Today, increasing quantities of geographic data take the form of electronic transactions, such as the locations telemetered from a collared mammal to a researcher studying its foraging habits and territorial behavior. Vast amounts of geographic data are now collected daily by imaging satellites, and distributed via the Internet; and increasing amounts are collected by networks of ground-based sensors, and through field observation.

This review concerns two topics related to geographic data: geographic information science (GIScience), which is the research field that studies the general principles underlying the acquisition, management, processing, analysis, visualization, and storage of geographic data; and geographic information systems (GIS), which are computer software packages designed to carry out these activities. The history of GIS began in the 1960s with primitive efforts to use computers to process geographic data (Foresman, 1998); the history of GIScience began in the late 1980s as the widespread use of GIS began to draw attention to the need for a deeper understanding of fundamental principles, and rejuvenated interest in older disciplines such as cartography, surveying, and navigation (Goodchild, 1992a; Wright *et al.*, 1997; Goodchild *et al.*, 1999).

Environmental management has been a prime motivator of developments in GIS, and a major area of application, throughout its history. The first GIS, the Canada Geographic Information System, was developed in the mid 1960s in order to handle the vast amount

of mapped information collected by the Canada Land Inventory, and from it to provide data to the Government of Canada on Canada's land resource, its utilization, and its management. The first commercially viable GIS, introduced in the early 1980s, found its initial customers among environmental management agencies and forestry companies. Environmental management continues to motivate developments in GIScience, and their implementation in GIS. Geographic data and GIS are of such importance to the environmental disciplines that today we tend to think of them as indispensable parts of the research, teaching, and policy arenas.

The argument for geographic data and GIS, and more generally for taking a geographic or spatial perspective on the environment, is essentially two-fold (Goodchild *et al.*, 2000). First, our understanding of the environment is at least in part derived from studying it directly, rather than from replicating its behavior in the laboratory under controlled conditions. We draw inferences from the correlations we observe between different factors at a location, from the differences we observe when locations are compared, and from the context in which changes occur. All of these are supported by studying the environment in spatial and temporal detail. Scientific knowledge is of course most valuable when it is general, in other words when it is known to be true everywhere, at all times. Thus the process of scientific knowledge creation is fundamentally a process of abstracting knowledge from space and time. The second argument for geographic data and GIS occurs when that general knowledge must be applied, in making decisions or in developing policy. In this phase general knowledge must be recombined with the specifics of a place and time; general knowledge is expressed in the procedures and

models implemented in the GIS, and the specifics of a location and time are expressed in the geographic data in the GIS's database.

This review begins with an overview of recent literature in GIS applications to environment and resources, including advances in environmental modeling with GIS. This is followed in Section 3 by a review of advances in geographic data sources, including the advent of several new and exciting passive and active sensors, growing interest in autonomous ground-based sensor networks, and the potential offered by mobile GIS functionality in the field. The mechanisms for disseminating the products of these sensors and systems remain fraught with difficulty, however, stemming from diverse practices in the design of online archives; lack of interoperability between systems; and the lack of effective search mechanisms over distributed data sources.

Recent advances in software engineering, including the trend towards reusable components, are having profound effects on GIS, and are reviewed in Section 4. It is now possible to combine components from a range of packages written to compliant standards, avoiding the traditional necessity to couple packages, a practice common in environmental modeling, where specialized modeling codes have frequently been coupled with GIS. These innovations offer advantages in a number of areas, including the design and development of spatial decision support systems, that is, systems designed to give decision-makers the ability to evaluate decisions and scenarios. However, the infrastructure for sharing methods and models, expressed in digital form, lags far behind the infrastructure for sharing data, although arguably methods and models represent a

higher form of scientific knowledge.

In GIScience, advances have been made in understanding the importance of ontology, which is defined as the science of representation, or the study of the things people choose to acquire information about. Ontology dominates the earliest stages of science, when researchers must decide what to describe, what to measure, and what to record in order to develop an understanding of an environmental system. Similarly, it dominates the design of GIS databases, and ultimately constrains what one can do with the representation created in such a database. Ontological choices, or their more practical, everyday expression in the designs of databases, are thus fundamental to all science, and particularly important in any science that is supported by information technology. Section 5 of the review discusses GIS representation, and reviews recent research on alternative ontologies, and the potential of new developments in information science to support the integration of data produced by different researchers and disciplines into a seamless research environment. It also reviews recent work on uncertainty, which focuses on issues such as accuracy, and approaches to deal with areas of environmental science where definitions are inherently vague. The chapter ends with a brief concluding section.

2. GIS ANALYSIS AND MODELING

2.1 Types of Geographic Data

In principle, a GIS can be designed to perform any conceivable operation on any type of

geographic data. Like many other computer applications, its success depends on a fundamental economy of scale: once the foundation has been built for managing geographic data, it is possible to extend the list of supported operations very quickly, at minimal cost. This same economy of scale underlies and explains the rich functionality of packages such as Excel, which performs a vast array of operations on data expressed in tables; or Word, which similarly performs almost any conceivable operation on text. GIS is simply the equivalent for geographic data.

However, this simple model fails in one crucial respect: there are many distinct types of geographic data. GIScientists distinguish between two fundamentally different conceptualizations of the geographic world (Couclelis, 1992; Goodchild, 1992b; Worboys, 1995). In the *continuous field* view, the surface of the Earth can be described by mapping a set of variables, each of which is a single-valued function of location, and perhaps time: $z = f(\mathbf{x})$, where $\mathbf{x}$ denotes location in space-time. Topography, for example, is often represented by mapping elevation as a function of the two horizontal dimensions, and atmospheric pressure as a function of the three spatial dimensions and time. In addition to these examples of measurements on interval/ratio scales, the mapped variable can be nominal or categorical; for example, ownership is a single-valued function of the two horizontal dimensions, as is land cover class, or county name.

In the second, or *discrete object* conceptualization, the Earth's surface is a space littered with objects. The objects may overlap, and there may be empty space between them. We often conceive of built environments in this manner, as spaces littered with buildings,

streets, trees, vehicles, and other well-defined and discrete objects. Discrete objects are countable and readily identified, and those that are useful tend to be persistent through time.

Both views are common in the environmental sciences, and they frequently interact. In ecology, for example, one might analyze the behavior of individual organisms, perhaps regarding distance between individuals as an important causal factor, reflecting a discrete object view. But at another, coarser scale, one might attempt to explain variation in the density of individuals in terms of variation in resources, by looking for correlations between continuous fields: the dependent variable, density, would be conceptualized as a field, as would the independent variables. One might even try to model animal behavior as a discrete object responding to such continuous fields as habitat suitability, or climate. Clearly a GIS that is intended for environmental applications must support both conceptualizations.

In practice, discrete objects are represented digitally by points, lines, areas, or volumes, as appropriate. Rivers might be represented as lines when they act as corridors or barriers, and as areas or volumes when the interest is in the distribution of organisms within the river; the term *polymorphism* is used to describe such multiple, application-specific representations. Each feature has one or more attributes, describing its characteristics, and one or more coordinates describing its shape. The shapes of lines are commonly represented as sequences of points connected by straight lines, and areas as closed sequences (the terms *polyline* and *polygon* are used respectively).

Continuous fields present a more difficult representation problem, because in principle the function $z=f(\mathbf{x})$ can stand for an infinite amount of information, if every point's corresponding value of z must be independently measured and recorded. In practice, any field representation must be an approximation for this reason, and six methods of approximation are commonly used in GIS (discussed here in the two-dimensional case):

- *Regularly spaced sample points*. Topography is most commonly represented in this form, as a *digital elevation model*.

- *Irregularly spaced sample points*. The continuous fields of meteorology – atmospheric temperature, pressure, precipitation, *etc*. – are sampled at irregularly spaced measuring stations.

- *Rectangular cells*. The continuous fields captured as remotely sensed images are represented as arrays of cells, each cell having as attribute the average spectral response across its extent.

- *Irregular polygons*. Nominal variables, such as land cover class, are most commonly represented as collections of non-overlapping, space-exhausting areas, each with a single value that is assumed to apply homogeneously to its extent.

- *Triangular mesh*. Topographic surfaces are sometimes represented as meshes of irregular triangles (*triangulated irregular networks*, or TINs), each with uniform slope and with continuity of value across triangle edges.

- *Digitized isolines*. Topographic surfaces are also sometimes represented as collections of lines, derived from the contours of the surface.

Of these six, the first two and the last are inherently different from the third, fourth, and fifth. While the latter three can be queried to obtain the value of the field at any location, the former three record values only at certain locations – points in the case of the first two, and lines in the case of the last. One might term the latter set *complete* representations, and the former set *incomplete* representations, for this reason, though note that completeness does not imply perfect accuracy. In order to support queries about the values of the field, or to support resampling, or various forms of visualization, an incomplete representation must be coupled with a method of *spatial interpolation*, defined as the means to estimate the field's value at locations where value is not recorded. A substantial number of methods of spatial interpolation are available (Goovaerts, 1997; Lam, 1983; Isaaks and Srivastava, 1989), many of them implemented in GIS.

The representations of both discrete objects and continuous fields fall into two categories, and are often described in these terms. Methods that record coordinates are termed *vector*, and include all of the discrete object representations, plus the irregularly spaced sample points, irregular polygons, triangular mesh, and digitized isoline representations of fields. *Raster* methods, on the other hand, establish position implicitly through the ordering of the array, and include the regularly spaced sample point and rectangular cell representations of continuous fields. For this reason rasters are often loosely associated with continuous fields, and vectors with discrete objects, but the association is more likely to confuse than to illuminate.

Of the six methods, the last two are restricted to interval/ratio variables, for obvious

reasons. The third and fourth are used for both nominal and interval/ratio variables, while

the first two might be used for both, but are in practice used for interval/ratio variables.

These six are in principle not the only methods that might be used to represent fields, but

they are the only methods widely implemented in GIS. In the scientific community more

generally, much use is made of *finite-element* methods (FEM), which represent fields

through polynomial functions over meshes that mix irregular triangles and quadrilaterals.

FEM are commonly used in applications that require the solution of partial differential

equations (PDEs), and there are many such applications in the Earth sciences, from tidal

movements to atmospheric modeling. Links have often been made between FEM-based

modeling software and GIS (Carey, 1995), but FEM has not been adopted as a basis for

field representation in GIS, perhaps because of its greater mathematical complexity

relative, say, to TINs.

Within this overall organization of geographic data it is possible to identify vast

resources, increasingly available over the Internet from archives, clearinghouses, and

digital libraries, and representing an investment over decades, and in some cases

centuries, that certainly exceeds a trillion dollars worldwide. Most of this investment has

been made by national governments, through national mapping agencies and space

agencies, but the commercial sector is growing rapidly, and geographic-data production

is increasingly a function of local government and even individuals. Developments in the

geographic data supply are reviewed in a subsequent section; the following sections

discuss the uses of these data resources in analysis and modeling.

2.2 Developments in GIS Analysis

The set of possible forms of analysis and manipulation that is possible with GIS is vast, and much effort has gone into finding useful systems of organization that might help users to navigate the possibilities. Any GIS must of course support basic housekeeping operations, such as copying data sets between storage devices, transforming coordinates to different map projections, conversion from paper maps to digital databases, reformatting for use by other systems, editing, visualization, and other routine functions. But the true power of GIS lies in its ability to search for patterns and anomalies, to summarize, to compare reality to the predictions of theories, or to reveal correlations. Tomlin (1990) made one of the first successful efforts to codify analysis, identifying four basic classes of operations, and defining an associated language that he termed cartographic modeling. The language, which bears some similarities to others defined in image processing (Serra, 1982), became the basis for command syntax in several GIS packages. But his work was limited to raster data, and efforts to extend it to vector data have thus far been unsuccessful.

Many texts on analysis of geographic data have adopted a codification based on data types. Bailey and Gatrell (1995) divide techniques into those appropriate for sets of points, sets of areas, measures of interactions between objects, and analyses of continuous surfaces, for example, and similar approaches are used by Haining (1990) and

by O'Sullivan and Unwin (2003).

Longley *et al.* (2001) recently used a very different approach based on classifying techniques according to their conceptual frameworks:

- *Simple queries*, which return results already existing in the database;
- *Measurements*, which return measures of such properties as distance, length, area, or shape;
- *Transformations*, which create new features from existing features;
- *Descriptive summaries*, which compute summary statistics for entire collections of features;
- *Optimization*, which results in designs that achieve user-defined objectives, such as the search for an optimum location; and
- *Hypthesis testing*, in which statistical methods are used to reason from a sample to a larger population.

Each of these categories might apply to any type of data, and to both discrete object and continuous field conceptualizations.

Today, GIS is used in a vast array of application domains, many of them strongly associated with the environment and with resources. Papers describing research that has made use of GIS to study problems in the environment and in resources appear in specialized journals, and several collections of papers have been published recently as

specialized books. GIS applications to environmental health have been described by

Gatrell and Loytonen (1998), Cromley and McLafferty (2002), Briggs (2002), and Lang

(2000). Haines-Young *et al.* (1993) and Johnston (1998) describe applications in

landscape ecology. A forthcoming book by Bishop (2003) contains solicited chapters

describing the use of GIS in mountain geomorphology.

2.3 Developments in GIS Modeling

The term *modeling* is of course vastly over-loaded, with many nuances of meaning in

different contexts. In GIS it has three important meanings, two of which are the focus of

this section. First, modeling is used in the context of *data modeling*, or the process by

which structures and templates are created that can be filled with measurements,

observations, and other forms of data. The basics of data modeling for GIS were covered

in a previous section at the conceptual level, and the more detailed physical levels of data

modeling that include discussions of indexes and coding schemes are beyond the scope of

this review.

In its second meaning, modeling refers to the use of GIS transformations and other

procedures to create composite variables that have significance in some aspect of a GIS

application. At a very primitive level the calculation of the Normalized Difference

Vegetation Index (NDVI; Campbell, 2002) in remote sensing is an example of this kind

of modeling, taking its inputs from two bands of a satellite-based sensor, and computing

the ratio of the difference to the sum, to obtain a useful index of greenness. NDVI is often

computed to show the march of the seasons across the mid-latitudes, as vegetation greens in the spring and decays in the fall. The Universal Soil Loss Equation (Wischmeier and Smith, 1965) is another example, combining inputs representing various factors of importance in determining soil erosion, and producing an index that is a useful estimate of soil loss. While the calculation of NDVI from raster image data is a straightforward arithmetic task, the calculation of USLE is more likely to involve the integration of field representations that use more than one of the six options listed earlier (perhaps elevation as a regular array of points, soil class as a collection of polygons, *etc.*), and hence to require a larger set of GIS functions, including raster-vector conversion. In summary, modeling in this second sense takes inputs and transforms them into outputs. All inputs and outputs are assumed to be valid at the same point in time, although the output may be used to estimate changes through time, as in the case of the USLE. This second meaning of modeling will be termed *static modeling* in this review.

The third meaning is strictly dynamic, and will be termed *dynamic modeling*. Dynamic models are iterative, taking a set of initial conditions and applying transformations to obtain a series of predictions, at time intervals stretching into the future. The transformations may be expressed in a number of forms, and this provides the basis for one system of classification of dynamic models. Some dynamic models implement the solution of PDEs, to obtain predictions of future states of the modeled system; such models are particularly applicable in systems involving the behavior of fluids, including water, ice, and the atmosphere. Underground flow through aquifers, for example, is often modeled through the solution of the Darcy flow equations (Darcy, 1856). PDE-based

models may be implemented through numerical operations on rasters, termed *finite-difference* methods, or through numerical operations on finite-element meshes, though as noted earlier FEM is normally implemented outside GIS. In both cases the mathematical expression of the model as a PDE must be approximated in its computational implementation through a series of operations on rasters or finite elements. For example, the mathematical concept of the derivative is implemented in finite-difference approximations as an arithmetic operation on small raster neighborhoods. In principle, then, PDEs could be implemented using the language of cartographic modeling discussed earlier, which includes all of the necessary operations.

In the discrete object domain, mathematical models address the interactions between objects, in the style of Newton's Law of Gravitation. Spatial interaction models attempt to replicate the interactions that exist between social entities, such as migration flows between states, flows of telephone traffic between cities, or flows of commuters between neighborhoods (Haynes and Fotheringham, 1984; Fotheringham and O'Kelly, 1989). Flows are modeled as the product of factors relating to the origin's propensity to generate flow, the destination's propensity to attract it, and the role of intervening distance as an impediment. Spatial interaction models have found applications in resource management, in the modeling of population pressure on recreational resources, and tourist flows to destinations. Unlike PDEs, such models deal directly with objects and their digital representations, and do not require the numerical approximations that occur when PDEs are transformed into finite-difference or finite-element models.

Other dynamic models lack the formal mathematical definition of PDEs and spatial interaction models, and instead define operations directly on digital representations. Such models are termed *computational*. Two important classes of computational models are *cellular automata* (CA) and *agent-based models* (ABM). In the former, the behavior of a system is modeled as a series of transition rules concerning the states of cells in a raster. For example, a number of research groups (Torrens and O'Sullivan, 2001; White and Engelen, 1997) have developed CA models of urban growth, relating the transition of a cell from agriculture or open space to urban development as a function of the state of neighboring cells, as well as proximity to transportation, physical suitability for development, and so on. ABM attempt to characterize the behavior of individuals and groups, and the impacts of their decisions on their surroundings, and have been applied to land use transition in rural areas (Parker, Berger, and Manson, 2002).

Dynamic models that invoke continuous-field conceptualizations, either as inputs or outputs, must of necessity be scale-dependent, since their predictions vary with the level of detail of the underlying field representations. Raster-based computational models give predictions that are specific to the physical dimensions of the raster. Scale-dependence in vector-based computational models is more difficult to characterize, however, since the concept of spatial resolution is not well-defined for any of the vector-based field representations (irregular points, irregular polygons, TINs, and digitized isolines). Thus an important test of any computational model is its degree of sensitivity to scale change. CA models are among the most problematic in this sense, since their definitions are scale-specific; while scale affects only the computational implementation of PDEs, not

the PDEs themselves.

Static models are readily implemented in GIS, and a large number of such models have been operationalized, often as GIS scripts, or extensions to standard GIS software. The concept of a script or macro is common to many computer applications, allowing the user to record and replay a sequence of commands. In some cases the recording occurs during the normal use of the software, by user actions that start and stop the recording at appropriate points. In other cases the script is written by the user, in a language designed for the purpose, tested and executed later, and possibly shared with others. The popular GIS ArcView, for example, is supplied by its developer ESRI with a scripting language Avenue (Version 8 of ArcView replaces the vendor-specific Avenue with the Microsoft language Visual Basic; for an introduction to Avenue see Razavi, 2002, and for Visual Basic see Bradley and Millspaugh, 1999). A large number of Avenue scripts have been coded or recorded, and made available for standard environmental and resource applications (see http://arcscripts.esri.com/).

Dynamic models are much more difficult to implement in GIS scripting languages. GIS software was designed largely for transforming and analyzing data, rather than for the rapid iterations needed by dynamic models. Although it is possible to implement an iterative process, such as a CA model, in Avenue, the resulting performance is typically very disappointing, to the point of being impractical. Instead, researchers have implemented dynamic models in other ways, that avoid these performance issues. Three approaches are commonly identified, as three forms of *coupling* of GIS and dynamic

modeling (Nyerges, 1993).

First, *loose coupling* is defined as the implementation of dynamic models in two software packages, one designed purely for the modeling, and the other the GIS. Data pass in both directions between the packages. Inputs often require reprojection, resampling, editing, and sometimes raster–vector conversion, and these operations are better performed in the GIS, and passed to the dynamic model. During and after execution of the model, selected results are passed back to the GIS for display, further analysis, and archiving, again taking advantage of the existence of these functions in the GIS. This approach requires a degree of compatibility between the two packages, such that each can read and write the other's data formats.. When no common formats can be found, it is necessary to add a third package, to do the necessary format conversions. The problem is exacerbated by the continuing insistence of some GIS vendors that their internal formats be proprietary.

Close coupling can be used when both packages are able to read and write the same formats, avoiding the need for file transfer or conversion. Because of the proprietary nature of some GIS formats, this option is most likely to be available when using open-source GIS packages, or GIS packages for which internal formats have been published.

Finally, *tight coupling* occurs when the dynamic model is written directly in the scripting language of the GIS. As noted earlier, this is uncommon because of the poor performance of many GIS products in these applications. But it is possible to achieve better performance if the GIS is designed from the start with dynamic modeling in mind.

PCRaster (http://www.geog.uu.nl/pcraster/) is such a GIS, developed at the University of Utrecht for modeling dynamic environmental processes. It supports a scripting language developed by van Deursen (1995) and others (Wesseling *et al.*, 1996) that uses simple symbols to refer to entire raster representations; thus the command A=B+C results in the cell-by-cell addition of two rasters, rather than the addition of two simple scalar quantities as in most programming languages. PCRaster has been applied to many physical processes, ranging from erosion and mass wasting to groundwater flow. It is readily adapted to the CA models of urban growth mentioned earlier, and to many other domains.

Underlying PCRaster is the notion that continuous fields can be manipulated and transformed through simple symbolic operations. Kemp (1997a, b) and Vckovski (1998) have argued that a symbolic representation of a field can be largely independent of the field's actual representation – for example, that B might represent either a raster or a TIN, or any of the other four field representations. Symbolic manipulation vastly simplifies the specification of GIS operations, since the addition of a TIN and a raster is expressed in the same way as the addition of two rasters, irrespective of the geometric relationship between the TIN triangles and the cells, or of whether the cells in each raster coincide, or have the same size. In this perspective the operation of overlay, often considered the core operation of GIS analysis (Foresman, 1998), becomes implicit and invisible to the user.

These concepts of coupling have been implemented in many examples of environmental modeling with GIS. The issues raised by such activities have been discussed in a series of

conferences beginning in 1991 (the International Conference/Workshop on Integrating GIS and Environmental Modeling), in their published proceedings (Goodchild, Parks, and Steyaert, 1993; Goodchild *et al*., 1996;

http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html), and in other books (Camara, 2002; Clarke, Parks, and Crane, 2001; Skidmore and Prins, 2002). Models have been applied to processes in the atmosphere, to ecological systems, and hydrologic systems, and to the couplings that exist between these systems.

Environmental modeling raises a number of important issues, many of them falling within the domain of GIScience. Scale has already been mentioned, since it is desirable that models be as far as possible invariant under changes of scale. In practice, modelers attempt to implement models at the scales that are characteristic of the process of interest; at coarser scales the predictions will be inaccurate, and at finer scales the model's operations will be to some degree redundant. Uncertainty is another fundamental issue. The inputs to any model are representations, and as such cannot capture all of the detail that exists in the real world, so it is important to understand how uncertainties in inputs propagate through the model to become confidence limits on outputs, particularly if the model is highly non-linear. There has been much interest in modeling uncertainty in geographic data in recent years, and Heuvelink provides an excellent summary of this work (Heuvelink,1998; and see also Burrough and McDonnell, 1998). Uncertainty also exists in the model itself, in its structure and the values of its parameters, and hence it is common to include sensitivity analysis in the application of a model. The topic is addressed in greater detail in Section 5.1.

3. ADVANCES IN THE DATA SUPPLY

3.1 New Sources of Imagery

The past three decades have seen steady advances in the availability of data from satellites, and today remote sensing dominates all other sources of data for environmental management. Satellite orbits are independent of national borders, and the data they produce are in principle cheap and readily available. A wide variety of types of sensors exists today, and the range of options is increasing steadily. Imaging sensors can also be mounted on aircraft, unmanned autonomous vehicles (UAVs), and on the ground, and all of these options are currently being pursued as sources of data for environmental management.

An important distinction should be made at the outset between two different types of application of imagery. *Mapping* applications, and those associated primarily with monitoring and management, make use of imagery to characterize the Earth's surface, and to detect and map change in such variables as land cover class, or in the positions of boundaries. Mapping applications rely heavily on human interpretation, and on automated methods for classification. Imagery is widely used for this purpose in environmental management. *Measurement* applications, on the other hand, treat images as assemblages of signals that can be transformed into estimates of useful parameters, such as biomass density, leaf area, or sea surface temperature. These estimates are then

used as input to dynamic models, or as measurements of the rate of change of critical Earth system parameters. Calculation of parameters from raw measurements often involves the type of static modeling discussed in the previous section.

Sensors and the imagery they produce can be characterized in many ways, and several excellent reviews of Earth imagery and its applications have appeared recently. Sensors can be *passive*, relying on the natural radiation that is reflected or emitted by the Earth's surface and the atmosphere; or they can be *active*, using radiation generated by the sensor itself. In the latter category are radar and laser sensors. The former have the ability to see through cloud, and interferometric radar is increasingly used as a source of precise measurements of topographic elevation (Campbell, 2002). The airborne laser systems known as LiDAR are capable of providing even-higher-precision elevation measurements, to sub-centimeter levels, and of acquiring three-dimensional information on vegetation and structures.

Sensors can also be characterized by their resolutions in the spatial, spectral, and temporal domains. Spatial resolution determines the level of detail that can be perceived on the Earth's surface, and today imagery is available from satellite sensors at sub-meter resolutions. Spectral resolution determines the amount of detail that can be extracted about the nature of the Earth's surface at any point. *Panchromatic* imagery integrates radiation into a single measurement, while sensors such as Landsat's Thematic Mapper integrate parts of the visible and near-infrared spectrum into several distinct *bands*, and *hyperspectral* sensors such as AVIRIS divide the spectrum into large numbers of bands

(224 in the case of AVIRIS). Finally, temporal resolution defines the frequency with which a sensor images any part of the Earth's surface, and is normally expressed in days.

The number of sensors designed for applications in environmental management has multiplied dramatically in the past few years. Several new *commercial* sensors such as IKONOS have been launched, and have pushed the lower limit of spatial resolution to below 1m. This has opened new applications in areas such as the detailed mapping of land cover, and high-precision mapping of infrastructure. Several new nations such as India have entered the business of remote sensing, launching their own satellites for applications in environmental management. The EOS series of satellites, designed by NASA for the measurement of parameters that are important in understanding the global environmental system, include the MODIS sensor, an increasingly popular source of essentially free data for the monitoring of environmental change. There is not sufficient space here to provide a complete review, but see for example Campbell, 2002; Skidmore and Prins, 2002.

3.2 Sensors and Sensor Networks

Besides sensors mounted on aircraft and satellites, environmental managers are just beginning to make use of various forms of ground-based sensors. The Global Positioning System (GPS) allows position on the Earth's surface to be measured using devices no larger than a hand calculator, to +/- 10m or better, and this has proven a boon to field workers who need to find their positions, and the positions of their measurements.

Although GPS signals are obscured by tall buildings and heavy tree canopy, their accuracy has been substantially enhanced in the past few years with the removal of Selective Availability, the protocol that limited the accuracies obtainable by civilian receivers. Differential GPS, which works by comparing signals at field locations to those received by fixed receivers in known positions, allows locations to be determined to 1m, and often less.

Environmental management has benefited from the continuing reduction in size of many ground-based sensors, particularly of such properties as atmospheric temperature, pressure, and humidity; soil moisture content and pH; cloud cover; and canopy closure. With miniaturization has come a lowering of cost, improvements in telemetering, and the potential for installing semi-permanent and dense networks of sensors (National Research Council, 2001). In the long term, there is interesting speculation about the potential of *digital dust*, ultra-miniature and extremely cheap sensors that may one day allow very dense networks of ground-based environmental sensing.

Sensor networks raise interesting questions of *interoperability*, or lack the of it. A network of sensors measuring different parameters, and manufactured by different companies to different specifications, must somehow be integrated if it is to be effective. Two systems are said to be interoperable if their outputs can be integrated and understood. The Open GIS Consortium (http://www.opengis.org/) is actively developing specifications for interoperable sensor networks; if these are successful, then manufacturers will be able to ensure interoperability through adherence to common,

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openly published specifications.

3.3 Archives and Digital Libraries

Our ability to acquire data is now so great that it commonly exceeds our ability both to distribute it, and to make effective use of it. It is said that only a small fraction of all of the bits collected by remote sensing are ever examined in any detail, and an even smaller fraction ultimately leads to new science. The EOS satellites are sending data to Earth at rates on the order of a terabyte a day (1 terabyte $= 10^{12}$ bytes, a quantity that would occupy a standard 56k phone modem for approximately 4 years), yet few researchers have access to storage devices with anything approaching that capacity. Dissemination and use of this cornucopia of data require effective archiving, the ability for users to search across distributed archives for data of interest, and the tools needed to visualize and analyze the data. In recent years an increasing proportion of the total being invested in satellite remote sensing programs has gone to the development of suitable dissemination systems.

A dissemination system has several essential components:

- A collection of archives, each with its own mechanism for search, allowing users who visit the archive to find data sets meeting specific requirements (*visit* normally means remotely, via the Internet). Examples of such archives for geographic data are NASA's system of Distributed Active Archive Centers

(http://nasadaacs.eos.nasa.gov/); the Federal Geographic Data Committee's National Geospatial Data Clearinghouse (http://www.fgdc.gov/); the Alexandria Digital Library (http://www.alexandria.ucsb.edu/); the Global Change Master Directory (http://gcmd.gsfc.nasa.gov/); and the EROS Data Center of the U.S. Geological Survey (http://edc.usgs.gov/).

- A set of recognized standard formats. While it is unreasonable to expect everyone to adopt a single standard for geographic data, it is important that the number of choices be limited to a few, well-documented options.

- A standard for description of data sets, that is, a standard for *metadata*. The Federal Geographic Data Committee's Content Standard for Digital Geospatial Metadata (CSDGM, or the "FGDC Standard"; http://www.fgdc.gov/) is widely used, and several other standards are very similar, including ISO 19115. Metadata are essential for search, as it allows users to express needs in terms that are readily understood by archives.

Ideally, it would be possible for a user to search across any collection of archives simultaneously, provided each archive was sufficiently interoperable with the others. The library community's Z39.50 standard supports this by establishing standard protocols. But the ideal, of a search mechanism that works across the entire Internet, finding any data sets that meet specified requirements, remains elusive (National Research Council, 1999). Unfortunately today's search engines, such as Google or Altavista, rely on keywords in text, and are not effective over the much more specific domain of geographic data. Progress is being made, however, with the development of software agents that search

over defined domains, recognizing and opening standard geographic data formats, and building custom catalogs (see, for example, MapFusion, a product of Global Geomatics Inc., http://www.globalgeo.com/).

Many geographic data sets are vast, and it is common for users to require only subsets. A standard Landsat image or *scene*, for example, covers an area of approximately 100km on a side, and it is very unlikely that a study area would coincide exactly with the boundaries of one or more scenes. Downloading more data than are required can swamp limited bandwidth, especially for users confined to telephone-line connections. Recently, therefore, standards have been developed that allow users to request custom areas, and require the archive to *clip* and *edgematch* data accordingly. These standards also place appropriate headers or *wrappers* on returned data, allowing the receiving system to open and process the data automatically without user intervention, for example by integrating the data with data from other archives, and possibly by changing projection to the one in use at the client. The OGC's web mapping specification (http://www.opengis.org/) is one example of this kind of standard, as is DODS (http://www.unidata.ucar.edu/packages/dods/), a protocol developed in the oceanographic community and now widely adopted in the Earth sciences. For an implementation see ESRI's Geography Network (http://www.geographynetwork.com/), which integrates fully with the company's GIS products, allowing users in effect to treat distributed archives as the equivalent of a vastly enlarged hard drive.

Although much progress has been made in recent years in improving the ability of

researchers and others working in the area of environmental management to discover and

access data, there continue to be serious impediments to this process. As a result, it is

common for the process of discovery and access to occupy substantial time, because of

the need for extensive and lengthy human intervention. Although technologies like

DODS in principle allow access to remote data sources at electronic speed, in practice

data access and integration can be major deterrents to research. Some of the remaining

problems include:

- The existence of multiple, incompatible standards, that work against
  interoperability. Although standards exist in many domains of science and in
  many areas of management, they are often specific to disciplines, organizations,
  and projects. The techniques for translation between different standards are still
  rudimentary, and the problem is becoming more rather than less severe as the use
  of information technology expands, and as new technologies are introduced.
- The lack of metadata for many datasets. Metadata are expensive and time-
  consuming to create, and its benefits are often regarded as too small to justify the
  investment.
- The lack of clear guidelines that would help a researcher in choosing between the
  vast number of possible WWW-based sources of data. Although many large
  archives exist, and most possess excellent search tools, it is generally difficult for
  users to know which archives to search for given types of data, since no
  overarching organization exists. In the absence of catalogs containing general
  descriptions of archive contents (or *collection-level metadata*; Goodchild and

Zhou, 2003), searches must too often rely on personal knowledge, personal

contacts, and time-consuming trial and error.

3.4 Institutional Arrangements

Several trends in recent years have made this situation more rather than less problematic.

Until the 1980s, Federal agencies were virtually the only sources of geographic data.

Virtually all imagery and digitized maps originated with the agencies that could afford

the massive investments needed for satellites, sensors, digitizers, data storage devices,

and human interpretation and compilation of data. Today, however, the situation is

dramatically different. Massive reductions by orders of magnitude in the costs of data

collection systems have meant that virtually anyone can now be a collector and publisher

of geographic data. Farmers investing in precision-agriculture systems now know more

about microscale variation of soil properties than the responsible Federal and state

agencies; cities can create their own maps using GPS and imagery at low cost; and other

countries and levels of government are now significant sources of digital geographic data.

Second, the ability of Federal agencies to supply the rapidly increasing demand for

geographic data has been severely curtailed by budget reductions, and the inability of

agencies to adapt to changing technology and new areas of application. In response to

these and other trends, the National Research Council proposed the concept of a National

Spatial Data Infrastructure (NSDI; National Research Council, 1993). In essence, NSDI

proposes to replace a centralized system of data creation and supply with a decentralized

system, in which spatially continuous coverage at uniform scale would be replaced by a patchwork, varying in scale depending on local needs, and produced by a variety of local and Federal agencies. For NSDI to work, there would have to be common standards, and the technical means to work across boundaries in spite of scale changes and possible mismatches. Since the original proposal, much of NSDI has been put in place, under the coordination of the FGDC, and mandated by an Executive Order.

Unfortunately the unified view promised by NSDI extends only over a subset of geographic data, and addresses only a limited number of national needs. The imagery supply from such agencies as NASA marches to a different drummer, and is managed to meet the needs of the Earth system science research community, under the standards established by this community, rather than as part of NSDI. Similarly the ecological community has established its own metadata standard, EML (ecological metadata language; http://knb.ecoinformatics.org/software/eml/), spanning all types of data of interest to the ecological research community, including geographic data. Searches for geographic data of ecological relevance must therefore use at least two metadata formats: EML and FGDC/CSDGM.

One way to avoid basic incompatibilities between the standards of different communities with overlapping interests would be to use a lighter form of metadata that includes only the elements common to all searches. Domain-specific standards such as EML might be mapped to more general standards for broadly based searches, and used only for relatively precise searches. The Dublin Core metadata standard (http://dublincore.org/) is

an example of such a general-purpose approach that is easily mapped to the more-specialized and domain-specific standards.

4. ADVANCES IN SOFTWARE

Today, a vast array of software resources exist for environmental management. They range from core GIS products to spatial decision support systems, image processing systems, systems for achieving interoperability between data sources, and systems to support search and discovery of geographic data. Although each of these software domains is more or less specific to the needs of environmental management and geographic data, there exist many other types of software that are regularly used by environmental managers and researchers. Besides the basic suite of office products, these include statistical packages such as S, SPSS, or SAS; mathematical packages such as Mathlab; general modeling packages such as STELLA; and visualization packages such as AVS. In all of these cases the software includes at least a rudimentary set of geographic data processing functions.

There is not sufficient space in this review to examine each of these areas separately; instead, the focus will be on changes that have occurred in software engineering and computing in general in the past few years, and their likely impacts on the field of environmental management. These include component-based software design; support for schema development; and the effort to integrate WWW-based services known as the *Grid*.

4.1 Component-Based Software Design

Traditionally, GIS packages have been constructed as monolithic agglomerations of code, and some large commercial GISs have reached on the order of 10^6 lines of source code (a widely used software industry rule of thumb estimates that a professional programmer can produce 10 lines of fully debugged code per day; a large operating system will contain on the order of 10^7 lines of code). In the early 1980s the GIS industry moved quickly to adopt standard relational database management systems, obviating the need to write code to manage basic input and output operations, and thus simplifying the task somewhat. Standard graphics packages were also adopted at about this time, again simplifying the task of managing display devices. But apart from these innovations, the task of constructing a GIS remained monolithic until well into the 1990s.

Recently, however, software developers have been able to take advantage of a new innovation in software engineering known as *component-based* design. In this paradigm, software is constructed as a collection of re-usable modules, each designed to perform well-defined and simple tasks. A given application may require the use of only a small number of these, so the others can be left unloaded. Moreover, component-based design greatly simplifies the task of software management, since each component can be managed, updated, and replaced independently. Components from one package can be readily integrated with components from another, making it possible for applications to take advantage of the functions available in different packages simultaneously. Finally, in

principle it is possible for customers to purchase only the subset of components that they

need, making it much easier for the vendor to customize products for particular niche

markets.

Several standards for component-based software development have been established, of

which perhaps the best-known is Microsoft's COM standard. Many major GIS products

are now COM-compliant, having been extensively re-written to take advantage of the

new architecture; in some cases this was the first complete re-engineering since the early

1980s. Ungerer and Goodchild (2002) use a simple example of GIS analysis to show how

the new approach can be used to build applications that span a popular GIS and a

standard office product, Excel, taking advantage of the geographic-data-processing power

of the former and the table-processing power of the latter. They use the example of a

simple areal interpolation (Goodchild and Lam, 1980), an operation that is conducted on

a routine basis when the zones for which demographic data have been tabulated do not

match the zones for which data are required.

The component-based approach is now widely used for GIS development. But an

interesting question remains concerning the dynamic simulation models reviewed in

Section 2.3. To date, the vast majority of such models have been constructed using

monolithic approaches, with each model being implemented in a separate and often very

large agglomeration of software. The same is generally true of spatial-decision support

systems (SDSS), which have by and large been built independently, from scratch, for

every application. There are obvious advantages to a modular approach that would

recombine each model from generic components, because the cost and time of development of a new model or new SDSS would be greatly reduced. Densham (1991) discusses the concept of a *model-base management system*, but to date such a system has proven remarkably difficult to operationalize (but see Bennett, 1997). The key issue is essentially one of granularity: What are the atomic pieces of a simulation model? Are they individual lines of code, or something larger? Although these questions have been answered effectively for GIS analysis by the developers of component-based systems, the equivalent answers for dynamic modeling have proven much more elusive.

4.2 Schema Development

The relational database management systems that were widely adopted in the 1980s were based on a very simple model of data that could be readily applied to a very wide range of examples, including geographic data. In the relational model (Date, 1975), all data are assumed to relate to well-defined *cases* or *instances*, and to describe those cases through a well-defined set of characteristics or *attributes*. In a GIS example, the cases might represent weather stations, and the attributes would be the weather measurements taken at each station. Data can be arrayed in a table, with the cases in the rows and the attributes in the columns. The power of the relational model lies in its ability to manage data in multiple tables that describe different types of objects and their associated attributes; and to link tables together through common keys. For example, one might record county as an attribute of each weather station, and use this attribute as a common key to link the weather station data to data available for counties, such as agricultural production

statistics. It is not uncommon for advanced GIS applications to involve tens or even hundreds of tables, each describing a different class of features on the Earth's surface.

The relational model dominated GIS thinking in the 1980s and most of the 1990s, and standard database management products such as Oracle, INFO, or Informix were widely used to manage data on a full range of GIS applications. But a sharp change occurred in the late 1990s, driven in large part by two fundamental deficiencies of the relational model. First, since the earliest adoption of the model it had been necessary to separate the tabular information about features and their attributes from the geometric information about feature form, because the latter could not be handled simply within the relational model. This led to an awkward *hybrid* structure (hence, for example, the dual name ARC/INFO for ESRI's leading GIS; see http://www.esri.com/) and meant that software developers could capitalize only partially on the benefits of database management. Second, the relational model had no way of representing the *hierarchical* relationships that exist between many types of geographic features. For example, there are hierarchical relationships between counties and states, and between individual streams and watersheds.

In the late 1990s the GIS industry began to shift to an *object-oriented* approach to data. Three principles underlie the approach. First, all objects are instances of more general classes, a principle that also underlies the relational model. Second, classes can have hierarchical relationships to more general classes, and can share their properties. For example, the class *cat* could be regarded as a subclass of *mammal*; some of the

characteristics of cats are also characteristic of all mammals, but others are specific to cats. This leads to a hierarchical approach to data, in which subclasses *inherit* some of their properties from more general classes. At the top of the inheritance hierarchy are the types of features that are common to all GIS applications: points, lines, and areas.

Third, the object-oriented approach allows *methods* to be *encapsulated* with the classes of objects to which they apply. Common methods include the editing rules that are applied whenever the digital representations of features are modified or created – for example, that all areas must have closed boundaries, or that isolines must not cross eachother.

The shift to object-oriented modeling has meant that GIS users can now take advantage of the many excellent tools that exist to support database design and development. These include Unified Modeling Language (UML; Rumbaugh, Jacobson, and Booch, 1999), and drawing packages such as Microsoft's Visio that allow database designs to be laid out graphically, and then automatically converted into collections of tables with appropriate links (Zeiler, 1999). One of the earliest areas of environmental management to take advantage of these capabilities has been hydrology. Maidment and Djokic (2000) describe a comprehensive schema for hydrologic data that is readily incorporated into an object-oriented GIS. A number of similar schemas have now been developed through the efforts of different application communities (http://arconline.esri.com/datamodels.cfm).

4.3 The Grid

In recent years there has been much research and development effort devoted to the development of a seamless, integrated approach to computing. Now that the vast majority of computers are connected through the Internet, it is argued, the opportunity exists to create a new kind of computing environment – a *cyberinfrastructure* – that will allow researchers and managers to work together in a more integrated way. Instead of needing to collect and integrate all data and software tools relevant to a particular project in the researcher's office computer, it would be possible in this new environment for researchers to access distributed data resources and distributed tools, and to make use of them as if they were local.

Some of the tools needed to achieve this kind of integration were discussed earlier in the section on data access. Another type of support is under development in the form of *services*, or processing capabilities that sites make available to remote users in much the same way that sites make data available to remote users. An example of such a service is a *gazetteer service*, which is defined as a remote capability to transform placenames into coordinates. Rather than having to provide this function locally through one's own GIS, as in the past, it is now possible to use the Alexandria Digital Library's gazetteer service (http://www.alexandria.ucsb.edu/) to do this remotely, by sending a simple message to the service, and receiving the results in return. Such services operate using protocols that allow the service to be fully automated, and therefore to occur at electronic speed. It is likely that such services will grow very rapidly in the next few years, and will replace large areas of processing that researchers now conduct locally.

5. ADVANCES IN GIS REPRESENTATION

The traditional representations used in GIS were discussed earlier in Section 2.1. This section focuses on recent research that has attempted to extend traditional representations, and on the parallel question of uncertainty. In effect, a GIS representation is a set of rules for converting aspects of the real world into the language of computers, which is limited to a two-character alphabet. Standards such as MP3 provide these rules for other domains such as music; in GIS, raster and vector approaches provide two general classes of coding schemes, the specific details being determined largely by the GIS developer.

GIS inherits many of its core concepts from paper maps, and it is still common for GIS to be explained as a technology for capturing and processing the contents of maps. But maps impose many restrictions on geographic data that are not necessary in a digital environment (Goodchild, 2000). First and perhaps most important, maps must of necessity be static, since once printed it is difficult to modify them, and it follows that maps tend therefore to capture only what is relatively static about the Earth's surface. The potential to incorporate time – to move from a spatial to a spatiotemporal basis for GIS – has stimulated much research over the years. Langran (1992) reviewed early work on the topic, while Peuquet (2002) provides a recent overview of the methodological basis of space and time. Today, GIS is increasingly used to store and analyze data on space-time tracks, on events occurring at specific points in space and time, and on changes through time detected by remote sensing.

A second constraint of paper maps is the inability to handle the third dimension effectively. In GIS, elevation is often treated as a function of the two horizontal dimensions, thus avoiding the need to move to a true three-dimensional approach. But applications in subsurface geology and hydrology, oceanography, and atmospheric science all require a full treatment of the third spatial dimension. Substantial effort has gone into integrating GIS with software for three-dimensional representation, but for most purposes GIS remains essentially a two-dimensional technology.

5.1 Uncertainty

The real geographic world is infinitely complex, revealing more and more detail apparently *ad infinitum*. In some cases the rate at which additional detail is revealed is predictable with remarkable precision, leading Mandelbrot (1983) and others to propose the concept of *fractals* to describe the behavior of many real-world phenomena such as coastlines and topography. Today, fractal concepts are widely used to analyze geographic form, and to create realistic simulations of natural landscapes, trees, and other structures (Barnsley, 1988).

It follows that no geographic representation can ever be complete, but must instead approximate, generalize, or abstract a simpler version than exists in reality. The *differences* between a representation and the truth are crucial in many applications of GIS to environmental management, since they ultimately determine the uncertainty associated with predictions and decisions. Early research on this topic focused on the analysis of

error, using conventional methods (Goodchild and Gopal, 1989). But error analysis assumes the existence of a truth, and it is clear that in many situations there is no easy way of defining the true value of an item of geographic information. For example, many if not all of the classifications used for mapping and characterizing soils, land cover, and vegetation are fundamentally vague, and there is no expectation that two independent observers would arrive at the same classification. Hence the term *uncertainty* is now more widely used to discuss the differences between GIS representations and the real world, and between one observer and another.

Extensive research on this topic began in the late 1980s (Goodchild and Gopal, 1989), and very substantial progress has been made. Models now exist to characterize many forms of uncertainty, and for all of the major types of geographic data. Major conferences have been held on the topic, several focusing on environmental management, and several collections have been published (Guptill and Morrison, 1995; Lowell and Jaton, 1999; Mowrer and Congalton, 2000; Shi, Fisher, and Goodchild, 2002). Zhang and Goodchild (2002) provide a recent review of uncertainty, while Hunsaker *et al.* (2001) address issues of geographic data uncertainty in ecology.

6. CONCLUSION

GIS is now widely accepted as an indispensible tool in environmental management. Although it is not the only computer application relevant to the field, or even the only one relevant to geographic data, it is without doubt the dominant application in the

development of environmental policy and in environmental decision-making. Many different GIS products exist from commercial vendors, and several have been developed by academics, some under the open-source paradigm that permits free use.

Given the limited space available, this review has provided little more than a high-level overview of some of the major issues and advances in the use of GIS for environmental management, and in the underlying GIScience. The references will provide much more extensive and detailed sources of additional information.

Several trends are likely to impact the use of GIS in environmental management in the near future. One is continuing progress on interoperability and associated technologies, which will increasingly allow researchers and managers to access and use distributed data and services in what will eventually become a largely seamless and global computing environment. Another is mobility, and the increasing ability to process and analyze information in the field, as it is collected. Field information technologies and field sensors have the potential to revolutionize the practice of environmental science and management, making it possible to perform virtually all tasks in the field, in the presence of ground truth. Third, the increasing sophistication and accuracy of environmental models, and the increasing ability to use them, and integrate them into different research and policy environments, will mean that GIS use becomes increasingly forward-looking, and increasingly relevant to the broader objectives of policy, rather than the narrower objectives of inventory and description.

REFERENCES

Bailey TC, Gatrell AC. 1995. *Interactive Spatial Data Analysis*. Harlow, England: Longman.

Barnsley MF. 1988. *Fractals Everywhere*. Boston: Academic Press.

Bennett DA. 1997. A framework for the integration of geographical information systems and modelbase management. *International Journal of Geographical Information Science* 11(4):337--357.

Bishop M. 2003. *GIScience and Mountain Geomorphology*. In press.

Bradley JC, Millspaugh AC. 1999. *Programming in Visual Basic, Version 6.0*. Boston: Irwin/McGraw-Hill.

Briggs DJ, editor. 2002. *GIS for Emergency Preparedness and Health Risk Reduction*. *Proceedings of a NATO Advanced Study Institute*. Dordrecht: Kluwer.

Burrough PA, McDonnell RA. 1998. *Principles of Geographical Information Systems*. New York: Oxford University Press.

Camara A. 2002. *Environmental Systems: A Multidimensional Approach*. New York:

Oxford University Press.

Campbell JB. 2002. *Introduction to Remote Sensing*. Third Edition. New York: Guilford.

Carey GF, editor. 1995. *Finite Element Modeling of Environmental Problems*. New York: Wiley.

Clarke KC, Parks BO, Crane MP, editors. 2002. *Geographic Information Systems and Environmental Modeling*. Upper Saddle River, NJ: Prentice Hall PTR.

Couclelis H. 1992. People manipulate objects (but cultivate fields): beyond the raster-vector debate in GIS. In *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*, edited by AU Frank, I Campari, U Formentini, pp. 66--77. Berlin: Springer.

Cromley EK, McLafferty SL. 2002. *GIS and Public Health*. New York: Guilford Press.

Darcy H. 1856. *Les Fontaines Publiques de la Ville de Dijon*. Paris: Dalmont.

Date CJ. 1975. *An Introduction to Database Systems*. Reading, Mass.: Addison-Wesley.

Densham PJ. 1991. Spatial decision support systems. In *Geographical Information Systems: Principles and Applications*, edited by DJ Maguire, MF Goodchild, DW Rhind

pp. 403--412. Harlow, UK: Longman Scientific and Technical.

Foresman TW, editor. 1998. *The History of Geographic Information Systems: Perspectives from the Pioneers*. Upper Saddle River, NJ: Prentice Hall PTR.

Fotheringham AS, O'Kelly ME. 1989. *Spatial Interaction Models: Formulations and Applications*. Dordrecht: Kluwer Academic Publishers.

Gatrell AC, Loytonen M, editors. 1998. *GIS and Health*. GISDATA Series No. 6. London: Taylor and Francis.

Goodchild MF. 1992a. Geographical information science. *International Journal of Geographical Information Systems* 6(1):31--45.

Goodchild MF. 1992b. Geographic data modeling. *Computers and Geosciences* 18(4):401--408.

Goodchild MF. 2000. Cartographic futures on a digital Earth. *Cartographic Perspectives* 36:3--11.

Goodchild MF, Lam NS-N. 1980. Areal interpolation: a variant of the traditional spatial problem. *Geoprocessing* 1:297--312.

Goodchild MF, Gopal S, editors. 1989. *Accuracy of Spatial Databases*. New York: Taylor and Francis.

Goodchild MF, Parks BO, Steyaert LT, editors. 1993. *Environmental Modeling with GIS*. New York: Oxford University Press.

Goodchild MF, Steyaert LT, Parks BO, and others. 1996. *GIS and Environmental Modeling: Progress and Research Issues*. Fort Collins, Colorado: GIS World Books.

Goodchild MF, Egenhofer MJ, Kemp KK, Mark DM, Sheppard E. 1999. Introduction to the Varenius project. *International Journal of Geographical Information Science* 13(8):731--745.

Goodchild MF, Anselin L, Appelbaum RP, Harthorn BH. 2000. Toward spatially integrated social science. *International Regional Science Review* 23(2):139--159.

Goodchild MF, Zhou J. 2003. Collection-level metadata. *Geoinformatica* (in press).

Goovaerts P. 1997. *Geostatistics for Natural Resources Evaluation*. New York: Oxford University Press.

Guptill SC, Morrison JL, editors. 1995. *Elements of Spatial Data Quality*. New York: Elsevier Science.

Haines-Young R, Green DR, Cousins S, editors. 1993. *Landscape Ecology and Geographic Information Systems*. New York: Taylor and Francis.

Haining RP. 1990. *Spatial Data Analysis in the Social and Environmental Sciences*. New York: Cambridge University Press.

Haynes KE, Fotheringham AS. 1984. *Gravity and Spatial Interaction Models*. Beverly Hills: Sage Publications.

Heuvelink GBM. 1998. *Error Propagation in Environmental Modelling with GIS*. New York: Taylor and Francis.

Hunsaker CT, Goodchild MF, Friedl MA, Case EJ, editors. 2001. *Spatial Uncertainty in Ecology*. New York: Springer.

Isaaks EH, Srivastava RM. 1989. *Applied Geostatistics*. New York: Oxford University Press.

Johnston, CA. 1998. *Geographic Information Systems in Ecology*. Oxford: Blackwell Science.

Kemp KK. 1997a. Fields as a framework for integrating GIS and environmental process

models. Part 1: Representing spatial continuity. *Transactions in GIS* 1(3):219--234.

Kemp KK. 1997b. Fields as a framework for integrating GIS and environmental process models. Part 2: Specifying field variables. *Transactions in GIS* 1(3):235--246.

Lam NS-N. 1983. Spatial interpolation methods: a review. *The American Cartographer* 10:129--49.

Lang L. 2000. *GIS for Health Organizations*. Redlands, Calif.: ESRI Press.

Langran G. 1992. *Time in Geographic Information Systems*. New York: Taylor and Francis.

Longley PA, Goodchild MF, Maguire DJ, Rhind DW. 2001. *Geographic Information Systems and Science*. New York: Wiley.

Lowell K, Jaton A. 1999. *Spatial Accuracy Assessment: Land Information Uncertainty in Natural Resources*. Chelsea, Michigan: Ann Arbor Press.

Maidment D, Djokic D, editors. 2000. *Hydrologic and Hydraulic Modeling Support with Geographic Information Systems*. Redlands, California: ESRI Press.

Mandelbrot BB. 1983. *The Fractal Geometry of Nature*. San Francisco: Freeman.

Mowrer HT, Congalton RG, editors. 2000. *Quantifying Spatial Uncertainty in Natural Resources: Theory and Applications for GIS and Remote Sensing*. Chelsea, Michigan: Ann Arbor Press.

National Research Council. 1993. *Toward a Coordinated Spatial Data Infrastructure for the Nation*. Washington, DC: National Academy Press.

National Research Council. 1999. *Distributed Geolibraries: Spatial Information Resources*. Washington, DC: National Academy Press.

National Research Council. 2001. *Embedded, Everywhere: A Research Agenda for Networked Systems of Embedded Computers*. Washington, DC: National Academy Press.

Nyerges TL. 1993. Understanding the scope of GIS: its relationship to environmental modeling. In *Environmental Modeling with GIS* edited by MF Goodchild, BOParks, LT Steyaert, pp. 75--93. New York: Oxford University Press,.

O'Sullivan D, Unwin DJ. 2003. *Geographic Information Analysis*. New York: Wiley.

Parker DC, Berger T, Manson SM, editors. 2002. *Meeting the Challenge of Complexity: Proceedings of a Special Workshop on Land Use/Land Cover Change, Irvine, California, October 4-7, 2001*. CIPEC Collaborative Report CCR-3. Bloomington: Indiana

University, Center for the Study of Institutions, Population, and Environmental Change.

http://www.csiss.org/events/other/agent-based/additional/proceedings.pdf

Peuquet DJ. 2002. *Representations of Space and Time*. New York: Guilford.

Razavi AH. 2002. *ArcView GIS Developer's Guide: Programming with Avenue*. 4th Edition. Albany, NY: Onword Press.

Rumbaugh J, Jacobson I, Booch G. 1999. *The Unified Modeling Language Reference Manual*. Reading, Mass.: Addison-Wesley.

Serra JP. 1982. *Image Analysis and Mathematical Morphology*. New York: Academic Press.

Shi W, Fisher PF, Goodchild MF, editors. 2002. *Spatial Data Quality*. New York: Taylor and Francis.

Skidmore AK, Prins H. 2002. Environmental Modelling with GIS and Remote Sensing. New York: Taylor and Francis.

Tomlin CD. 1990. *Geographic Information Systems and Cartographic Modeling*. Englewood Cliffs, NJ: Prentice Hall.

Torrens PM, O'Sullivan D. 2001. Cellular automata and urban simulation: where do we go from here? *Environment and Planning B* 28:163--168.

Ungerer MJ, Goodchild MF. 2002. Integrating spatial data analysis and GIS: a new implementation using the Component Object Model (COM). *International Journal of Geographical Information Science* 16(1):41--54.

van Deursen WPA. 1995. *Geographical Information Systems and Dynamic Models: Development and Application of a Prototype Spatial Modelling Language*. Utrecht: Koninklijk Nederlands Aardrijkskundig Genntschap/Faculteit Ruimtelijke Wetenschappen Universiteit Utrecht.

Vckovski A. 1998. *Interoperable and Distributed Processing in GIS*. New York: Taylor and Francis.

Wesseling CG, Karssenberg D, Burrough PA, van Deursen WPA. 1996. Integrating dynamic environmental models in GIS: the development of a dynamic modelling language. *Transactions in GIS* 1(1):40--48.

White R, Engelen G. 1997. Cellular automata as a basis for integrated dynamic regional modelling. *Environment and Planning B* 24:235--246.

Wischmeier WH, Smith DD. 1965. *Predicting Rainfall-Erosion Losses from Cropland*

East of the Rocky Mountains: Guide for Selection of Practices for Soil and Water Conservation. Agriculture Handbook No. 282. Washington, DC: U.S. Department of Agriculture.

Worboys MF. 1995. *GIS: A Computing Perspective*. New York: Taylor and Francis.

Wright DJ, Goodchild MF, Proctor JD. 1997. Demystifying the persistent ambiguity of GIS as 'tool' versus 'science'. *Annals of the Association of American Geographers* 87(2):346--362.

Zeiler M. 1999. *Modeling Our World: The ESRI Guide to Geodatabase Design*. Redlands, California: ESRI Press.

Zhang J, Goodchild MF. 2002. *Uncertainty in Geographic Information*. New York: Taylor and Francis.